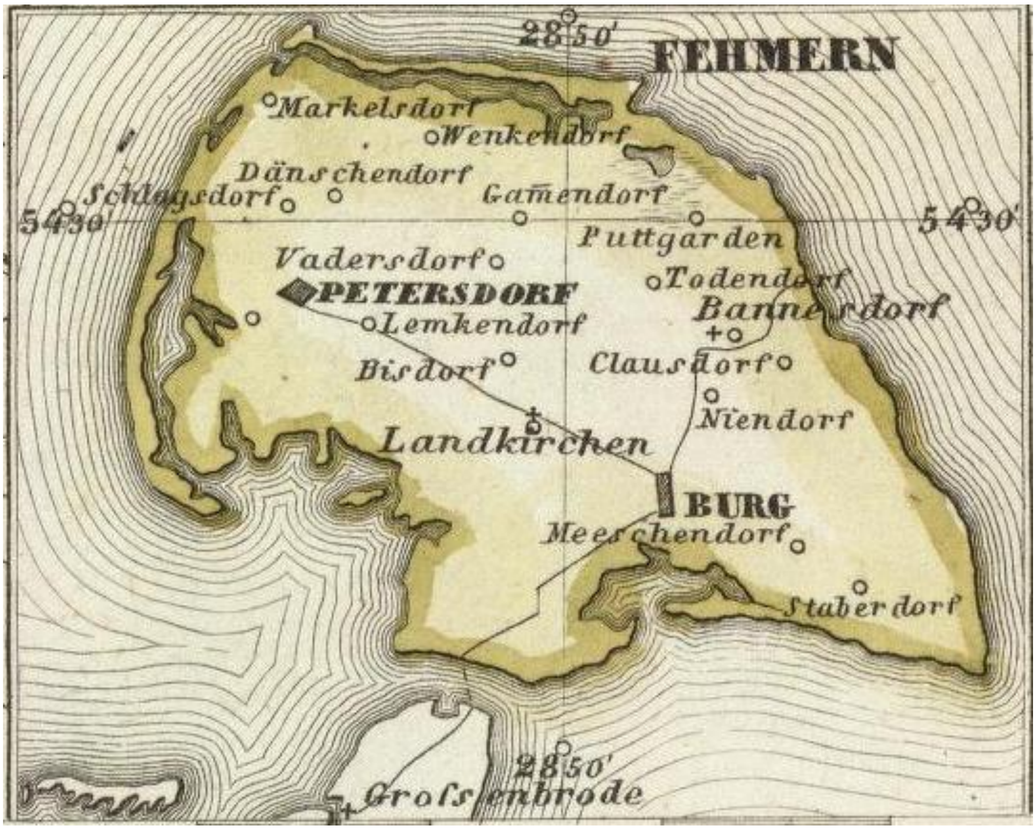
Final Report

FEHMARNBELT FIXED LINK HYDROGRAPHIC SERVICES (FEHY)

Marine Soil - Baseline

Coastal Morphology along Fehmarn and Lolland

E1TR0056 - Volume III



Historical Map of Fehmarn. Meyer's Handatlas 1852, No 138, Herzogthum Schleswig. From David Rumsey Map Collection, www.davidrumsey.com

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Please cite as:

FEHY (2013). Fehmarnbelt Fixed Link EIA.

Marine Soil - Baseline.

Coastal Morphology along Fehmarn and Lolland.

Report no. E1TR0056 - Volume III

Report 212 pp
One appendix (ISBN 978-87-92416-34-6)

May 2013

ISBN 978-87-92416-71-1

Maps:
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Landesamt für Vermessung und Geoinformation Schleswig-Holstein (formerly Landesvermessungsamt Schleswig-Holstein) GeoBasis-DE/LVermGeo SH.
Model software geographic plots: Also data from Farvandsvæsenet and Bundesamt für Seeschifffahrt und Hydrographie

Photos:
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Co-financed by the European Union
Trans-European Transport Network (TEN-T)

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APPENDICES

Note to the reader:
In this report the time for start of construction is artificially set to 1 October 2014 for the tunnel and 1 January 2015 for the bridge alternative. In the Danish EIA (VVM) and the German EIA (UVS/LBP) absolute year references are not used. Instead the time references are relative to start of construction works. In the VVM the same time reference is used for tunnel and bridge, i.e. year 0 corresponds to 2014/start of tunnel construction; year 1 corresponds to 2015/start of bridge construction etc. In the UVS/LBP individual time references are used for tunnel and bridge, i.e. for tunnel construction year 1 is equivalent to 2014 (construction starts 1 October in year 1) and for bridge construction year 1 is equivalent to 2015 (construction starts 1st January).

1 EXTENDED SUMMARY

This report covers the baseline description of the coastal section at Lolland and Fehmarn. The description covers the stretch between Kramnitze and Hyllekrog along the south coast of Lolland. At Fehmarn, the coastline between Markelsdorfer Huk and the beach off Klausdorf are described.

The report covers the following main parts:

- Geological description
- Description of the coastlines of Lolland and Fehmarn including:
    - State of the present coastline and structures
    - Historical and recent shoreline changes
    - Coastal profiles and sea bed conditions
    - Longshore sediment and transport evolution
- Present pressures
- Mapping of importance of coastal sections

A summary of the main findings is included below.

1.1 Geology

The landscape of the area is shaped by the ice masses mainly during the last Ice Age. Since the final retreat of glaciers from the south-western Baltic area, the Fehmarnbelt has been characterised by highly variable sedimentary processes and environments, when the outflow from the Baltic Sea to Kattegat through the Great Belt and Øresund changed position several times. The present day topography and bathymetry originate from the last Ice Age which ended about 10 000 Before Present [B.P.], however with varying water level in the period.

The upper subsoils in the Fehmarnbelt consist mostly of glacial meltwater sand covered by clays and topped by post glacial marine sand, gyttja and peat. Beneath these layers are mostly glacial tills (also called boulder clay or moraine clay) of different types with local pockets of meltwater sand and silt, see Figure 1.1. Deeper layers are chalk and paleogene clay older than the Quaternary.

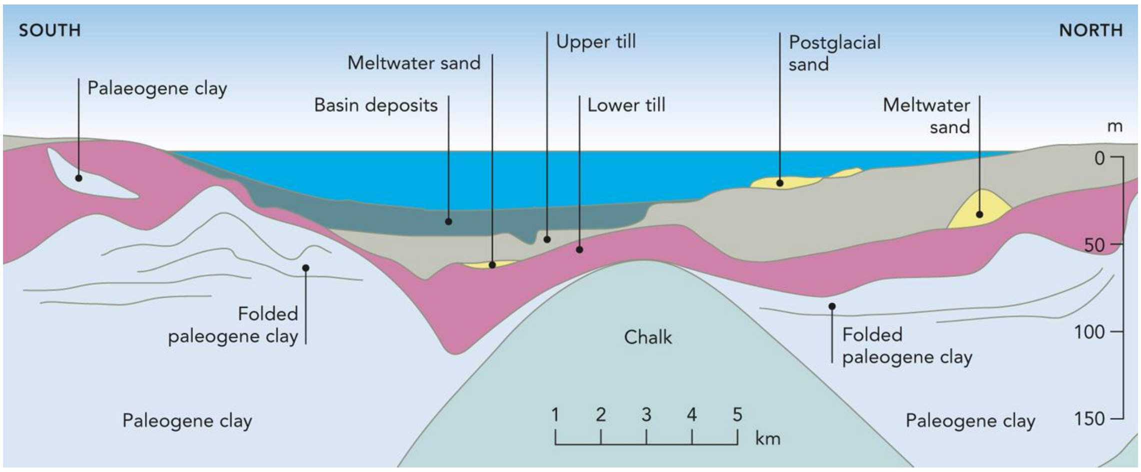

Figure 1.1 The geology in the Fehmarnbelt. From http://www.femern.com/

1.2 Lolland coast

1.2.1 State of the present coastline and structures

The south coast of Lolland consists of low-lying land, which is protected by a major sea-dike constructed following a severe storm in 1872. The sea-dike was finished in 1877 and covers the entire south coast of Lolland from Hyllekrog in the east to "Albuen" in the west, see Figure 1.2.

Kramnitze to Rødbyhavn

The characteristics of this coastal section, a stretch of about 8.4 km, vary between sections with sandy beaches and sections, where the dike is protected by revetments to prevent erosion. The revetments consist of large stones. An overview of the structures along the section is provided in Figure 1.3.

Kramnitze Harbour creates a semi-sheltered area for waves from westerly directions east of the harbour. The beach, along this about 800 m long stretch, is 15-20 m wide and high dunes are present. From the central part of Kramnitze town and about 700 m further eastward, there is no beach in front of the dike, and the dike is protected by a revetment along this section.

The beach in front of the lake/wetland area Skarholm is characterised by having a sandy beach with some gravel and a narrow dune in front of the dike. Further east of Skarholm towards Bredfjed summerhouse area, the shoreline is again protected by a revetment, see photo in Figure 1.4.

The 3 km stretch from the western part of Bredfjed to Lalandia has a fine sandy beach with some gravel, and in front of the eastern part of Lalandia there is a wide sandy beach.

Rødbyhavn

The present Rødbyhavn was built in 1962-1963. The breakwaters of the harbour extend 560 m from the coast and the dredged channel to the harbour is maintained to a depth of 8.5 m DVR90. Rødbyhavn blocks the natural net eastward littoral drift along the shoreline and west of the harbour a 0.9 km long sand accumulation has built up, see Figure 1.5. Accumulation still takes place and some sediment is bypassing the harbour breakwater. Practically all the sand bypassing the breakwater is depositing in a sedimentation reservoir constructed along the west side of the navigation channel. The reservoir reduces sedimentation in the navigation channel or in the harbour basin. The shoreline east of the harbour is heavily protected by a rubble mound. No accumulation of sand is seen east of the harbour.

Rødbyhavn to Rødsand Lagoon
The coastline between Rødbyhavn and Hyllekrog, a stretch of about 8.2 km, is generally a fairly straight coastline. For an overview of this section of the coastline and the coastal structures along the coast, see Figure 1.6. The western part of the section between Rødbyhavn and Hyldtofte Østersøbad is characterised by a revetment and no beach. Stretches of the coast between Hyldtofte Østersøbad and Hyllekrog vary between sections protected by a revetment (typically without a beach) and sections with sandy beaches.

The revetment protecting the shoreline and dike against erosion extends about 3.8 km towards the southeast from the eastern breakwater of Rødbyhavn to Hyldtofte Østersøbad. No beach is seen in front of the revetment due to the lack of supply of sediments from east since Rødbyhavn blocks the natural transport of sand along the coast as described above.

Ten individual shore-parallel breakwaters were constructed and sand was filled in behind the breakwaters in front of the summerhouse area, Hyldtofte Østersøbad, in 1999, see Figure 1.7. Small sections of beaches are now suspended between the breakwaters.

Along the 1.9 km long stretch from Hyldtofte Østersøbad to Brunddragene, the dike is protected by a revetment. The revetment along this section is partly exposed and partly covered in sand and low dunes are found. Sand undulations of the coastline and remains of small groynes are also seen.

The beach off Brunddragene is characterised by sandy beaches and a dune area.

The Hyllekrog, Western Rødsand and Eastern Rødsand are natural barrier islands by which the Rødsand Lagoon is partly separated from the Fehmarnbelt. The gaps between the barrier islands are as such important for the water exchange between the Rødsand Lagoon and the Fehmarnbelt. Hyllekrog is connected to Lolland in its western part and does therefore have the characteristics of a spit.

The barrier islands exist as natural formations formed by a combination of onshore transport of sand from the seabed in front of the formations and supply of sand from the adjacent coasts by the littoral drift.

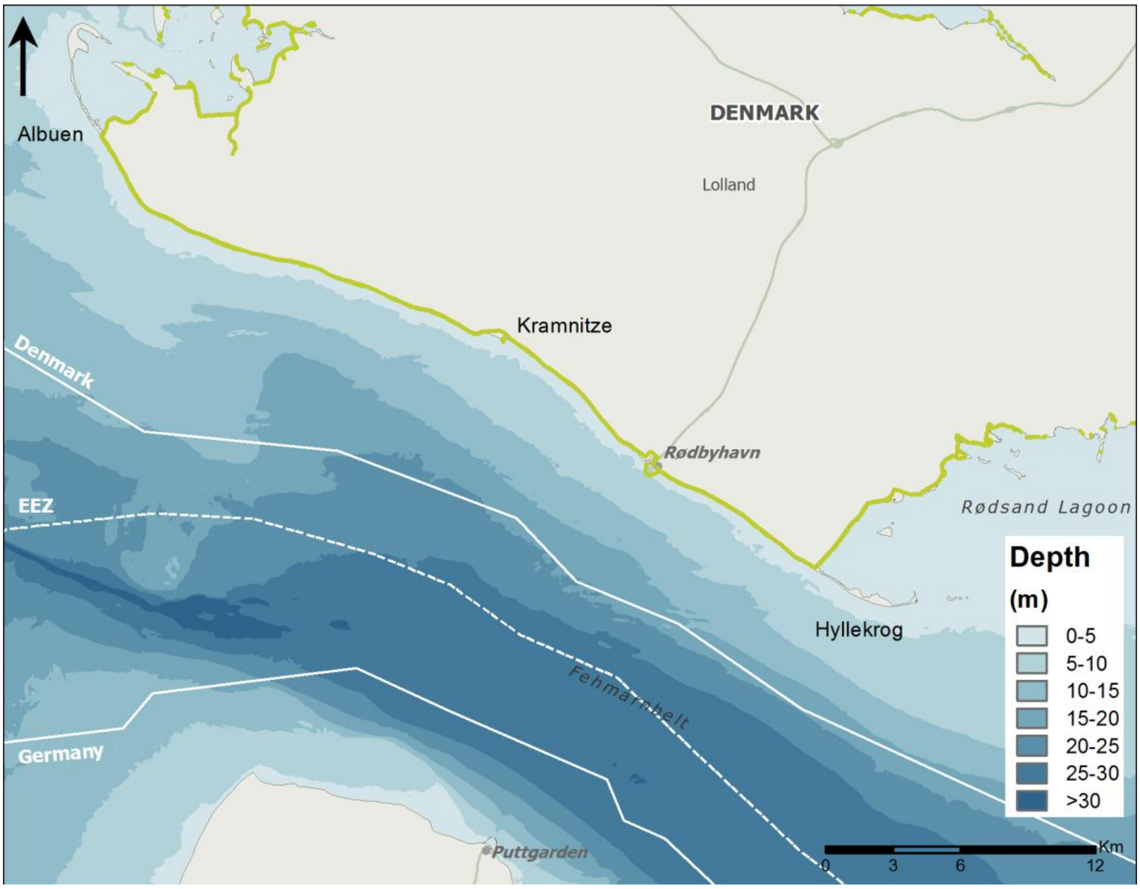

Figure 1.2 Overview over the dike along the South coast of Lolland (green line)

Figure 1.3 Overview of coastline and coastal structures from Kramnitze to Rødbyhavn. Aerial photo from 2009 (©COWI Orthophoto April 2009)

Figure 1.4 Protected section between Skarholm and Bredfjed summerhouse village, photo taken from the west end of the village

Figure 1.5 Sand accumulation with a wide beach and dune area west of Rødbyhavn

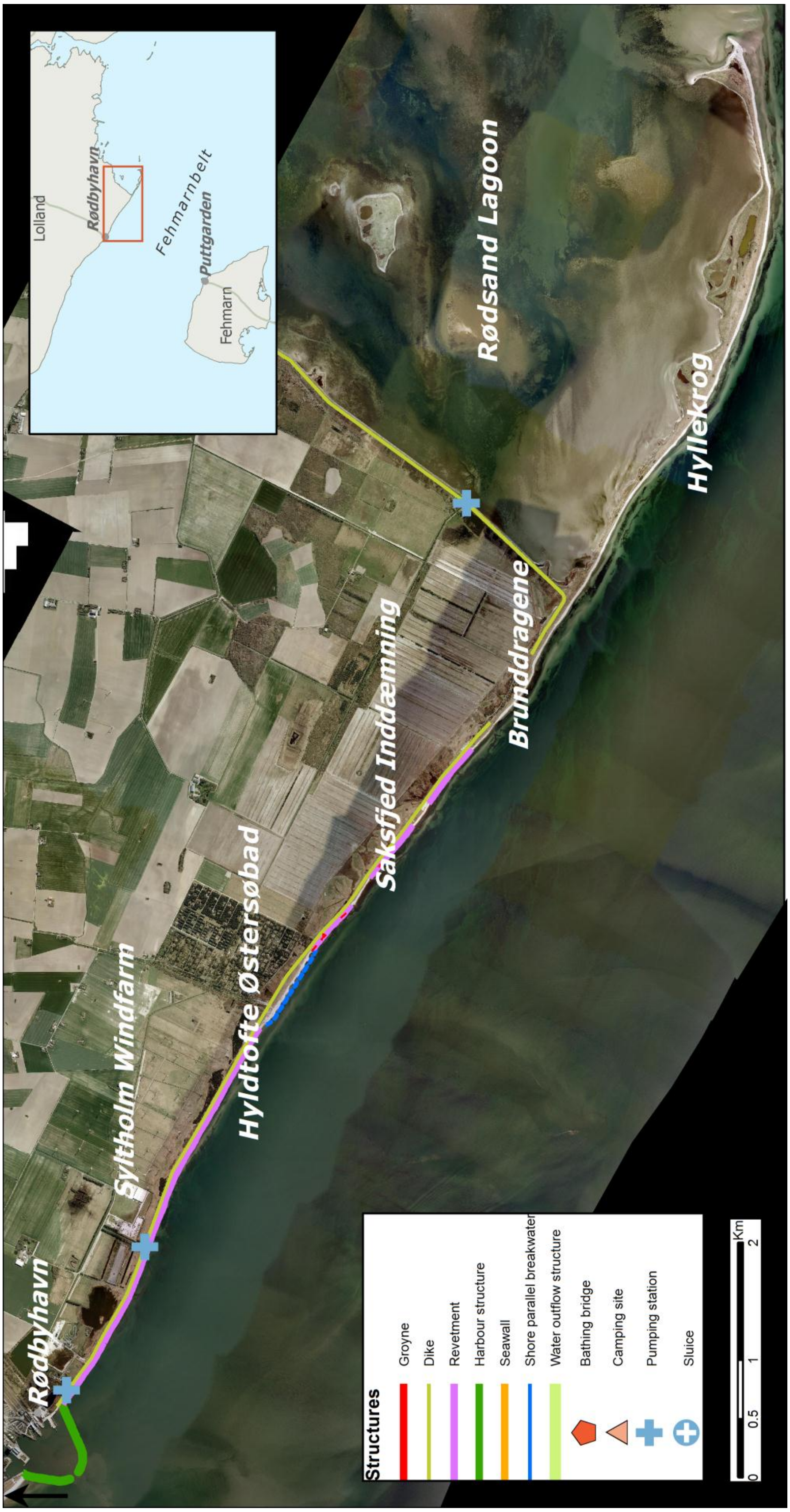

Figure 1.6 *Overview of coastline and coastal structures from Rødby Ferry Harbour to Hyllekrog. Aerial photo from 2009 (©COWI Orthophoto April 2009)*

Figure 1.7 Hyldtofte Østersøbad. Aerial photo from 2009 (©COWI Orthophoto April 2009)

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1.2.2 Historical shoreline changes

An extreme storm hit the Baltic area on 12-14 November 1872. The event caused major flooding on Lolland and initiated construction of massive dikes to protect the hinterland.

Large shallow coastal lagoons were cut off from the sea by the construction of the dike and were reclaimed; see an example in Figure 1.8. The historic dikes and associated reclamation works are of major importance for the present-day appearance of the coastal areas.

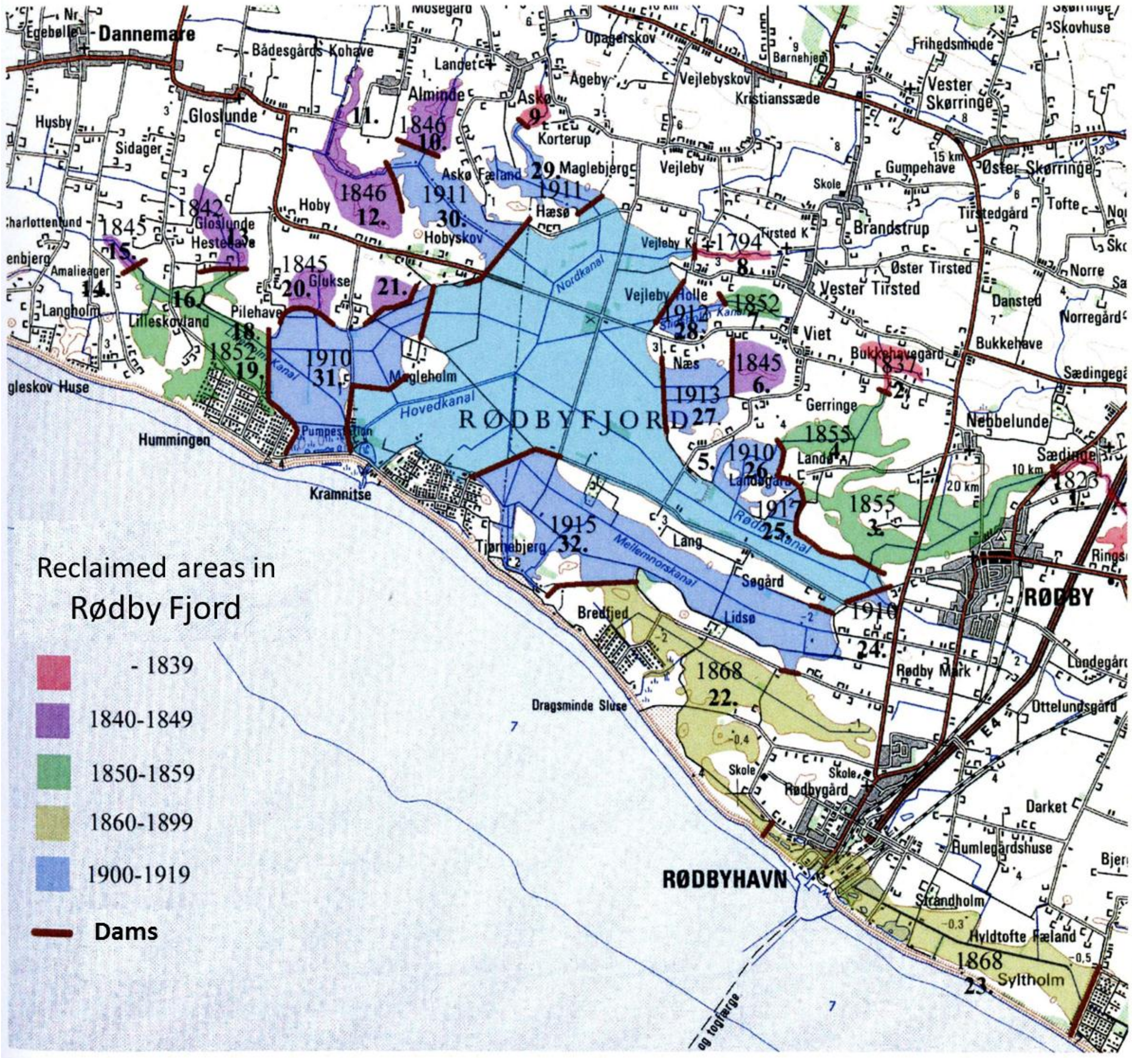

Figure 1.8 Overview of reclamations around Rødbyhavn and the year of finalisation of the reclamations (Translated to English from Hyldtoft, 2009, ©Museum Lolland-Falster)

1.2.3 Coastal profiles and sea bed conditions

The coastal profiles show in general a relatively steep shoreface to a water depth of 4-6 m. Further offshore the slope becomes gentler. The nearshore parts of the coastal profiles east of Rødbyhavn are very steep and the revetment extends into the water to a depth of about 1.5-2.5 m.

A narrow band of mobile sediments (mainly sand) is found along the coast of Lolland, while coarser sediments with patches of sand are seen at greater water depths. The band has a width of less than a few hundred metres along the Lolland coast, except for the accumulation zone west of Rødbyhavn where fine material extends to about 500 m from the shoreline.

1.2.4 Sediment budget

The transport of sediment in the nearshore zone is calculated. The variation in the transport rates along the coastline, i.e. the sediment budget, indicates areas prone to retreat (erosion) or advance (accumulation) of the shoreline. The sediment budgets west and east of Rødbyhavn are shown in Figure 1.9 and Figure 1.10.

West of Rødbyhavn
A net eastwards transport rate of 17,000-32,000 m^3/year is found along this section, see Figure 1.9. The net transport rate decreases from about 32,000 m^3/year west of Bredfjed to about 17,000 m^3/year at the harbour. This indicates a net input of about 15,000 m^3/year to this coastal section from the west.

The majority of this volume deposits in the accumulation area west of Rødbyhavn, where the transport rate decreases rapidly.

The sand accumulation along the 800-900 m long beach corresponds well to observations of the deposited volumes of sand in this area estimated from the advance of the shoreline. The calculated by-pass of sand around the western breakwater corresponds to the maintenance dredging of sand in the access channel, reservoir and harbour basins.

West of Rødbyhavn at the bay east of Lalandia, the shoreline curves around. This gives a tendency for erosion. A revetment has been constructed to protect the coast at this section.

Between Bredfjed and Lalandia there is a tendency for persistent deposition leading to an average shoreline advance of about 0.5-1.0 m/year. The deposition corresponds to a reduction in the net transport caused primarily by the gradual change in the beach orientation.

The gross transport rates along the coastal section are in the order of 50,000-70,000 m^3/year.

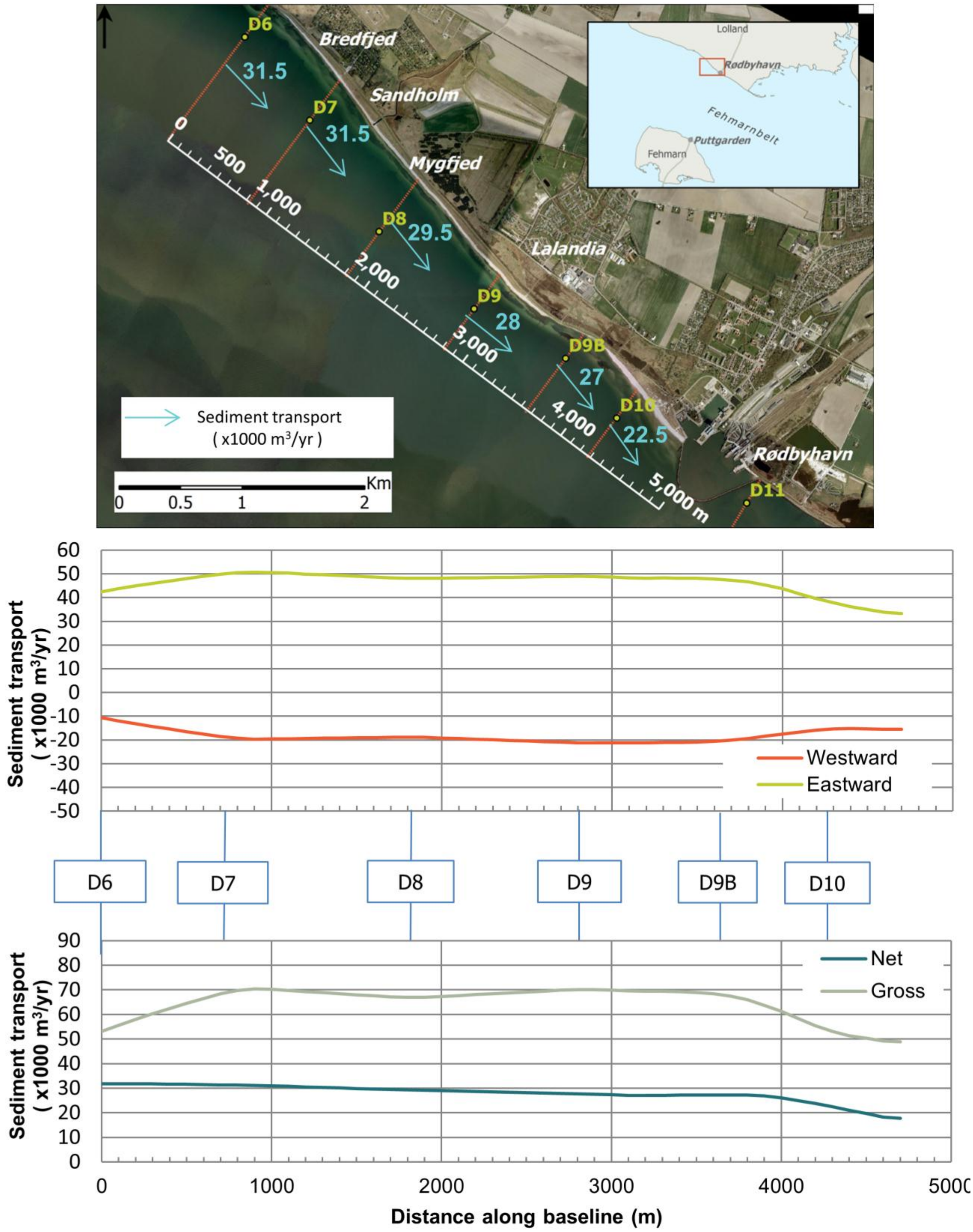

Figure 1.9 Average littoral drift transport rates west of Rødbyhavn (top figure). Middle figure: west- and east going transport components. Lower figure: net and gross transport rates. Aerial photo from 2009 (©COWI Orthophoto April 2009)

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East of Rødbyhavn

The net transport gradually increases east of the harbour to be about 15,000-20,000 m^3/year west of Hyldtofte Østersøbad. The increase in the net transport along this stretch is reflected in the situation with no sandy beaches east of the harbour and a hard seabed with coarse sediments which has been starved from finer sediments. Artificial nourishment (1993 and 1999) and erosion from the coastal profile balance the sediment budget in this area.

The net transport rates increase slightly towards the east in the area of the breakwater scheme at Hyldtofte Østersøbad. This is due to the waves turning slightly clockwise and the coast gets more exposed to waves from west and west-northwest.

Southeast of Hyldtofte Østersøbad, the beach curves clockwis and the net transport rates reduce slightly causing a small accumulation area southeast of the breakwater scheme, around D15 in Figure 1.10.

Further southeast of Hyldtofte Østersøbad in front of Saksfjed Inddæmning and towards Brunddragene a slightly increasing net transport rate is found causing shoreline retreat. The increase of the transport is the result of several physical mechanisms. The coast becomes more exposed to westerly and north-westerly waves as well as the south-easterly waves, which become more important. The beach orientation turns slightly anti-clockwise increasing the eastward transport rates. On the other hand, the beach gradually becomes less steep from about Hyldtofte Østersøbad and eastwards. The littoral drift decreases for decreasing profile steepness. The gross transport rates increase from about 15,000 m^3/year at the harbour to about 80,000 m^3/year off Brunddragene.

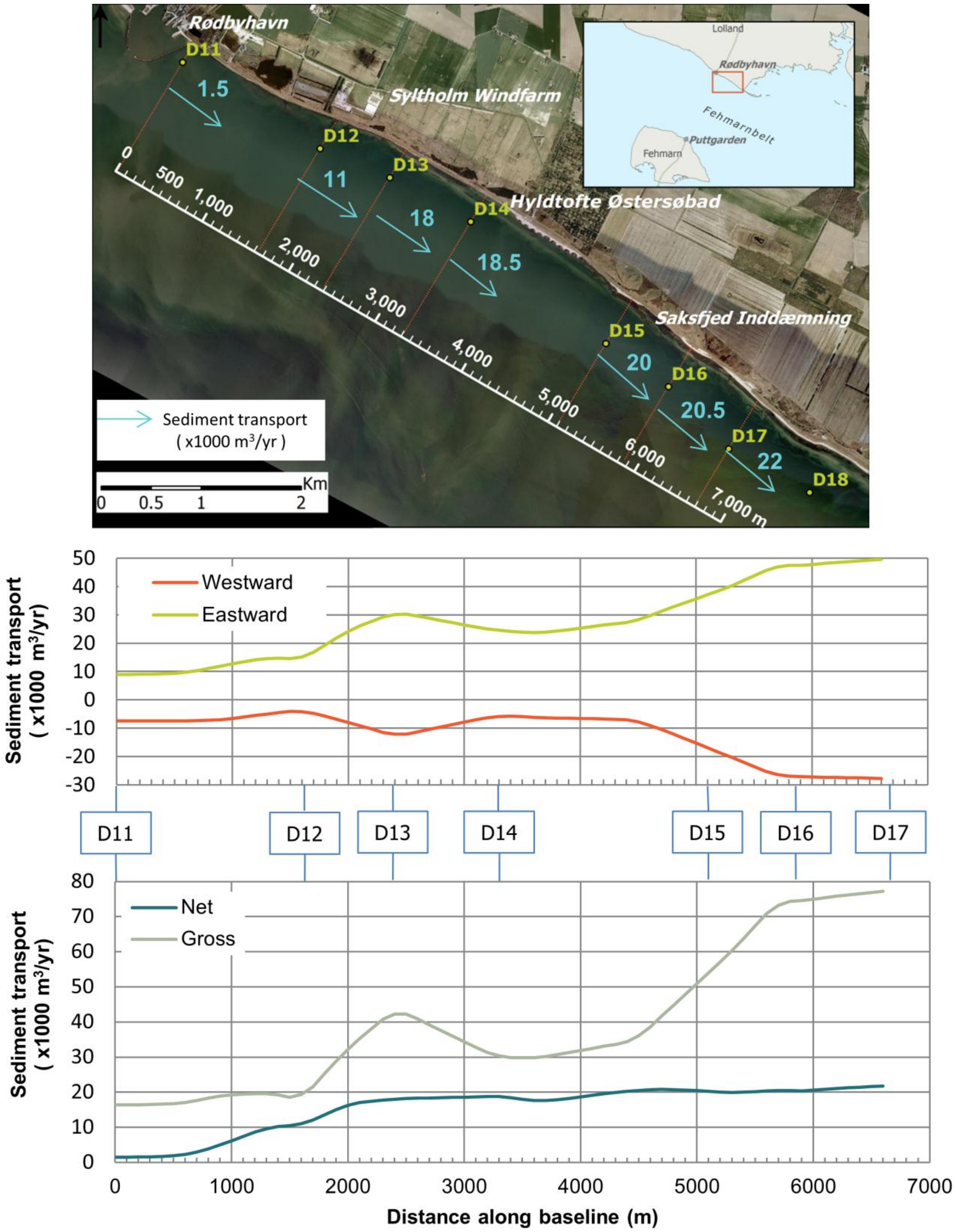


Figure 1.10 *Average littoral drift transport rates east of Rødbyhavn (top figure). Middle figure: east- and west going transport conditions. Lower figures: net and gross transport rates. Aerial photo from 2009 (©COWI Orthophoto April 2009)*

1.3 Fehmarn coast

1.3.1 State of the present coastline and structures

The north and northeast coast of Fehmarn from Markelsdorfer Huk in the west to the beach off the village of Klausdorf in the southeast is low-lying land. The entire north coast of Fehmarn is protected by a dike constructed after the severe 1872-storm, see Figure 1.11.

Markelsdorfer Huk to Grüner Brink

The entire north coast of Fehmarn is characterised by beaches, sand spits, coastal lagoons, dune areas, meadows and salt marches. An aerial photo from 2009 of the coastline and an overview of the structures along the coast are provided in Figure 1.12.

Markelsdorfer Huk is a marine foreland. Markelsdorfer Huk is composed of a system of spits and barrier island formations consisting of sand, gravel and shingle. The system of sand spits has formed some coastal lagoons.

Along the stretch from Markeksdorfer Huk to Gammendorf a series of irregular beach undulations is present. The width of the beach varies along this stretch and some places a relatively wide coastal area can be seen with dunes in front of the dike.

Grüner Brink to Puttgarden

Grüner Brink is a special coastal morphological feature, which stretches along the coast from 2.4 km to 4.7 km west of Puttgarden.

The Grüner Brink is a system of coastal lagoons created by the formation of natural sand spits, which have developed as a result of the special wave conditions in the area. The wave climate off Grüner Brink is dominated by very oblique waves from WNW - NW-erly directions which cause the formation of sand spits separated from the coast, as in the case of Grüner Brink.

The morphological development of Grüner Brink is sketched in Figure 1.13. The alongshore transport of sand from the coast east of Grüner Brink is transported along the submerged part of the formation (extending 300-600 m into the water from the shoreline) and feeds the spit in the east, but also the submerged 'offshore front'.

East of Grüner Brink there is an approximately 1 km long sandy beach. There is a drainage outlet in the middle of this section from the Blankenwisch wetland, which is protected by two 30 m long rubble mound jetties.

Between the eastern part of Grüner Brink and Puttgarden, a 350 m long groyne was constructed in 1960 at the same time as Puttgarden. The groyne is detached from the shoreline with a gap between the groyne and the shoreline of about 90 m.

Between the long groyne and Puttgarden, there is only a very narrow shingle beach in front of the dike.

Puttgarden

Puttgarden was constructed in 1962-1963. The harbour extends to about 520 m from the shoreline. The navigation channel leading to the harbour has a depth of 8.5 m.

It is also noted that there is hardly any sand accumulation west of Puttgarden, which indicates that there is no sand supply to this area. Also, no sedimentation in the navigation channel is reported.

A small sand accumulation is located SE of the east breakwater of Puttgarden, in the corner between the breakwater and the coastline, see Figure 1.14.

Puttgarden to Klausdorf
The coastline southeast of Puttgarden is in general characterised by low cliff formations. A low grass-covered dike, however, protects the low-lying land in the area off the village Presen. For an overview of this part of the coastline and the coastal structures see Figure 1.15.

The village of Marienleuchte is located about 700 m SE of Puttgarden immediately south of the headland Ohlenborgs Huk, which is an about 5 m high till formation. Small groynes, a vertical seawall, and stone glacis/revetments protect the coastal stretch off Ohlenborgs Huk and Marienleuchte from erosion. Accumulation of sediment occurs at the southeastern side of the small groynes and indicates a net transport of sand towards northwest.

Immediately south of Marienleuchte, the level of the hinterland falls. A low grass covered dike protects the low-lying land in the area of the village of Presen from just south of the village of Marienleuchte to the cliff east of Klausdorf, see Figure 1.16. The beach in front of the dike is sandy with some gravel.

The drainage outlet in the northern part of Presen is protected by rubble mound jetties, which act as groynes.

The dike terminates towards south where it meets the high till formation off Klausdorf. The shoreline along the coast off Klausdorf is an open till cliff. A shingle beach with boulders is in front of the cliff. The cliff and shingle/boulder type of beach continues further SSE-ward.

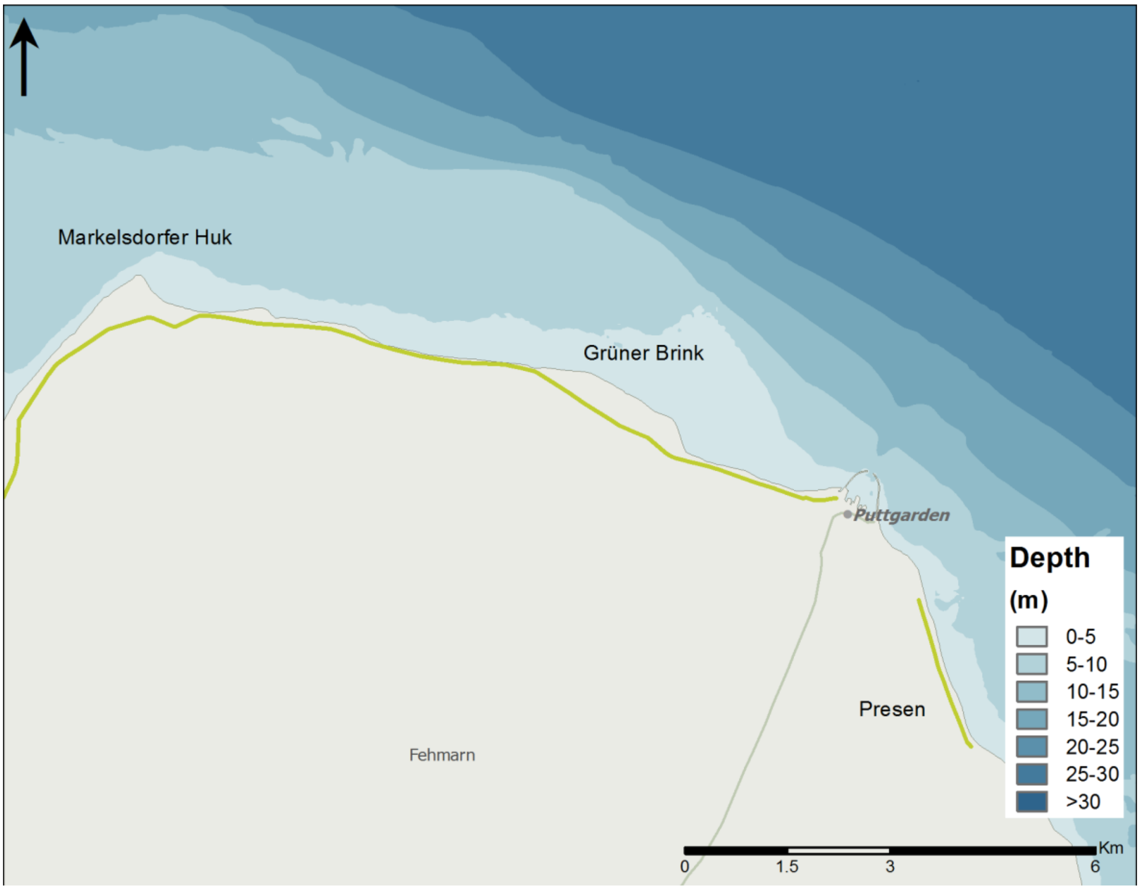


Figure 1.11 Overview over the dike along the west, north and northeast coasts of Fehmarn (green line)

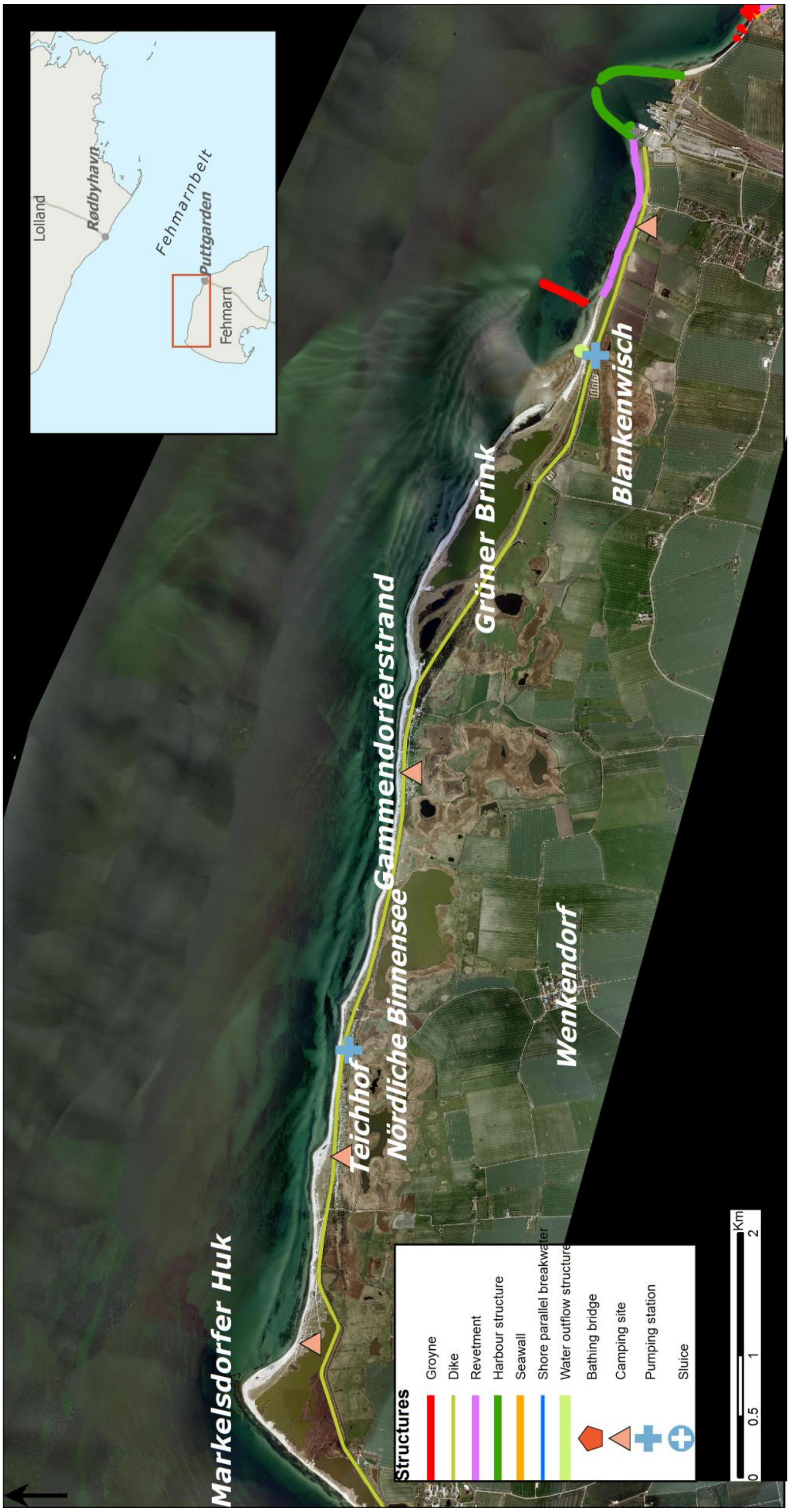


Figure 1.12 Overview of coastline and coastal structures from Markelsdorfer Huk to Puttgarden. Aerial photo from 2009 (©COWI Orthophoto April 2009)

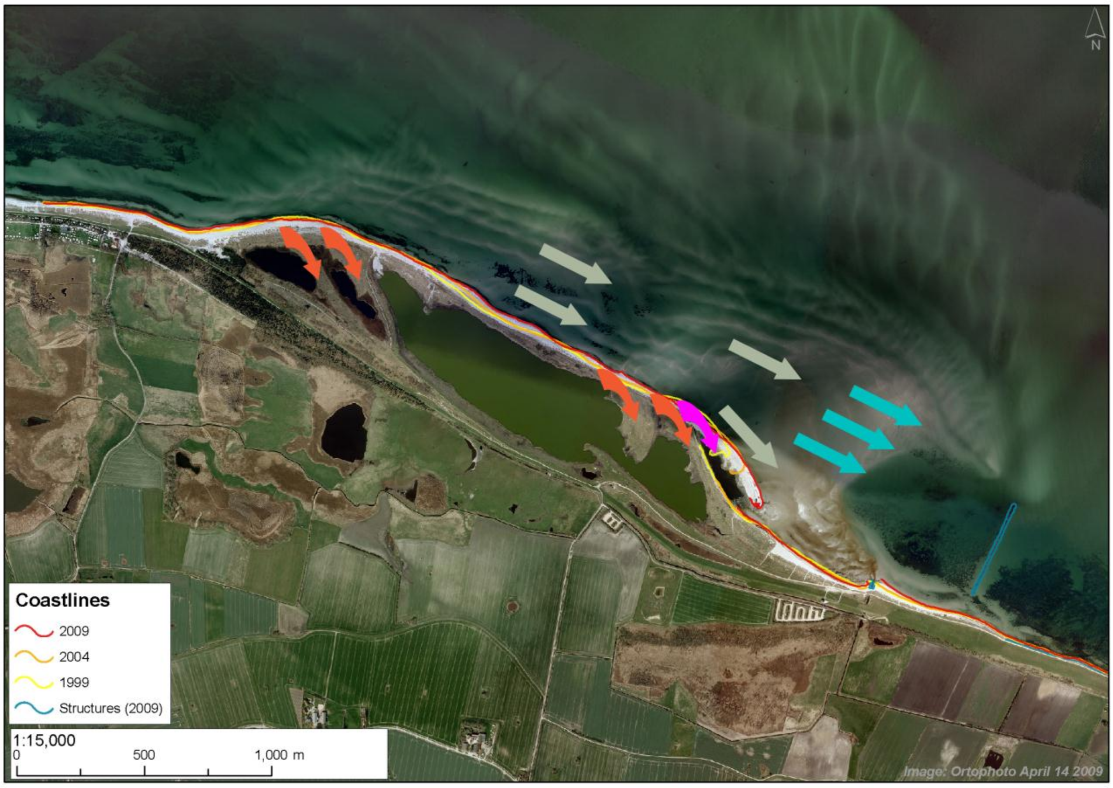


Figure 1.13 *Grüner Brink formation, aerial photo 2009, with coastlines from 1999, 2004 and 2009, see Section 4.3. Overall morphological development of Grüner Brink indicated with arrows: red arrows indicate remains of old spits. Pink arrow indicates present day movement of the spit. Blue arrows indicate progression of the formation below the water level. Grey arrows indicate transport of sediment which deposits on the steep slope or offshore front. Aerial photo from 2009 (©COWI Orthophoto April 2009)*

Figure 1.14 Sand accumulation SE of Puttgarden

Figure 1.15 *Overview of coastline and coastal structures from Puttgarden and Klausdorf. Aerial photo from 2009 (©COWI Orthophoto April 2009). Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen*

Figure 1.16 Dike between Marienleuchte and the till cliff off Klausdorf, protecting the low-lying land around Presen

1.3.2 Historical shoreline changes

An extreme storm hit the Baltic Sea area on 12-14 November 1872. The event caused major flooding on Fehmarn and initiated construction of dikes to protect the hinterland.

The construction of the dikes at Fehmarn resulted in loss of coastal lagoons and lowlands. Areas behind the dike such as the Nördliche Binnensee east of Markelsdorfer Huk and Blankenwisch east of Grüner Brink, see locations in Figure 1.12, are presently partly dried out lakes and wetland areas, see historical map of Fehmarn from 1858 in Figure 1.17.

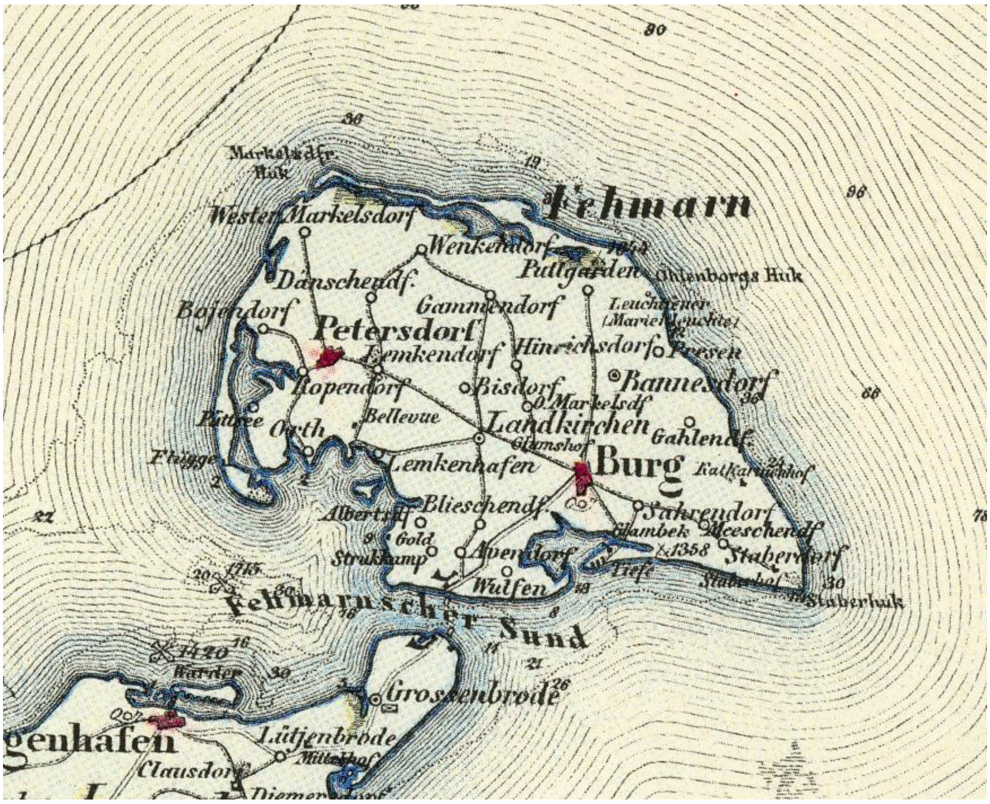


Figure 1.17 Section of historical map showing Fehmarn from 1858. General-Karte von den Hertogthümern Schleswig, Holstein und Lauenburg (Landesvermessungsamt Schleswig-Holstein)

1.3.3 Coastal profiles and sea bed conditions

Off the main part of the morphological active and complicated area at Grüner Brink the profiles have a very gentle slope of the shoreface extending to about 300-500 m from the coast at a water depth of about 2.5 to 3 m. Further offshore the slope increases.

Immediately west of Puttgarden, the coastal profiles drop quickly to a water depth of about 2 m. At water depths between 2 m and 7 m, the slopes of the profiles are gentle.

East of the harbour the profiles have a moderate steepness, but further southeast the profiles are all characterised by being very steep for water depths less than about 4-5 m.

A narrow band of mobile sand is present along the coastline between the long groyne (west of Puttgarden) and Puttgarden, and also along the coast southeast of the harbour. Coarser sea bed material or hard bed is found at water depths larger than about 3-4 m. In the area of Grüner Brink, a larger availability of mobile sand was found.

1.3.4 *Sediment budget*

The transport of sediment in the nearshore zone is calculated for the average year conditions in the period 1989-2010. The variation in the transport rates along the coastline, i.e. the sediment budget, indicates areas prone to retreat (erosion) or advance (accumulation) of the shoreline.

West of Puttgarden

The net eastward transport rate off Gammensdorferstrand is about 40,000 m^3/year. At Puttgarden the net transport rates zero and the calculations therefore indicate a net input of 40,000 m^3/year to this section of the coast. Deposition of this volume of sediment takes place mainly at the Grüner Brink formation and some is transported offshore and feeds sediment to the area of sand waves off Grüner Brink.

The sediment budget is illustrated in Figure 1.18. The net annual littoral drift decreases from about 40,000 m^3/year off Gammensdorf (location G1) to 15-20,000 m^3/year along the main section of Grüner Brink (locations G3-G4). The change in the orientation of the shoreline between these two locations combined with the very oblique angle of the dominant waves is the reasons for this abrupt drop in the transport rates and the formation of Grüner Brink.

About half of the 40,000 m^3/year transported towards the east at Gammensdorferstrand is predicted to be transported offshore as described above. The vast majority of transport along Grüner Brink is depositing at the submerged front formation at the eastern end and a smaller part is depositing at the spit.

The migration of the offshore front of Grüner Brink causes sediment to by-pass the end of the long groyne west of Puttgarden. The by-passing has started within the last approximately 10 years and as Grüner Brink migrates further east, more sediment will deposit in the area around the long groyne. The Grüner Brink formation will reach the groyne and bury the structure in sand, however on a time scale of several decades. Along the beach west of the long groyne, inshore of the submerged part of Grüner Brink, the net transport direction is westwards. This is due to the turning of and sheltering against the westerly waves as they propagate across the submerged front of Grüner Brink which leads to northeasterly and easterly being the more dominant wave directions. This corresponds well to a small built up of sand against the water outlet structures seen between 1999 and 2009.

The net annual transport rates along the stretch between Grüner Brink and Puttgarden are small (less than 5,000 m^3/year). No shoreline changes have been observed in this area. Just west of Puttgarden (G8), the net transport rate is 0, corresponding well to the fact that there is no sign of sand accumulation west of Puttgarden.

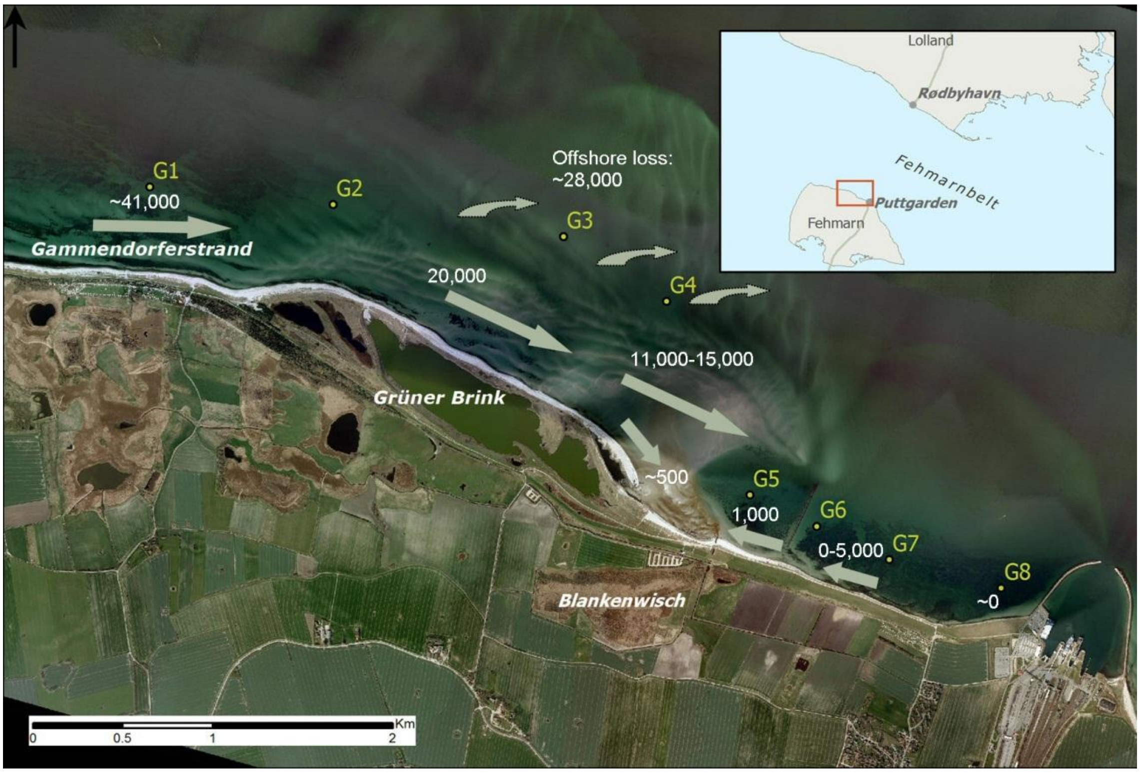


Figure 1.18 Littoral drift budget along the coast west of Puttgarden. Littoral drift rates in m³/year. Aerial photo from 2009 (©COWI Orthophoto April 2009)

East of Puttgarden

The littoral drift budget for the coast east of Puttgarden is shown in Figure 1.19.

The littoral budget along this section shows a small net transport of about 500-2,500 m^3/year towards the north along the entire stretch. The transport rates drop slightly between the coast approximately 2 km south of Presen and are then nearly constant between Presen and Puttgarden with only minor variability indicating a very stable coast with only small shoreline changes.

The net transport rate just southeast of the eastern harbour breakwater is about 1,000 m^3/year. This fits well with the very small shoreline changes observed in this area and the small built up of sand in the profiles. At location G10 further southeast, a high net *potential* transport rate towards the north is calculated. This transport is not effectuated due to small groynes, the seawall/revetment protecting the Ohlenborgs Huk from erosion and the lack of loose sea bed material on the sea bed.

Between Marienleuchte and Presen the net transport rates are very small. The net sediment transport magnitudes are less than 2,000 m^3/year mainly because the beach orientations face the dominant wave direction along this stretch (G11 to G13). The transport components towards the northwest and the southeast, respectively, reach about 15,000 m^3/year and decrease towards the beach off Presen (location G13). This is mainly because the mobile sediment becomes more limited and coarser in the littoral zone towards the south.

Between Presen and further south (G13-G14) the beach orientation turns clockwise by about 20°. This induces an increase in the net sediment input of sand from south to this section. This leads to a deposition along this section.

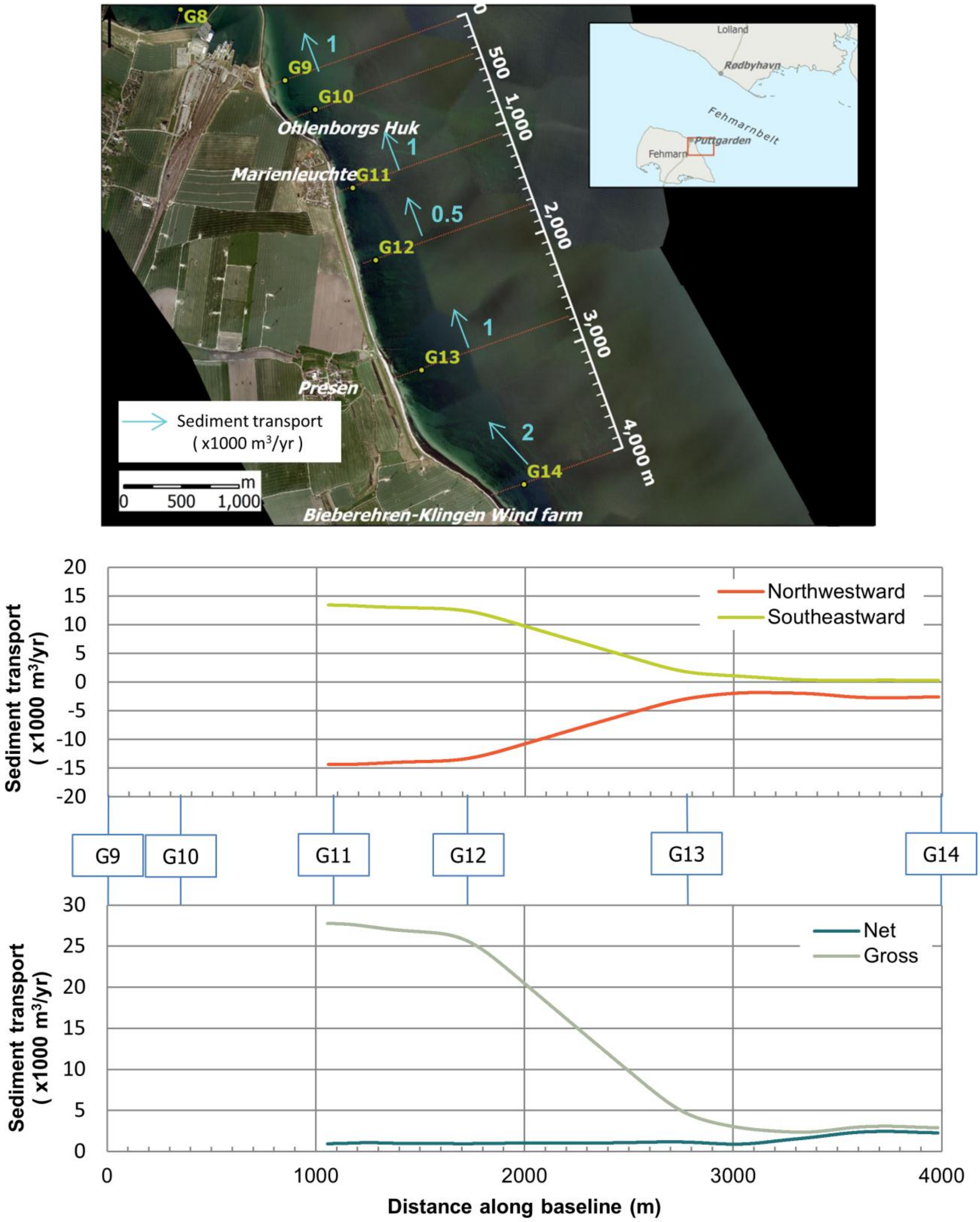


Figure 1.19 Littoral drift transport rates east of Puttgarden (top figure). Central figure:northwest- and southeast going transport conditions. Lower figure: net and gross transport rates. Aerial photo from 2009 (©COWI Orthophoto April 2009). Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen

1.4 Mapping of importance

Maps showing the importance for coastal morphology along relevant sections of the Lolland and the Fehmarn coasts are presented in Figure 1.20 and Figure 1.21.

The importance criteria applied are summarised in Table 1.1.

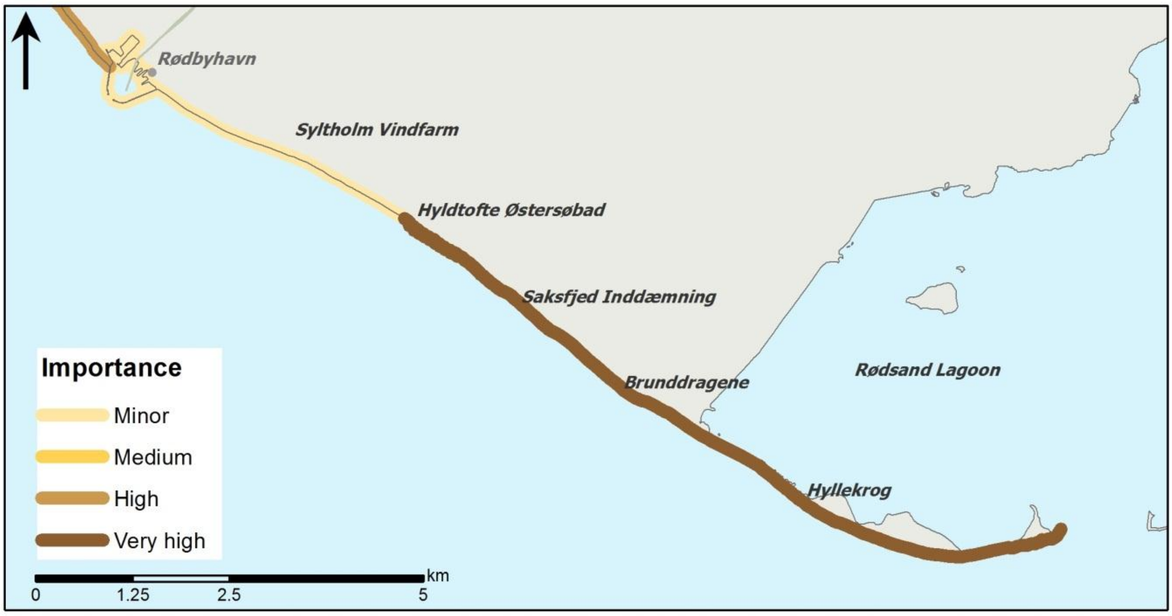
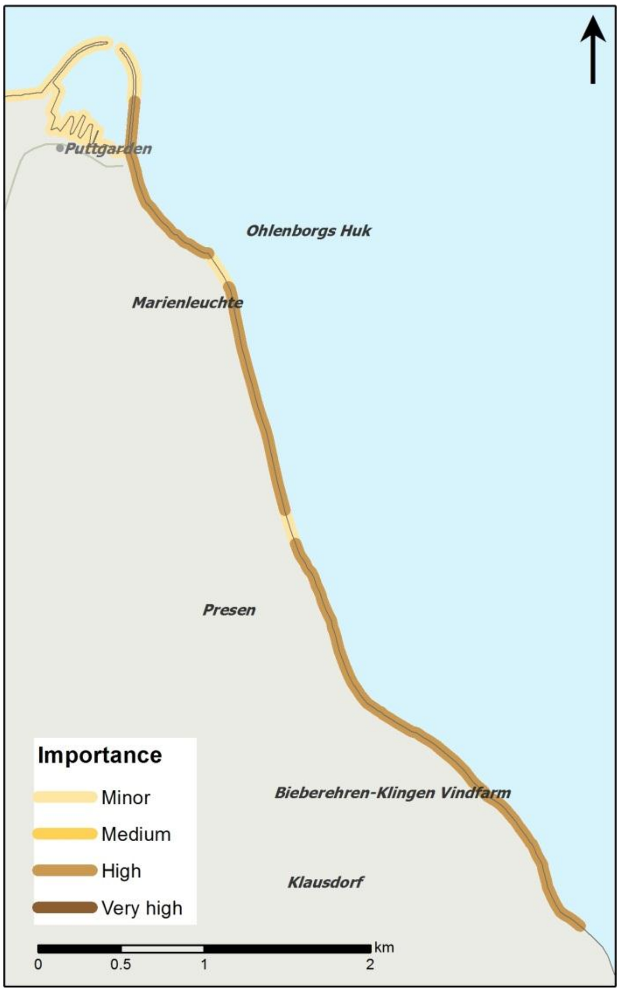


Figure 1.20 Importance levels for the sub-factor Marine Soil component Coastal Morphology along the Lolland coast



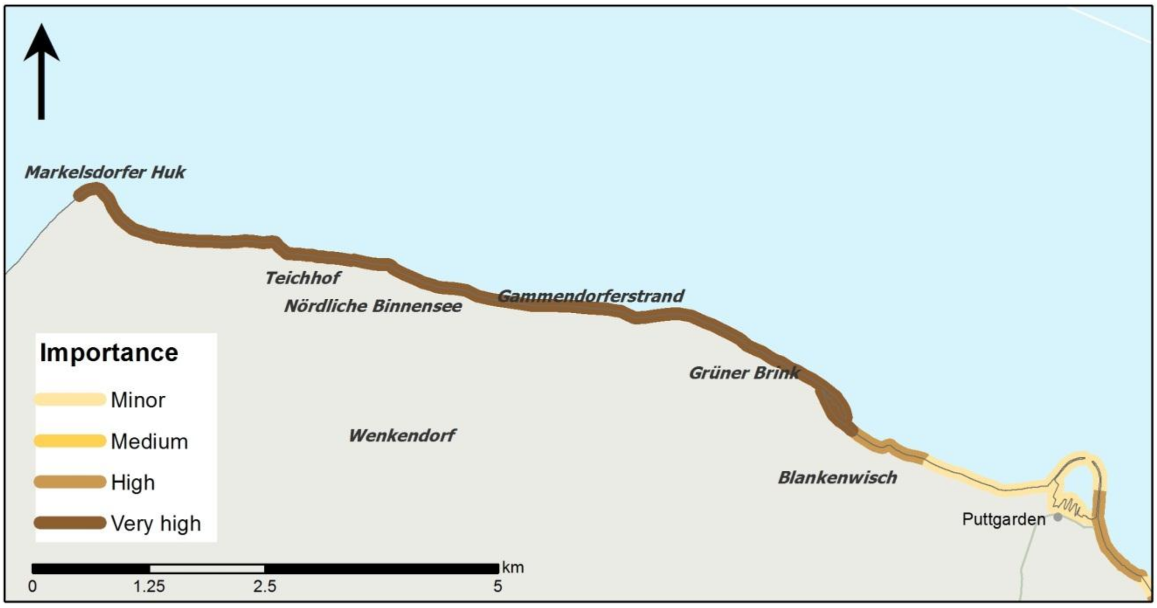


Figure 1.21 Importance levels for the sub-factor Marine Soil component Coastal Morphology along the Fehmarn coast. Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen

Table 1.1 Importance criteria for the Coastal Morphology component of the Marine Soil subfactor in relation to baseline

Importance level	**Description**
Very high	Coastal areas within Natura 2000 areas, where coastal morphological elements are part of the conservation objectives. Coastal sections, which are protected under German legislation as NGS areas.
High	Coastal stretches with sandy beaches and cusp areas (cuspate foreland) including coastal lagoons, not included under the 'Very high' category.
Medium	All other coastal stretches, which are not heavily influenced by anthropogenic activities as mentioned under the "Minor" category
Minor	Coastal stretches under heavy influence of anthropogenic activities

2 INTRODUCTION

FEHY ATR ENV010027, Issue 3, “Coastal Morphology Baseline and Impact Assessment” was sent to Femern A/S on 4th of March 2010 and the activity started shortly thereafter. The work continued in 2011 under FEHY ATR ENV010042, Issue 1, dated 23th December 2010.

2.1 Objectives of the baseline study

The objectives of the ATR are to analyse the baseline coastal morphological conditions along the two coastal sections adjacent to Rødby and Puttgardens.

2.2 The report

The baseline conditions are described under the following headings:

3 Available data and methods

4 The investigation area

5 Overall hydrodynamic conditions

6 Geological description of the Fehmarnbelt Area

7 Lolland coast

8 Fehmarn coast

9 Present pressures

10 Assessment of importance

Chapter 7 and 8 describe the baseline conditions for the coastal sections of Lolland and Fehmarn under the following subsections:

- Present coastline and coastal structures
- Historical shorelines and coastal structures
- Recent shoreline development
- Coastal profiles
- Sea bed conditions near the coast
- Nearshore wave and currents
- Sediment budget and shoreline evolution

3 THE INVESTIGATION AREA

The Fehmarnbelt is part of a narrow transition area between the North Sea/Katttegat and the Baltic Sea, connecting the southern part of the Great Belt and the Kiel Bight with the Mecklenburg Bight and further over the shallow Darss Sill into the Arcona Basin of the Baltic Sea Figure 3.1.

This report focuses on the coastal areas near the alignment, see Figure 3.1. These coastal areas cover the coastal stretch between Markelsdorfer Huk and the coast off the village of Klausdorf on Fehmarn and the coastal stretch between Kramnitze and the barrier formation, Hyllekrog, on Lolland.

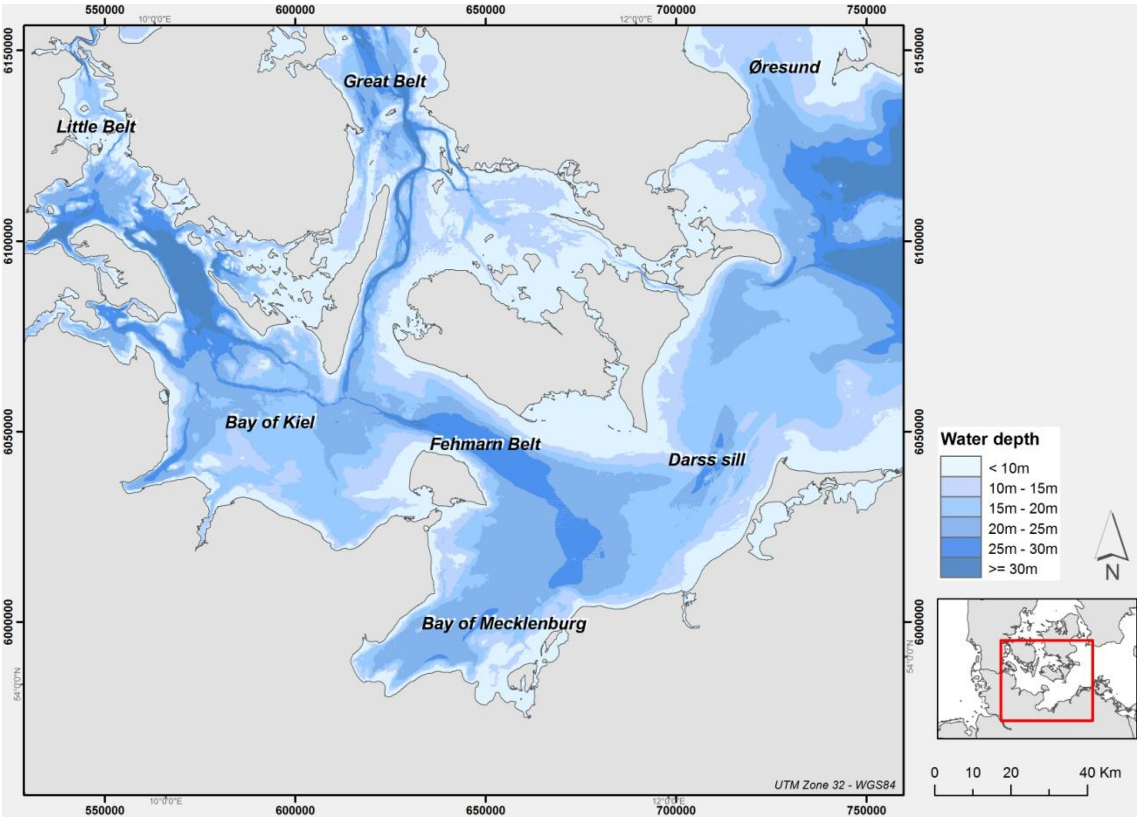


Figure 3.1 Bathymetry of the Fehmarnbelt region

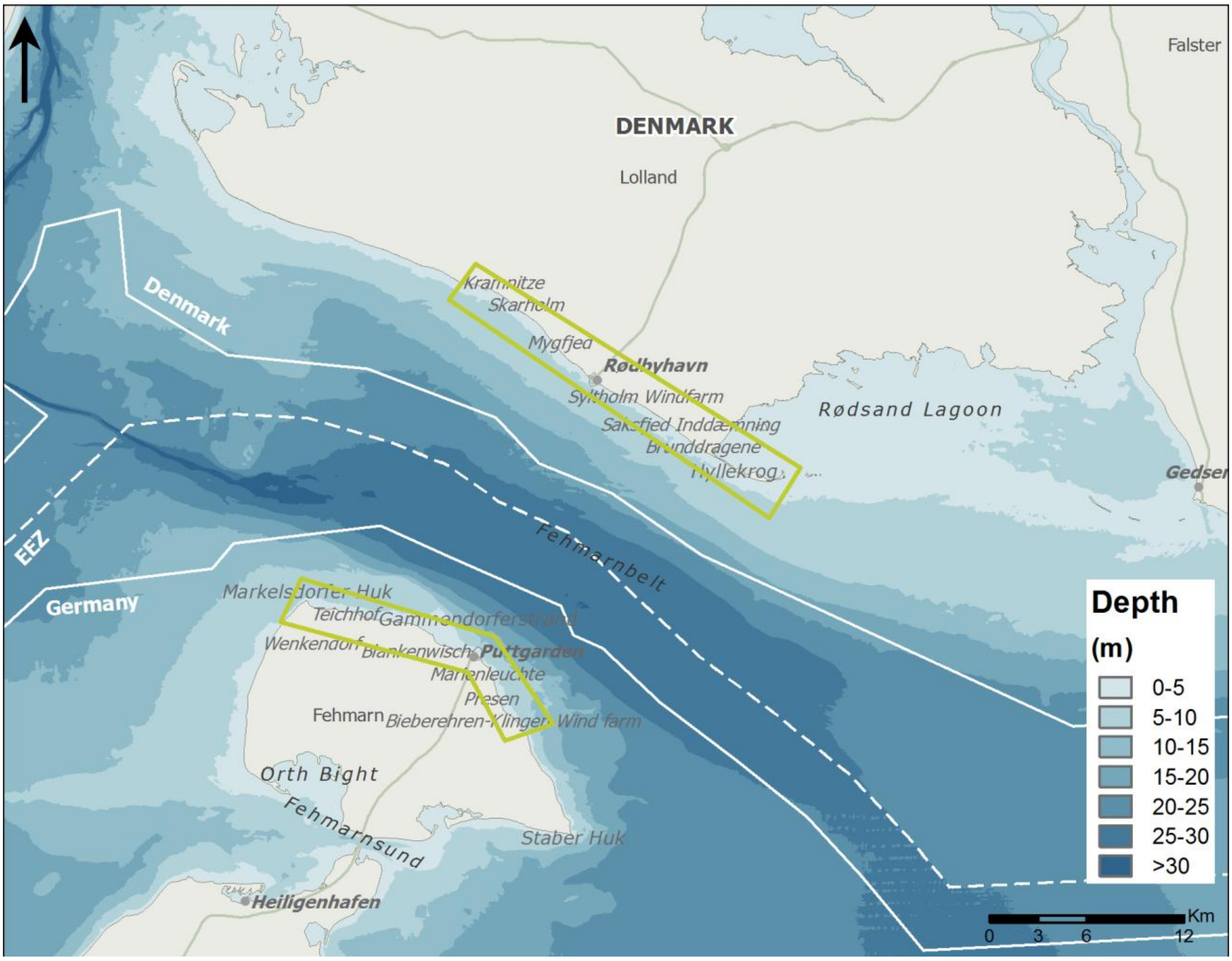


Figure 3.2 Investigation areas on Fehmarn and Lolland. Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen

4 AVAILABLE DATA AND METHODS

4.1 Geological information

The development of the landscape in the Fehmarnbelt area and the formation of the sedimentary deposits are presented in Chapter 5 and are based on existing literature and available information from recent geotechnical investigations carried out in the alignment area by Rambøll Danmark A/S and Arup JV (Rambøll Denmark and Arup JV 2010).

An overview of the applied literature is listed in Table 4.1.

Table 4.1 Overview of literature applied in the geological description

Literature	Type of information
Novak and Björck 2003	Landscape development (Fehmarnbelt area)
Björck 1994	Landscape development (Fehmarnbelt area)
Smed 1981	Map of geological landscape (Danish side)
Von Post 1929	Landscape development (Fehmarnbelt)
DGU 1996	Geological map and map of sea bed sediment (Fehmarnbelt)
Jensen et al 2002	Landscape development (Fehmarnbelt area)

4.2 Bathymetry data

The description of the bathymetry in the coastal areas along the coasts of Fehmarn and Lolland is based on bathymetric surveys performed in 1998 and in 2008/2009.

4.2.1 Coastal areas – water depths less than 6 m

Bathymetric surveys of coastal profiles along the coasts of Lolland and Fehmarn were performed in 1998 and 2009:

1998 survey

A topographic and bathymetric survey using levelling and a precision echosounder was carried out by DHI in 1998 (DHI 1998). In total 32 coastal profiles along the Lolland and Fehmarn coasts were surveyed, see Figure 4.1. The survey lines extended from a water depth of approximately 8 m to approximately 3 m above DVR90. The spacing between the profiles is 250-1000 m.

The surveys were carried out using a rubber dinghy equipped with a precision echosounder and differential GPS positioning system.

The 1998 survey lines are so far apart that an interpolated bathymetric map of the coastal areas cannot be produced.

2009 survey

In 2009, GEUS carried out a bathymetric survey using levelling and echosounding, (GEUS 2009).

The survey covers 445 coastal profiles, 220 on the Danish side and 225 on the German side. Survey lines from 1998 were repeated in the 2009 survey campaign. Close to the harbours, the spacing between the coastal profiles is approximately 25 m, further away the profiles were spaced from 250 m to 1000 m.

The 2009-survey lines extended from a water depth of approximately 6 m to approximately 4 m above DVR90. Section of the profiles located at water depths greater than 1.3 m was surveyed from a small survey boat equipped with a dual frequency echosounder Navisound Reson (200 kHz) and a RTK GPS positioning system. Water depths less than 1.3 m and levels above DVR90 were measured using a Leica TC600 total station. An overlap between the levelling and the echosounding was ensured.

Bathymetric models over the coastal areas are produced by interpolation in the profile data in the areas with spacing between the profiles of 25 m, whereas an area bathymetry is not produced in the marginal area, see Figure 4.1 for the German side and Figure 4.2 for the Danish side.

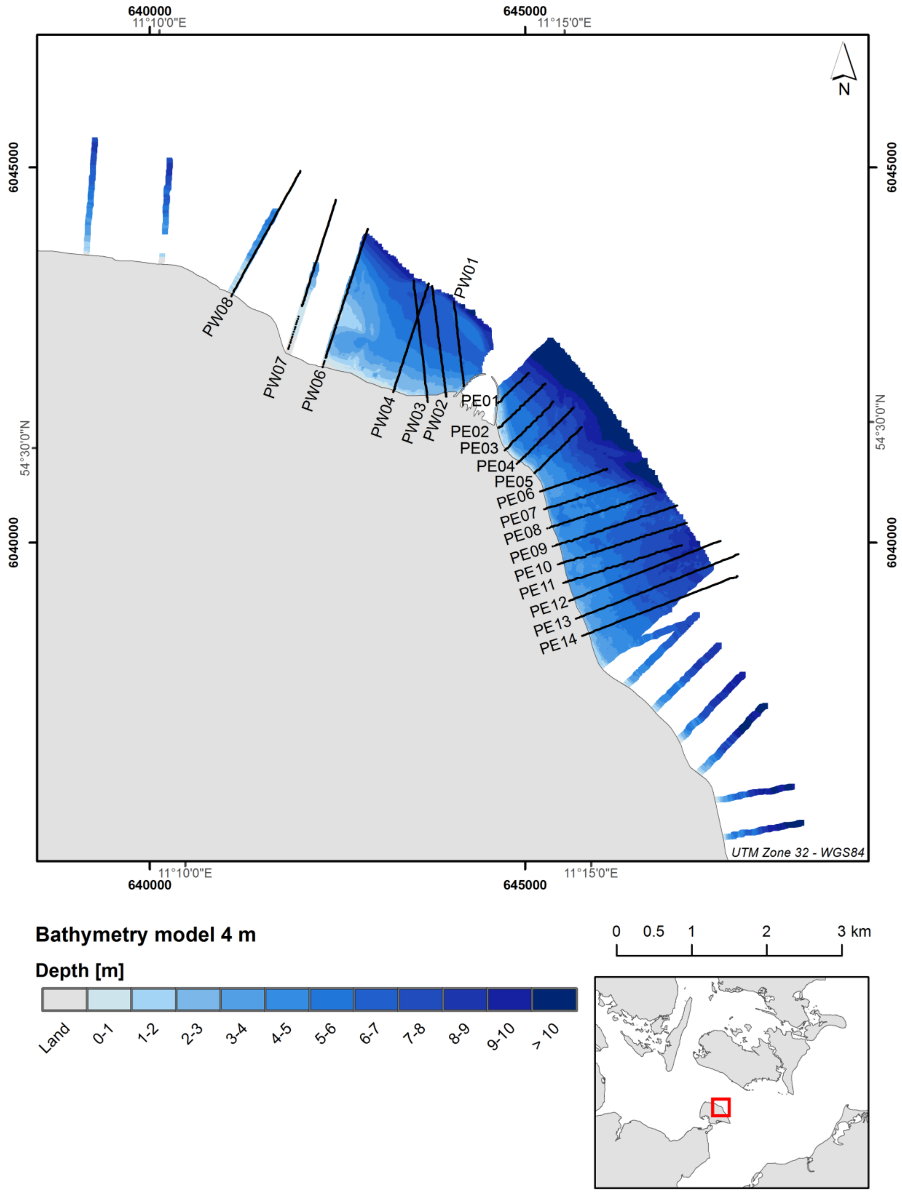


Figure 4.1 Survey lines 1998 along the north coast of Fehmarn. Interpolated bathymetry from 2009-survey lines

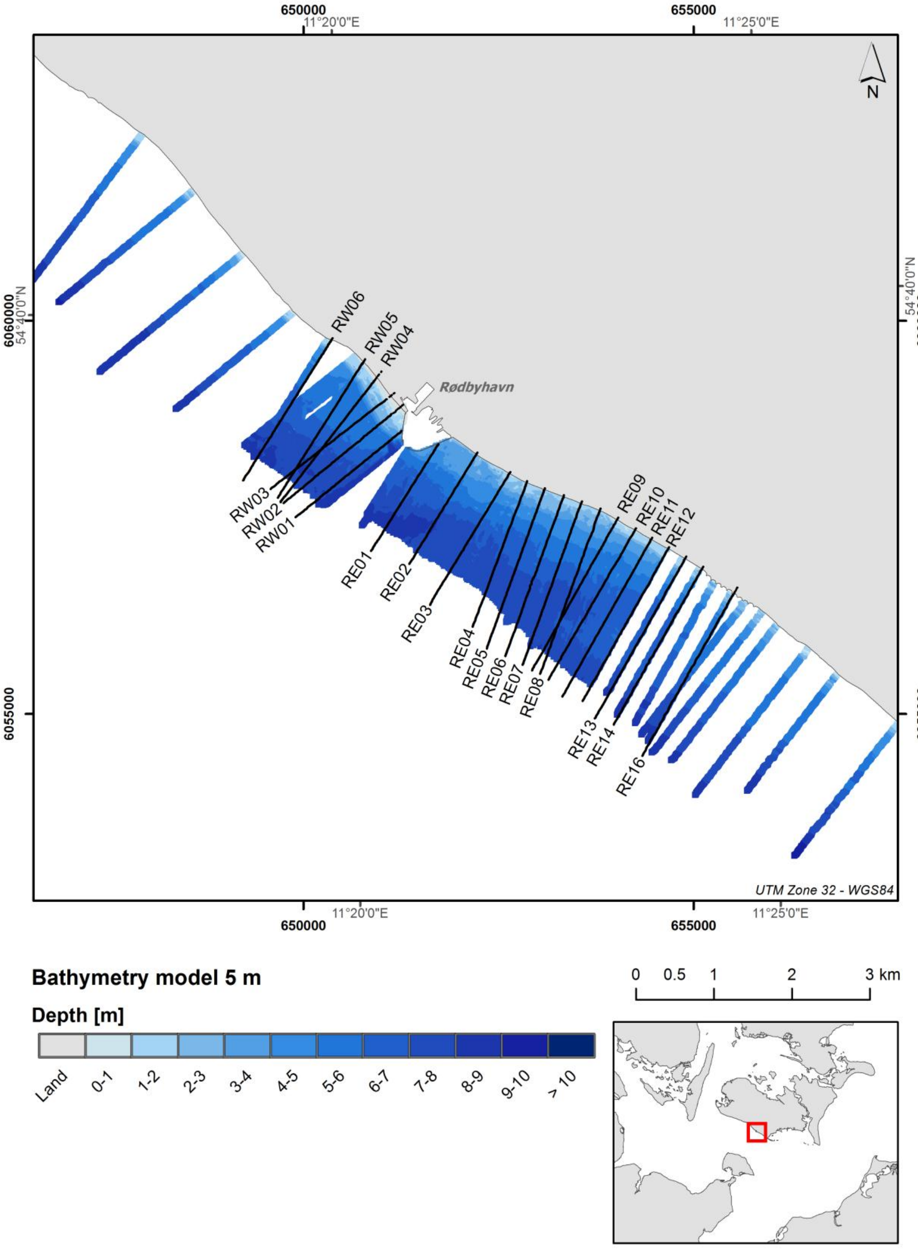


Figure 4.2 *Survey lines 1998 along the south coast of Lolland. Interpolated bathymetry from 2009-survey lines*

4.2.2 Central Fehmarnbelt – water depths greater than 6 m

The bathymetry in the central part of the Fehmarnbelt is based on detailed mapping performed by Rambøll/Marin Mätteknik using multibeam echosounder (Rambøl Danmark A/S and Arup JV 2009). The multibeam measurements were carried out for water depths greater than approximately 6 m. The area covered by the survey is about 900 km^2, see Figure 4.3. The horizontal resolution of the provided soundings is 2 m. The survey in the corridor was performed in 2008, whereas the rest of the surveys were performed in 2009. For further details, see (Rambøl Denmark A/S and Arup JV 2009).

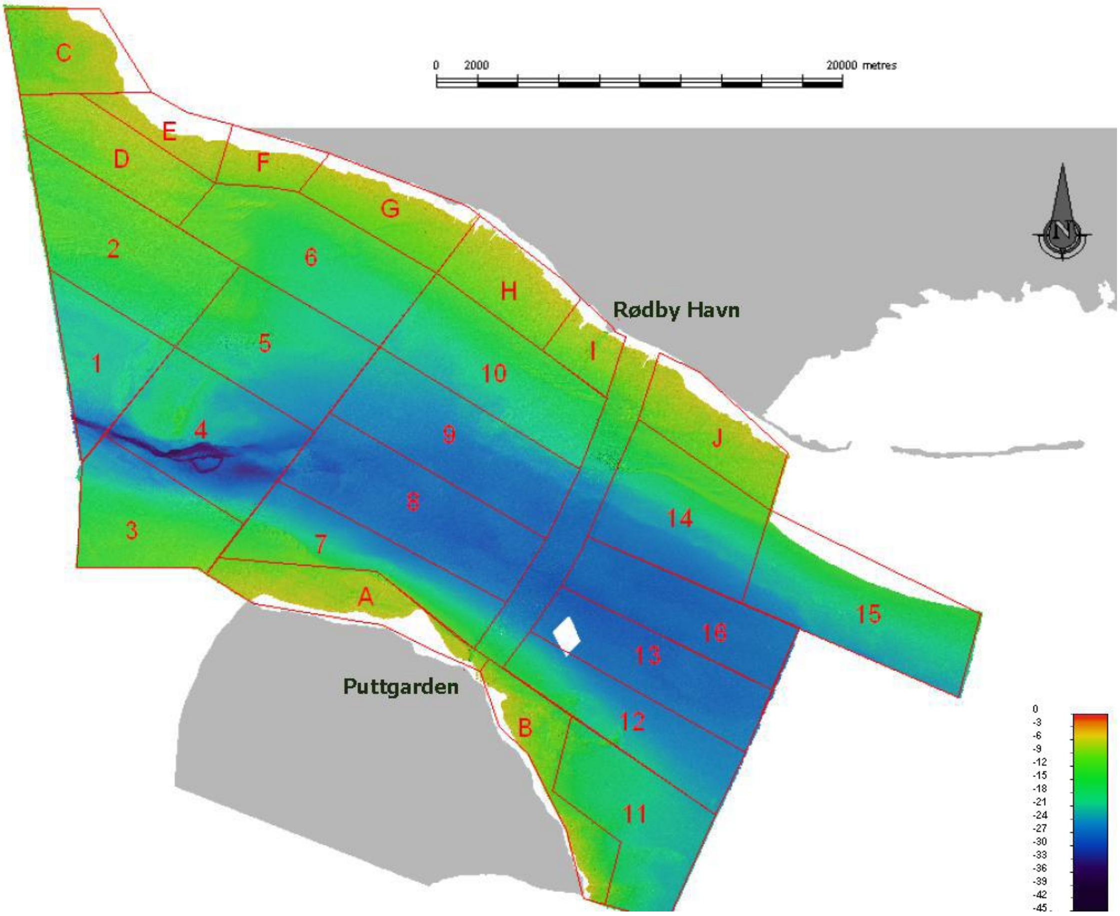


Figure 4.3 Bathymetry of the Fehmarnbelt and overview over surveyed area in 2008 (corridor between Rødby and Puttgarden) and in 2009 (named blocks) by Rambøll-Arup JV/Marin Mätteknik, see Rambøl Danmark A/S and Arup JV, 2009

4.3 Historical shorelines and coast protection structures

4.3.1 Shorelines and morphological features

The historical and more recent development of the shorelines of Lolland and Fehmarn, including the shoreline development of special morphological features such as the Grüner Brink and Hyllekrog formations, have been studied on basis of the data described in the following.

Historical development

The long-term development of historical shorelines has been studied on basis of historical maps and literature describing for instance the construction of the sea dikes on Lolland and Fehmarn following the storm in 1872. An overview over the applied maps and data is presented in Table 4.2.

Table 4.2 Overview over historical maps and references used for the long-term historical shoreline analysis

Country	Type of data	Period	Data provider
Denmark	Topographical map by "Scientific Society" (in Danish: "Videnskabernes Selskab")	1763 - 1805	Danish Geodata Agency, Denmark
	"Generalkvartermester eralkvartermester-staben" map: Rødby Havn	1842	Danish Geodata Agency, Denmark
	"De høje målebordsblade"	1842 - 1899	Danish Geodata Agency, Denmark
	Topographic maps, 1:25.000	1905, 1931, 1942, 1945, 1965, 1967, 1989 and 1995	Danish Geodata Agency, Denmark, partly via (Fehmarnbelt Environmental Consultants 1996) and (Jensen 2006)
	Map showing flooded area at Lolland during storm in 1872	1872	Det Lollandske Digelag: Stormflodsdiget 1872, 13 November 1972. (Det Lollandske Digelag 1972)
	Map showing reclaimed areas and year of finalised reclamation inside Rødby Fiord	1839 - 1919	Bag diger og dæmninger i Rødby Fjord. (Hyldtoft, 2009)
	Aerial photos	1945, 1964, 1974 and 1995	Danish Geodata Agency, partly via (Fehmarnbelt Environmental Consultants 1996)
	Satellite images, Hyllekrog	1973, 1986 and 2003	Via (DHI Water & Environment 2004)
Germany	Map of Fehmarn from Meyer's Handatlas, no 138, Herzogthum Schleswig	1852	http://rumsey.geogarage.com/maps/g4807080.html
	Map of Schleswig-Holstein including Fehmarn, "General-Karte von den Herzogthümern Schleswig, Holstein und Lauenburg". Vom Hauptmann F. Geerz.	1858	Landesvermessungsamt Schleswig-Holstein
	Topographic Maps, Preußische Landesaufnahme 1:25.000, 1432, 1433, 1532 and 1533	1879, 1945, 1953 and 1994	Landesvermessungsamt Schleswig-Holstein, partly via (Fehmarnbelt Environmental Consultants 1996)
	Aerial photos	1937, 1954, 1966, 1979, 1980, 1984, 1989 and 1994	Landesvermessungsamt Schleswig-Holstein Analysed in (Fehmarnbelt Environmental Consultants 1996)
	Map showing coastal flood.prone lowlands in NE Schleswig-Holstein including Fehmarn	2004	(Hofstede 2004)

Recent Shoreline Changes

The shoreline evolution in the recent 10 years has been mapped based on aerial photos of the coasts of the northern Fehmarn and southern Lolland. Aerial photos from 1999, 2004 and 2009 have been used as the mapping basis, see Table 4.3.

Table 4.3 Overview over aerial photos used for the analysis of recent shoreline changes

Year	Months	Coverage Dansh/German coast	Precise time available	Spatial resolution [m]	Horizontal mean accuracy [m]	Data provider
1999	Spring/ Summer	DK	No	0.40	1	COWI
2004	Spring/ summer	DK	Yes	0.25	1	COWI
2009	April	DK/G	Yes	0.20	0.6	COWI
1999	na	G	No	0.4	est. 1.5	GeoBasis-DE/LVermA-SH Landesvermess-ungsamt Schleswig-Holstein
2004	na	G	No	0.4	est. 1.5	GeoBasis-DE/LVermA-SH Landesvermess-ungsamt Schleswig-Holstein

The quality of the geo-referencing of each of the aerial photos has been checked by visual inspection in order to make sure that the alignment of the aerial photos could ensure an accurate comparison of the changes. This was done by comparing the images with GIS themes in maps from KMS' Kort10 (maps from the Danish Geodata Agency, Danish Ministry of Environment) and by comparing the images to each other. The geo-reference of the images was found to be of high quality and it was concluded that a further rectification would not improve the accuracy.

Shorelines have been manually digitized for all three years. Interpretations of the images are subjective and the appearance of the shoreline may differ from place to place. The definition of the shoreline is taken as the intersection between the coastal profile and the instantaneous water level as this makes it possible to utilize a stable method for definition of the shoreline. Consequently, the instantaneous waterline has been digitized on all the aerial photos. Examples are shown in Figure 4.4 and Figure 4.5. No shorelines have been mapped in areas where there is no shoreline, for example where there is a revetment without any beach fronting it. The estimated accuracy of the digitized shorelines is approximately 2.0 m.

The instantaneous waterline has been used to estimate the mean waterline. The region of interest covers a stretch of approximately 23 km centred around Rødbyhavn and a 10 km stretch around Puttgarden. Within this area, the shorelines from each of the three years have been mapped. Shoreline structures such as groynes, revetments, breakwaters (but not dikes) have been digitized.

The shoreline changes in the period 1999 to 2009 are discussed in Section 7.3 and Section 8.3 for the Lolland and the Fehmarn coasts, respectively.

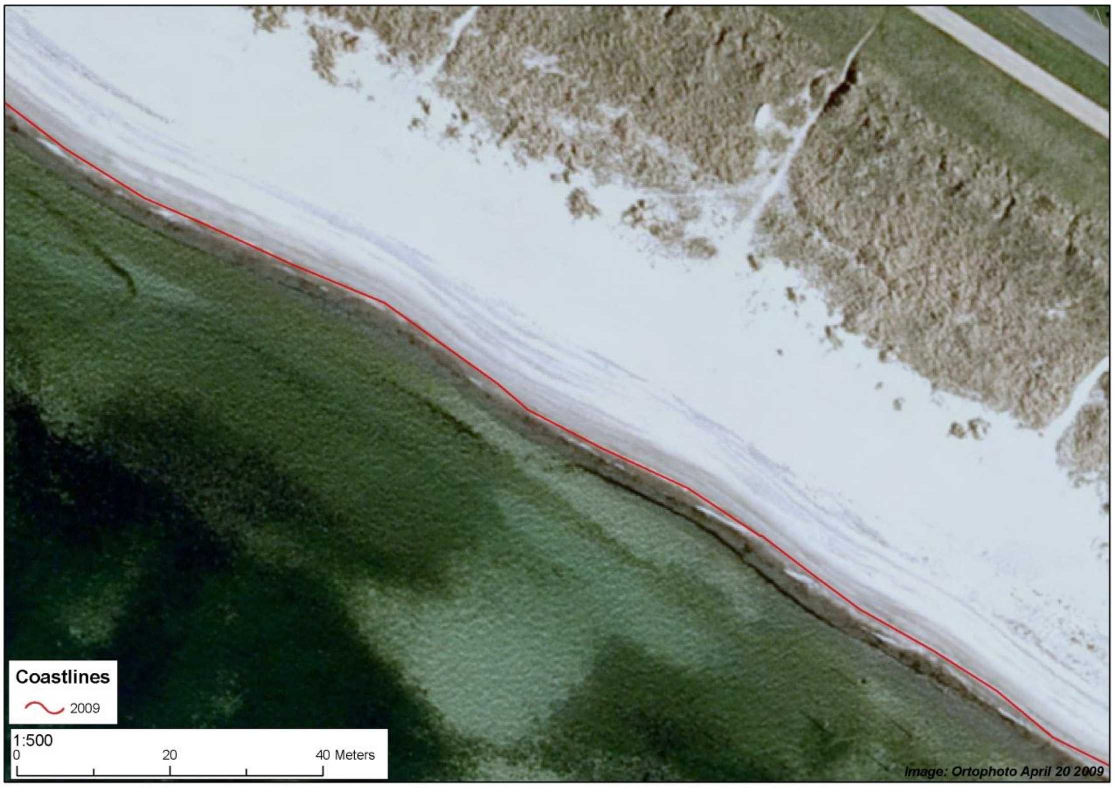


Figure 4.4 *Example of digitizing of instantaneous waterline on 2009 image. Aerial photo from 2009 (©COWI Orthophoto April 2009)*

Figure 4.5 *Example of digitizing of instantaneous waterline on 2004 image. Aerial photo from 2004 (©COWI Orthophoto Spring/Summer 2004)*

4.3.2 *Coastal protection structures*

The present day coastal protection structures are described based on information from topographic maps, aerial photos and records of coastal structures.

Coastal structures have been identified and digitized from the most recent aerial photo from 2009, see Table 4.3. Depending on the character of the coastal structures they can be difficult to identify from aerial photos. Sea dikes are, for instance, often grass-covered and it has not been possible to identify these accurately from the photos. Revetments or sea walls can often be identified from the aerial photo, but are at some sections difficult to distinguish from other landscape elements. Groynes, breakwaters and harbours are other types of coastal structures, and these are usually easy to identify from the photos.

Information on the coastal structures along the Danish Coast in 1999 has also been retrieved (June 2010) from the home page of the Danish Coastal Authority: www.kyst.dk.

All information was compared in GIS and verified by site inspection on 27th-28th January 2011 at the Lolland and the Fehmarn coasts, respectively, to ensure the available information was accurate and up to date.

The coastal protection structures are described in Section 7.2 and Section 8.2 for the Lolland and the Fehmarn coasts, respectively.

4.4 *Sedimentation in harbours*

Sedimentation in the two ferry harbours, Puttgarden and Rødby, has been analysed based on annual maintenance dredging volumes received from the ferry operator, Scanlines, and from the harbour authorities (Fehmarnbelt Environmental Consultants 1996). Maintenance dredging has never been performed in Puttgarden. Data on maintenance dredging volumes for Rødbyhavn are available for the period 1977 to 2008.

4.5 *Natura 2000 areas*

The areas of Hyllekrog-Rødsand and Grüner Brink are Natura 2000 SCI areas with conservation targets specifically related to coastal landscape types. The Natura areas are shown in Figure 4.6.

The two SCI areas of relevance are the following:

SCI DE 1532-391 Coastal area of western and northern Fehmarn (Küstenstreifen West- und Nordfehmarn)

SCI DK 006X238 Smålandsfarvandet, north of Lolland, Guldborg Sound, Bøtø Nor and Hyllekrog-Rødsand (Smålandsfarvandet nord for Lolland, Guldborg Sund, Bøtø Nor og Hyllekrog-Rødsand).

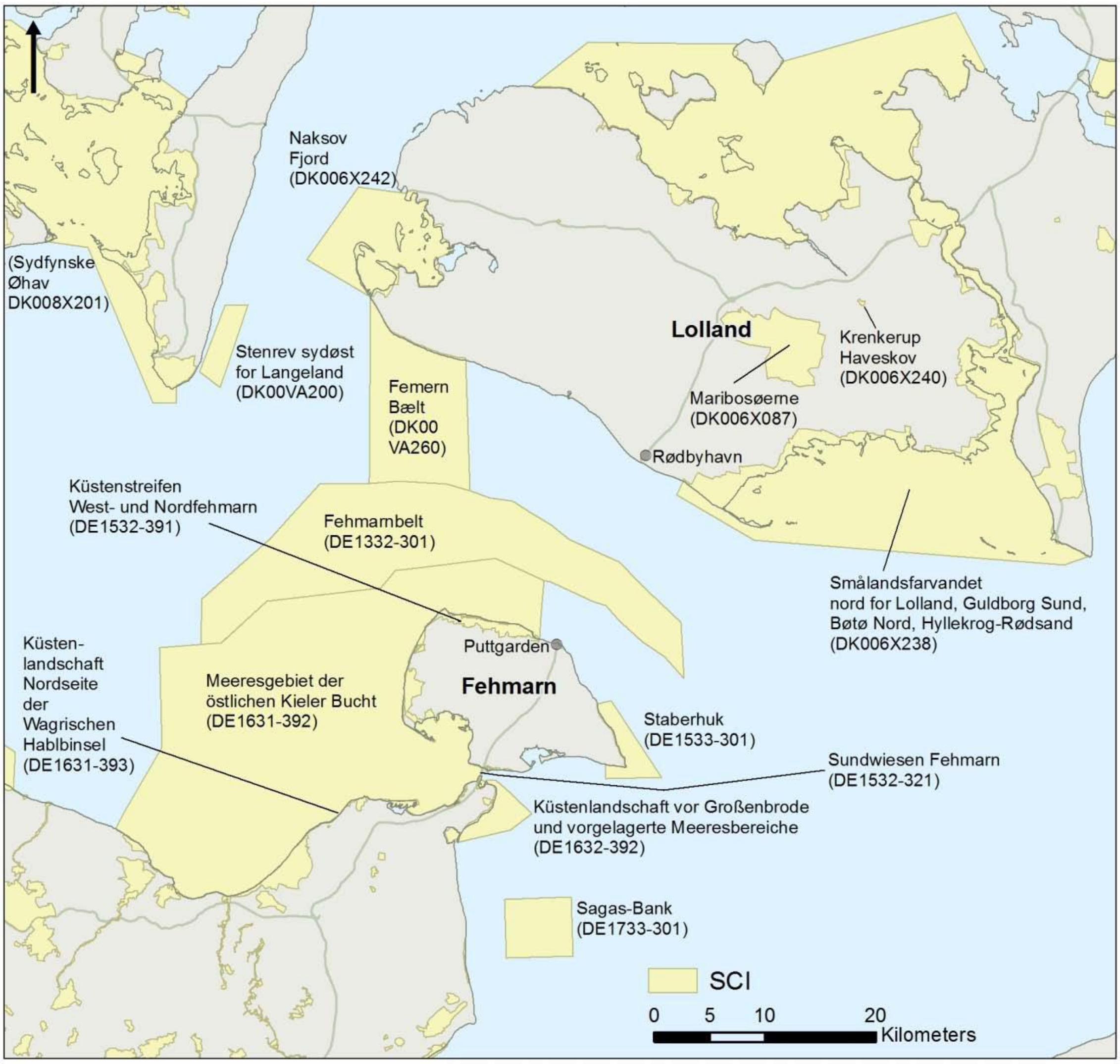


Figure 4.6 Natura 2000 areas in the Fehmarnbelt area

4.6 Surface sea bed conditions near the coast

The surface sea bed conditions in the nearshore zone are described based on

- Grab samples
- Substrate mapping
- Diver observations of sediment characteristics and macroalgae vegetation
- Aerial photos

Grab samples
Sea bed samples were collected in 1998 and 2009.

In 2009 several hundreds of grab samples were collected covering all depths in the Fehmarnbelt. In all, 8 sets of grab samples are included in the analysis:

- DHI spring 2009. Danish side at 3, 6 and 9 m depth

- DHI autumn 2009. Danish side at 3, 6 and 9 m depth
- Marilim spring 2009. German side at 3, 6 and 9 m depth
- Marilim autumn 2009. German side at 3, 6 and 9 m depth
- IOW spring 2009. Deep water 10-35 m depth (both sides)
- IOW autumn 2009. Deep water 10-35 m depth (both sides)
- GEUS summer 2009. 0, 1, 2, 3, 4, 5 and 6 m on both sides
- Rambøll winter 2009. All depths

The locations of the grab samples are shown in Figure 4.7.

In 1998 DHI collected sea bed samples in seven of the Danish survey profiles and in five of the German survey profiles mentioned in Section 4.2.1.

The analysis of the grab samples is based on determination of the median grain size d_{50} and the geometric standard deviation σ_g as well as grain size distribution curves. d_{50} is the grain size for which 50% of the grains have a smaller diameter and 50% have a larger diameter. The homogeneity of the surface sediments is described by $\sigma_g = \sqrt{d_{84}/d_{16}}$.

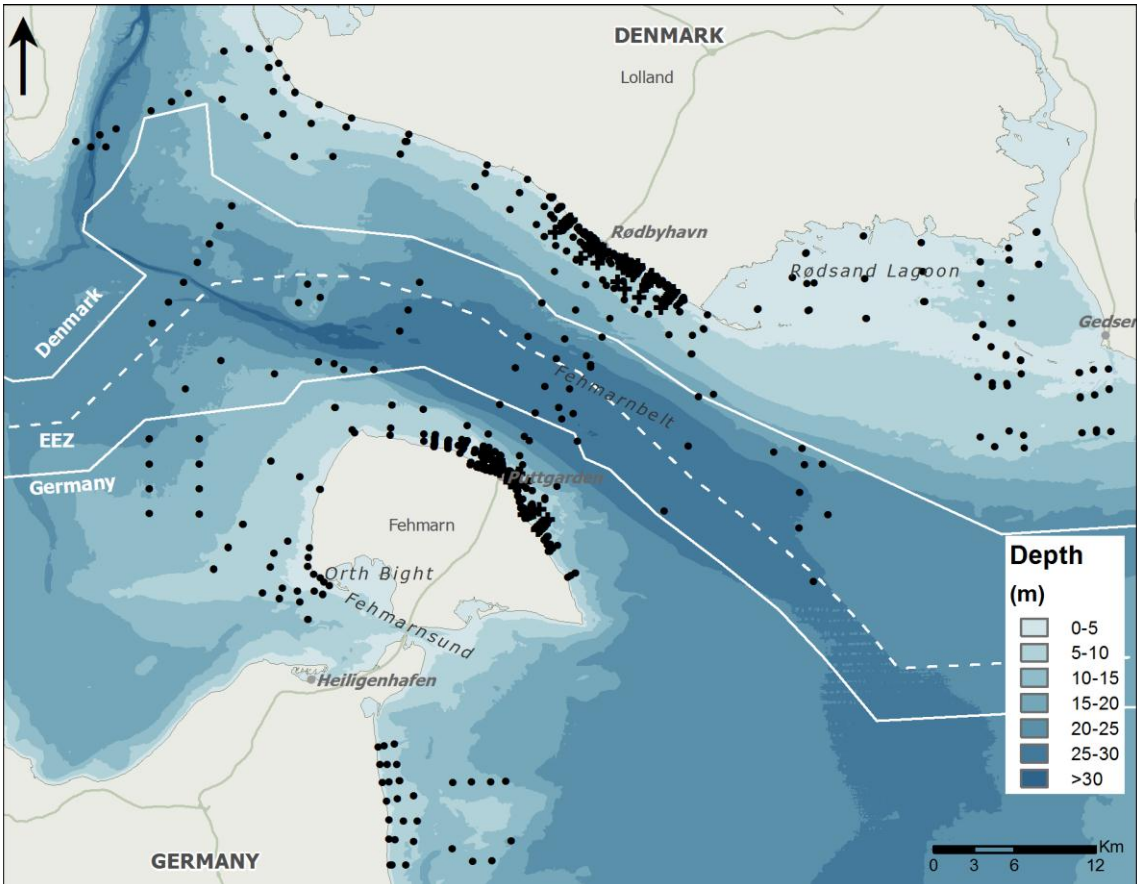


Figure 4.7 Locations of surface sediment grab samples collected in 1998 and 2009 indicated by black markers

Substrate map

The substrate mapping was carried out by Centre for Environment, Fisheries and Aquacultural Science (CEFAS) of the wider Fehmarnbelt area encompassing parts of Kiel and Mecklenburg Bays (FEMA 2013a). The interpretation is based on different data sources. In the Fehmarnbelt area including the Lagoon of Rødsand and the coastline around Fehmarn, a high resolution was achieved through the use of aerial photography (in shallow waters) and multibeam data (in deeper waters), classified with Definiens image analysis software and ground-truthed with grain-size data from the 2009-baseline sampling (see above).

Diver observations of sediment characteristics and macroalgaes

Coverage of specific vegetation elements, sediment characteristics and mussel coverages were estimated by divers in the 2009 Field Programme carried out by FEMA (FEMA 2013a).

Estimates of the coverage of sediment classes (boulders, cobbles, pebbles, gravel, sand, mud/clay/silt and clay reef) within areas of 25 m^2 were estimated at depths from the shoreline to the lower vegetation limit. Locations, where coverage was estimated, are shown in Figure 4.8.

Divers estimated the coverage of macroalgaes at the locations shown in Figure 4.8. Macroalgaes require hard substrate and a high degree of macroalgae coverage is therefore an indicator for an immobile (or less mobile) bed.

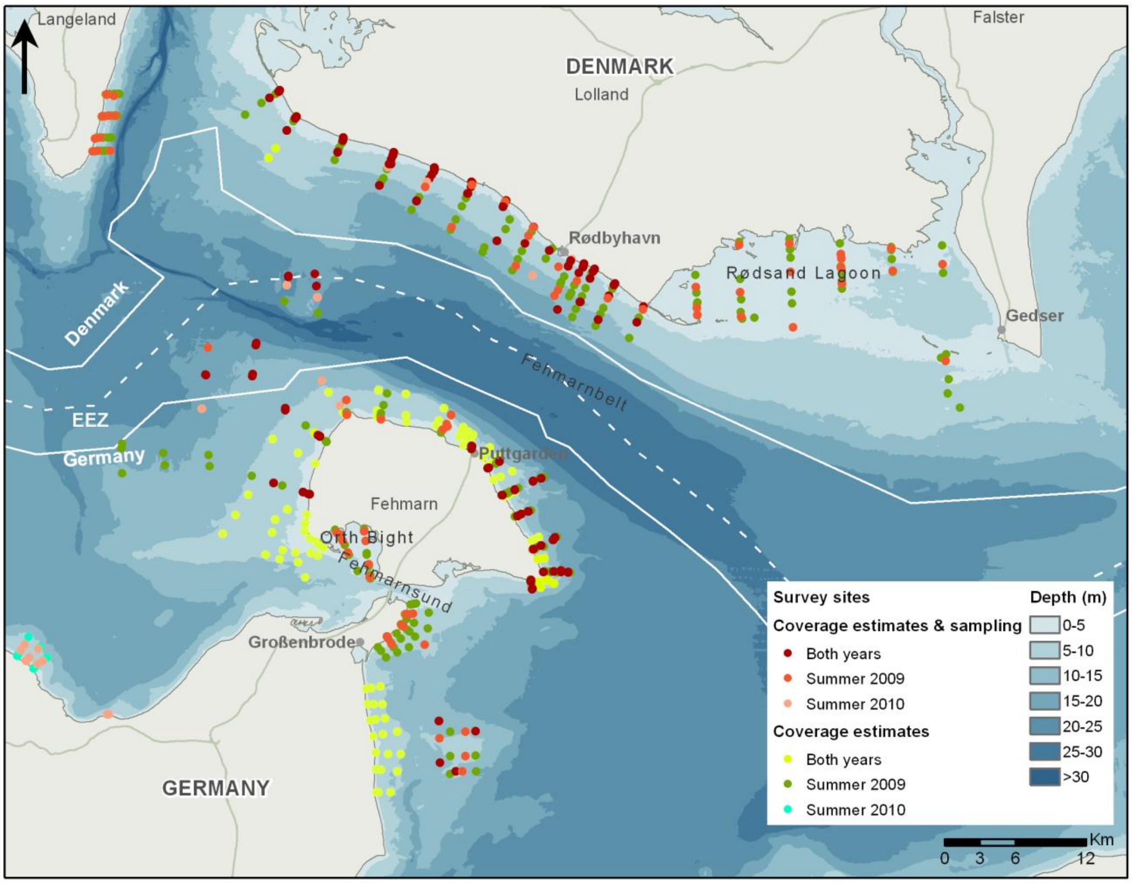


Figure 4.8 Study area and positions of diver estimated coverage of sediment characteristics, vegetation elements and mussels

Aerial photos
Vegetation limits and bands of mobile sand can to some degree be estimated from high quality satellite images at water depths less than approximately 2-3 m. The April 2009 image from COWI, see Table 4.3, is applied for estimating these limits in combination with the other types of information mentioned in this section.

4.7 Wave measurements

Femern A/S has conducted measurements of wave conditions at two measuring stations, MS01 and MS02, in the central part of the Fehmarnbelt.

MS01 is located approximately 7km south of Rødbyhavn at a water depth of -20 m DVR90. MS02 is located approximately 6 km north-northeast of Puttgarden at a water depth of -29 m DVR90. Both of the measuring stations were deployed in March 2009. The locations of the measuring stations are shown in Figure 4.9. Details are provided in Table 4.4.

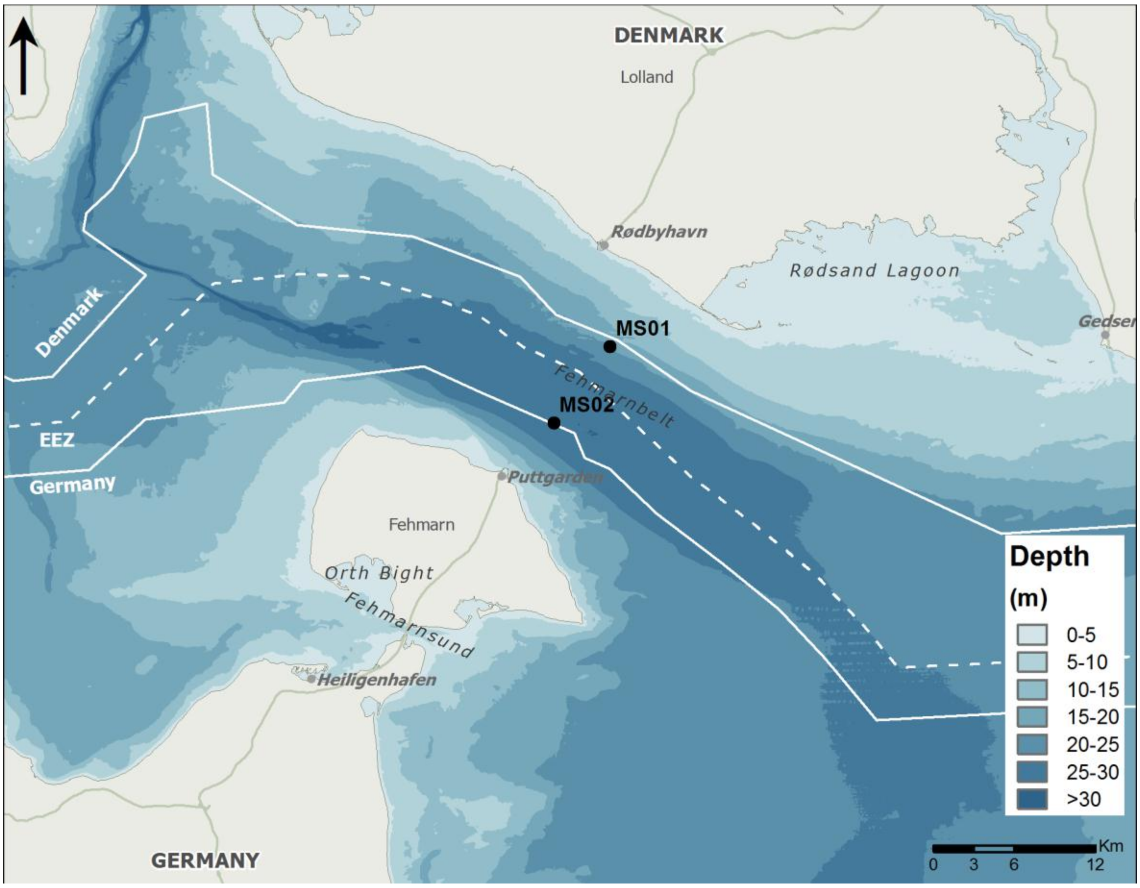


Figure 4.9 Measuring stations MS01 and MS02 in the central part of the Fehmarnbelt

Table 4.4 Wave measurements

Station	Lon. °E	Lat. °N	Depth m	Deployment yyyy-mm	Freq.	Device
MS01[1]	11.3553	54.5859	20	2009-03	1h	ADCP[1]
MS02[1]	11.2880	54.5340	29	2009-03	1h	ADCP[1]

[1] Bottom mounted.

4.8 Numerical modelling tools

4.8.1 Wave modelling tool

Information on the nearshore wave conditions is the most important hydrodynamic parameters for predicting littoral drift rates and erosional /depositional conditions along the Lolland and Fehmarn coasts. The nearshore wave conditions in this study are obtained by simulations of wave fields applying DHI's numerical wave model, MIKE 21 SW, developed by DHI.

MIKE 21 Spectral Wave Model is a third generation spectral wind-wave model. The model simulates the growth, decay and transformation of wind generated waves and swells in offshore and coastal areas.

MIKE 21 SW solves the spectral wave action balance equation. At each calculation point (mesh point), the wave field is represented by a discrete two-dimensional wave action density spectrum. The model includes the following physical phenomena:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation by white capping
- Dissipation by depth induced wave breaking
- Dissipation due to bottom friction
- Refraction due to variation in the water depth
- Wave-current interaction

The model can be run in 4 different modes: a) non-stationary and fully spectral; b) stationary and fully spectral; c) non-stationary and parametric frequency, discrete directional spectra; d) stationary and parametric frequency, discrete directional spectra.

More detailed information about the model can be found in (DHI 2007a).

A description of the model setup used in the present study is described in (FEHY 2013b).

4.8.2 Littoral drift modelling tool

The littoral drift calculations are carried out using LITDRIFT in DHI's LITPACK modelling system. The LITDRIFT module is used to determine the annual littoral drift at a given section of the coast. It simulates the cross-shore distribution of wave height, set-up and set down, longshore current and sediment transport for an arbitrary coastal profile.

Littoral drift calculations from LITDRIFT at selected locations along the coasts are used to calculate a continuous variation of the littoral drift rates along the coastline, by applying interpolates between these. The variation in the wave conditions and changes in the coastline orientation or the coastal profile are therefore integrated into the results.

A description of the LITDRIFT is can be found in DHI (1998).

5 OVERALL HYDRODYNAMIC CONDITIONS

As a narrow but relatively deep strait between Kattegat and the Baltic Sea, the hydrodynamic conditions in the Fehmarnbelt are affected by local and remote forcing. Irregular weather patterns and storms with time scales of a few days are typical for the area.

5.1 Currents

The remote forcing for the currents is mainly due to the large-scale weather systems which build up hydraulic pressure gradients due to atmospheric gradients and associated wind fields, which form different wind set-up of the sea levels in the Kattegat and Arkona Basin. When the wind changes, the barotropic pressure gradient manifested by a large scale sea level slope is not balanced and forces strong return currents through the narrow straits in the transition zone, and in particular through the narrow Fehmarnbelt. A baroclinic pressure gradient between the saline and dense water in Kattegat and the lighter and less saline Baltic Sea is more or less permanent and causes a long term average outflow near the surface and inflow near the bed. The meteorological conditions are the main forcing for the current conditions and the water exchange between the Kattegat and the Baltic through the Fehmarnbelt.

In the nearshore zone, waves - primarily locally wind-generated waves – cause wave breaking along the shorelines, which force longshore currents and littoral transport. Local wind forcing may also generate local wind-driven currents. Locally-generated phenomenon such as eddies, up-welling and down-welling and Ekman flows also influence the local current pattern.

Mean current speeds in the upper 10 m of the water column in the Fehmarnbelt are about 0.3-0.5 m/s and slightly lower when approaching the Danish coast. Current speeds in the central part of the Fehmarnbelt exceed 1 m/s. For detailed information, see (FEHY 2013b).

5.2 Waves

Waves in the Fehmarnbelt are primarily wind generated. The nearby land areas on both sides of the Fehmarnbelt restrict the fetch available for the waves to grow and limit the wave heights and periods for waves from some directional sections depending on the geographical position in the Belt.

The waves in the Fehmarnbelt are illustrated by two wave roses showing the distribution of waves on wave heights and wave directions in Figure 5.1. Wave heights are shown as so-called ‘significant wave heights’, which is a measure for the average wave height for the highest one third of the waves in an irregular wave field. Wave directions are ‘coming-from’ directions.

The predominant waves at MS01 in the northern part of the Fehmarnbelt are from west- and west-northwesterly directions. Winds from these directions are frequent, and the distance from the Fehmarnbelt to upstream land areas towards the west is also relatively large. Waves from these distances are therefore the largest and most frequent; however, the waves are in general relatively small with significant wave heights rarely exceeding 1.5 m. The waves are short with mean wave periods primarily in the range of 1.5s – 4.0s. Waves from southwestern to southern directions are small due to the shadow effect from Fehmarn. Secondary and less frequent waves are from southeasterly directions.

At measuring station MS02 further south and nearer the German coast, the dominating wave directions have shifted to west-northwest and east. The shadow effect from the western part of Fehmarn influences the wave directions from these directions. Waves from western to south-southeastern directions are small due to the shadow effect from Fehmarn. Secondary and less frequent waves are from south-easterly directions.

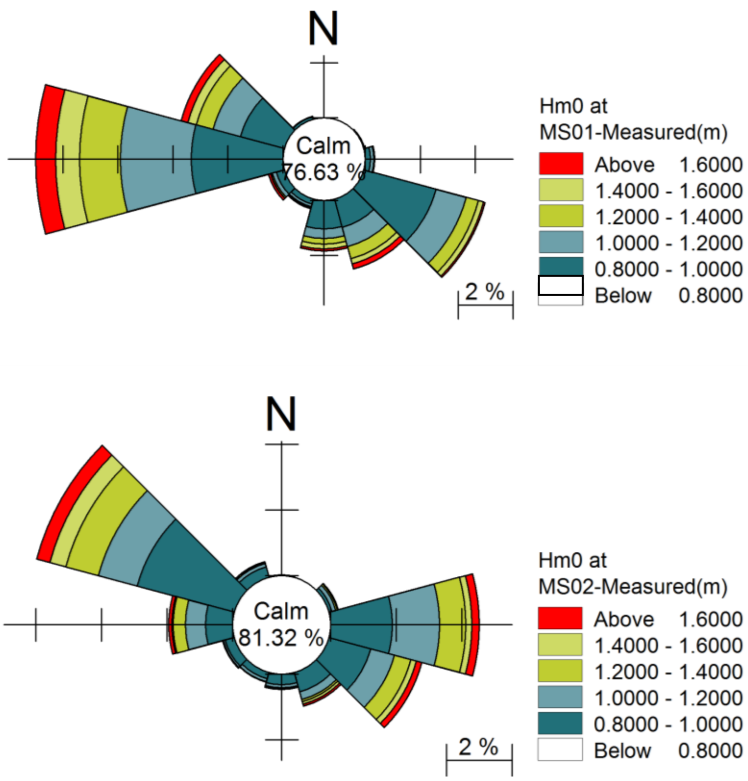


Figure 5.1 Measured waves for wave heights> 0.8m at two locations in the Fehmarnbelt, MS01 (upper figure) and MS02 (lower figure), 30. April 2009-1. May 2010. For the locations see Figure 4.9

6 GEOLOGICAL DESCRIPTION OF THE FEHMARNBELT AREA

6.1 Landscape

The landscape in the Fehmarnbelt area was formed during the last Ice Age – Weichsel (about 120 000 – 10 000 years Before Present [B.P.]). The topography was mainly formed by Weichsel's last great ice advance – "The Young Baltic Ice Advance", which came from an ESE direction about 15 000 years B.P.

It is generally accepted that the last glaciers melted away from the Baltic area about 15 000 years B.P. The deep central-southern part of the Fehmarnbelt, see Figure 3.1 and Figure 6.2, must have existed at that time, and it is supposed that melt water from the receding glaciers flowed through this deep canal in a westerly direction at this time.

Since the final retreat of glaciers from the south-western Baltic area, the Fehmarnbelt has been characterised by highly variable sedimentary processes and environments, (Novak and Björck 2003). Isostatic rebound dominated after the ice recession, and lakes in the present Baltic Sea and Belt Sea were formed and kept in place by uplifted threshold areas. Overflow from the lakes to Kattegat through the Great Belt and Øresund changed position several times. The present Baltic Sea area was at times a lake, at other times a sea connected with the Kattegat. The estimated extensions of the socalled Baltic Ice Lake, the Baltic Yoldia Sea and the Ancylus Lake are presented in Figure 6.1 according to the description of these conditions in (Jensen et al 2002).

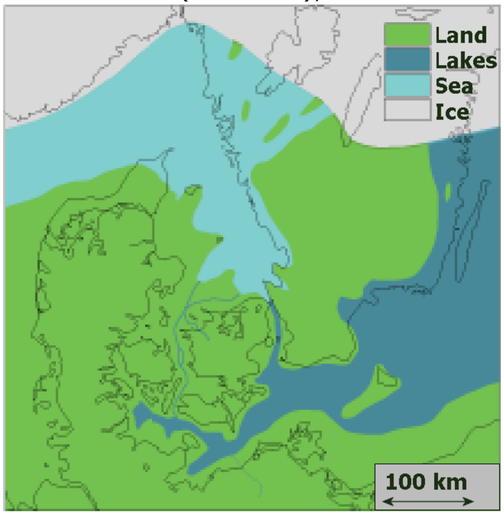
Reminiscences of the ancient fluvial system (Figure 6.2) in the Fehmarnbelt, "the Dana River", due to these occurrences are reported in several reports; for a review see (Novak and Björck 2003). This fluvial system contains features like "oxbow morphology" or "pool like morphology", both originating from a meandering river during the drainage of the Ancylus Lake. The hypothesis of the "Dana River" by von Post proposes the drainage of the Ancylus Lake through a river in the Great Belt.

Coastal areas and present shorelines
About 7 800 B.P., the sea broke through at Øresund and later at Lillebælt and connected again the Baltic Sea to the North Sea. This situation has continued since then. The sea level rose to about the present level and the approximate location of the present day shorelines origins from this period.

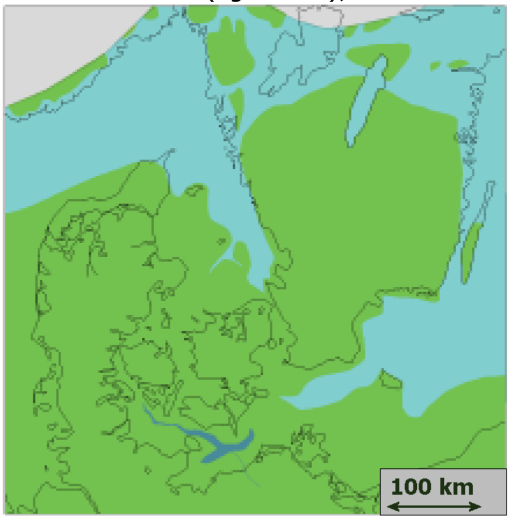
The landscape of the southeast of Lolland is gently undulated as it consists of parallel ridges and runnels that are WNW-ESE oriented. The ridges some places have their top level at 11-13 m above sea level and are 0.5-1 km wide. The height of the ridges compared to the runnels is 4-6 m. These ridges are remains of elongated islands as seen from historical maps of Lolland; some of the ridges are shown in Figure 6.3 as red lines on the historical map from 1763 – 1805 (for other examples of historical maps of Lolland where this phenomenon can be seen, see Figure 7.25 and Figure 7.26). This gently undulating glacial landscape system was formed during the last part of the last Ice Age and is called ridge-runnel or drumlin morphology.

The landscape of Fehmarn shows similar features. In the eastern part of the otherwise flat Fehmarn Island, there are long ridges, sometimes over 20 m high, in the east-west direction. The 19 m high Wulfsberg on the south coast of Fehmarn is a particularly typical drumlin of Schleswig-Holstein.

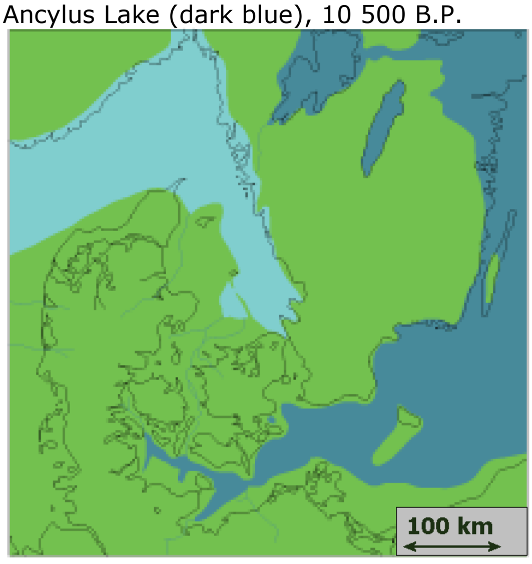
Baltic Ice Lake (dark blue), 12 000 B.P:



Baltic Yoldia Sea (light blue), 11 500 B.P.:



Ancylus Lake (dark blue), 10 500 B.P.



10 000 B.P:

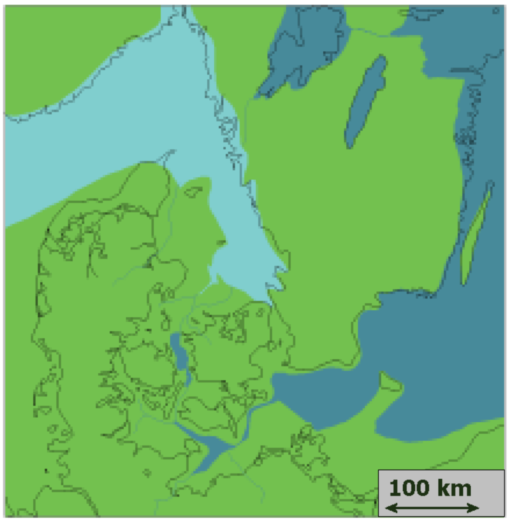


Figure 6.1 Stages in the late/post-glacial development of land and sea/lake conditions in the Fehmarnbelt area. Modified from (Jensen et al 2002)

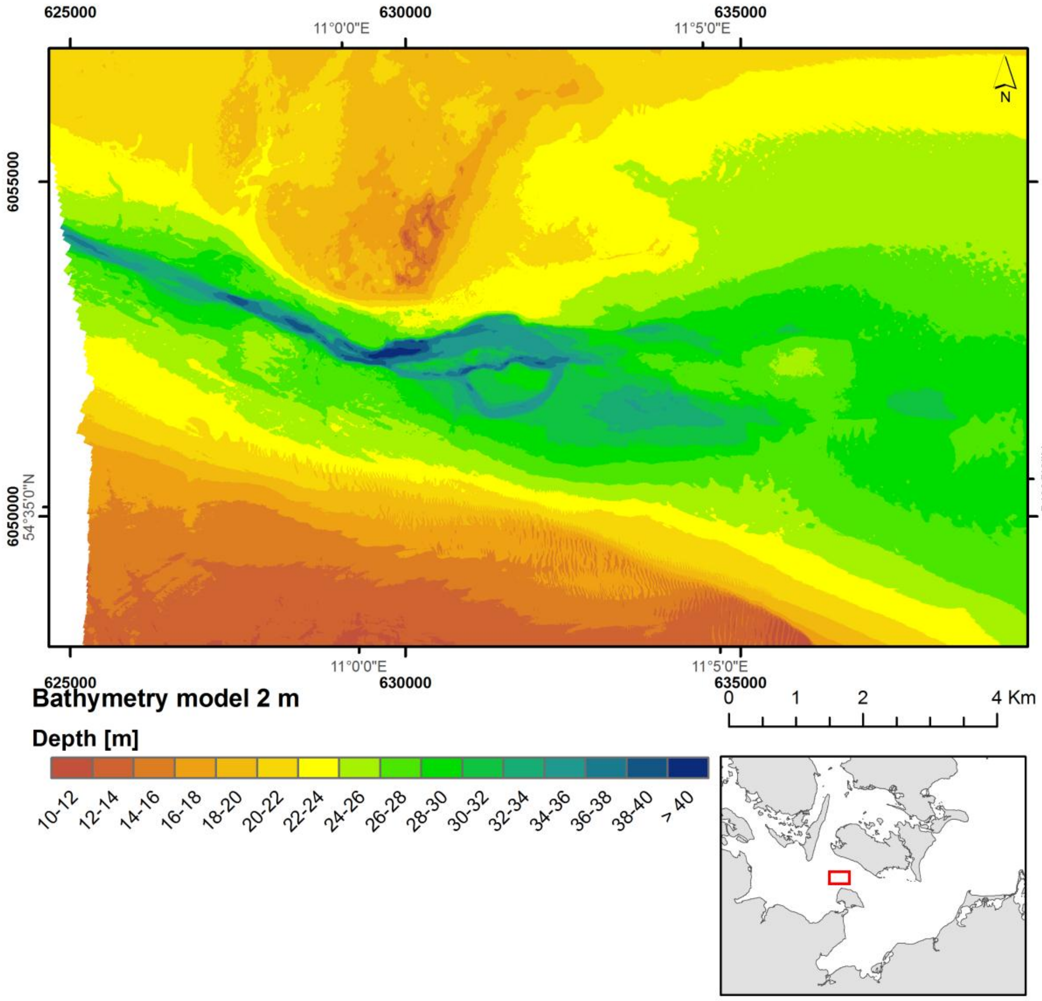


Figure 6.2 Reminiscences of the ancient fluvial system in the Fehmarnbelt, "the Dana River, North-west of Fehmarn. Bathymetry measured by multibeam echosounder, 2009

Figure 6.3 Ridge-runnel morphology at the southern part of Lolland shown as red lines on top of the historical map from 1763 – 1805 by Scientific Society (Contains data from the Danish Geodata Agency, 2010, "Videnskabernes Selskab")

6.2 Sediment deposits

The upper subsoils in the Fehmarnbelt consist mostly of glacial meltwater sand covered by silty, varved clays, topped by post glacial marine sand, gyttja and peat. Beneath these layers are mostly glacial tills (also called boulder clay or moraine clay) of different types with local pockets of melt water sand and silt, see Figure 6.4. Deeper layers are chalk and paleogene clay older than the Quaternary.

Close to Lolland, the glacial till is exposed at the seabed or only covered by very thin layers of marine sand/gravel, while it is buried below up to 10–15 m thick late and post-glacial deposits in the central, deep part of the Fehmarnbelt. Close to the Fehmarn coast, paleogene clay is exposed at the seabed.

A summary of the depositional environment and the character of the deposition in the late/post-glacial period are presented in Table 6.1 following (Rambøl Denmark A/S and Arup JV 2010) in which a more detailed description can be found. Please note that the timing of the development in this figure is slightly different from the time-line in Figure 6.1; however, the overall description and processes are in agreement.

When the last glaciers melted away from the Baltic area about 15 000 years B.P. it is supposed that melt water from the receding glaciers flowed through the - at this time already existing - deep central-southern part of the Fehmarnbelt in a westerly direction. No continuous, typical melt water river deposits have been detected in the area, but it is supposed that at least the deepest layers of the basin deposits (Figure 6.4) in the central part of the Fehmarnbelt can be interpreted as remnants of such a deposit, which originally may have been present all over the deep canal, but later eroded away locally.

During the post-glacial periods the Baltic Ice Lake stage, the Yoldia Sea stage and the Ancylus Lake stage (Figure 6.1), clay and silt have by far been the dominating sediment types deposited. According to descriptions from older investigations, see (Nuygård, Knudsen and Hovmark-Nielsen 2006), the deposits from the Baltic Ice Lake are characterised by a distinct layering/lamination, where each (sand)/silt/clay layer/lamina represents a year ("varv" sediment). According to (Novak and Björck 2003), terraces from the lake can be detected in elevations between -25 m and -30 m in the Fehmarnbelt area, which means that only clay/silt deposits situated below that level can be Ice Lake deposits. Varved clay/silt sediment found in the central part of the Fehmarnbelt is supposed to be a deposit from the Baltic Ice Lake stage.

Even though most of the period for the Baltic Ice Lake was rather cold, warmer periods as the Allerød Period appeared. Therefore, above the lake shoreline for the Baltic Ice Lake, peat and freshwater gyttja are present in local depressions, some of which are today situated below the bottom of the present day Baltic Sea.

Deposits from the Baltic Yoldia Sea stage, in which the Baltic Ice Lake got connected to the sea through a connection in the central Sweden (Björk 1994) and the water in the Baltic became saline, are less layered, and shells are more common.

It is uncertain in which – present day - level the shore of the Ancylus lake following the Baltic Yoldia Sea was situated in the Fehmarnbelt area. A clay layer in boring 09.A.009 approximately 1.5-2 km from the German shoreline between elevation -17.2 m and -20 m is interpreted as typical Ancylus clay, and the shore level must then have been at least as high as -17.2 m, see (Rambøll Denmark A/S and Arup JV 2010) for details of geotechnical borings.

About 7 800 B.P. the Kattegat and the Baltic region was connected through the Belt Sea and this situation has been unchanged since then. In the first part of the period, the Littorina Sea period, the water in the Baltic was significantly more saline than today. Sand with shells is by far the most common deposit from this period in the Fehmarnbelt area.

The above description, which is mainly based on (Rambøll Denmark A/S and Arup JV 2010), fits well with the general substrate map presented in FEHY 2013a and Figure 6.5.

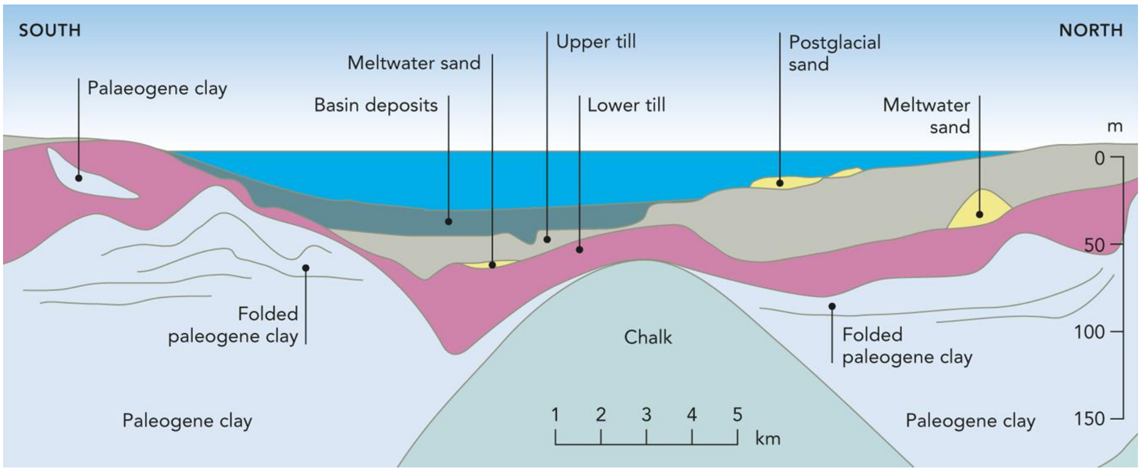


Figure 6.4 The geology in the Fehmarnbelt. From http://www.femern.com/

Table 6.1 Overview over stages of the late/post-glacial development in the Fehmarnbelt area. According to (Rambøll Danmark and Arum JV 2010)

Stage	Period (Before Present)	Typical deposit	Level of the lake/sea in the Fehmarnbelt area relative to present DVR90
Litorina Sea/ Present sea	7.800–now	Sand in exposed areas, Gyttja very locally in deepest, low oxygen parts.	~0m
Ancylus Lake	9.000–7.800	Mostly silty clay. Sometimes layered/laminated.	~-16m
Yoldia Sea, higher salinity	9.500-9.000	Medium plasticity clays, often without visible layering. A few shells. Maybe nearshore sand deposits.	~-20m
Yoldia Sea, low salinity	10.250-9.500	Mostly silty clay and silt without a distinct layering. Local sand deposits in areas where rivers entered the lake. No or almost no shells.	
Baltic Ice Lake	13.000-10.250	Distinctly layered/laminated ("varved") clay/silt. Maybe sand deposits in areas for inflow to the lake. Allerød peat and freshwater gyttja at levels higher than the level of the Ice Lake.	~-25m to -30m
Meltwater stage	15.000-13.000	Melt water sand and gravel	
End of glaciation in the area	15.000	Clay till deposition stops	

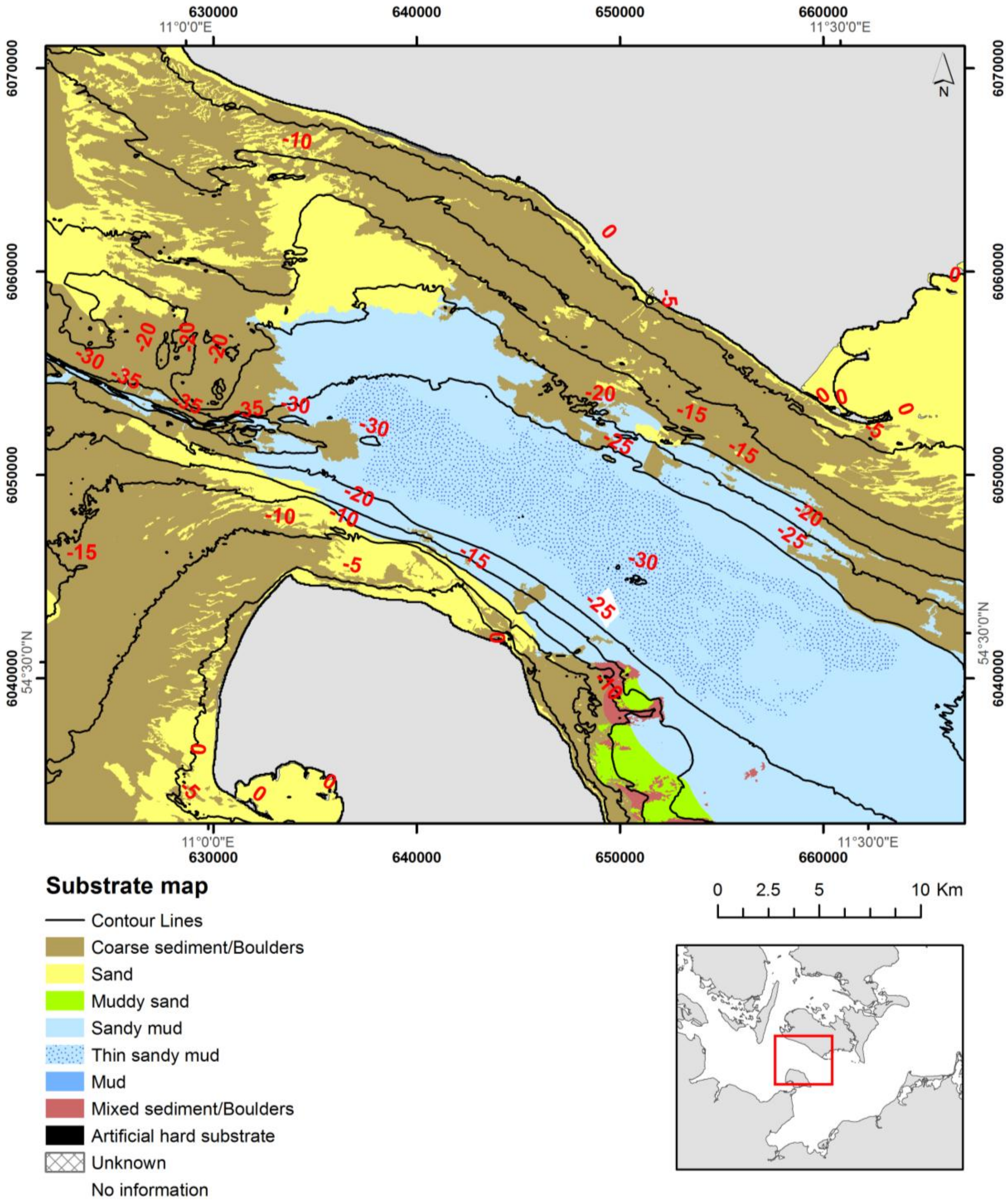


Figure 6.5 Substrate map. FEMA (2013a)

7 LOLLAND COAST

7.1 Present coastline and coastal structures

The south coast of Lolland consists of low-lying land, which is protected by a major sea-dike constructed following a severe storm in 1872. The sea-dike was finished in 1877 and covers the entire south coast of Lolland from Hyllekrog in the east to "Albuen" in the west, see Figure 7.1. The dike continues north along the west coast of Lolland and north along the western shoreline of Rødsand Lagoon. The crest of the dike is in level 3.9 m above DRV90.

Large coastal areas were reclaimed by the construction of the dike; in total 9 pumping stations are active along the Lolland dike. The entire coastline between the south-western part of Lolland, Albuen, and Hyllekrog is in general characterised as a topographically low area with narrow beaches. Along large parts of the coast, the dike is protected by revetments. Other stretches are natural with some accumulation of loose sediment, sand/gravel or pebbles in front of the dike.

The littoral zone is narrow extending to just 2-4 m of water depth. The coastal profiles along the Lolland south coast are in general characterised by a steep shoreface and a rather flat beach. At some locations, low dunes are found.

The present coastline and the coastal structures between Kramnitze and Hyllekrog are described below. The coastline was inspected on 28th January 2011. Photos shown in the following are from this site inspection. An overview of the coastline and the structures is supplied in Figure 7.2 (Kramnitze to Rødbyhavn) and Figure 7.3 (Rødbyhavn to Hyllekrog).

Aerial photos of sections along the entire stretch between Kramnitze and Hyllekrog showing details of the shoreline and structures can be found in Appendix A.

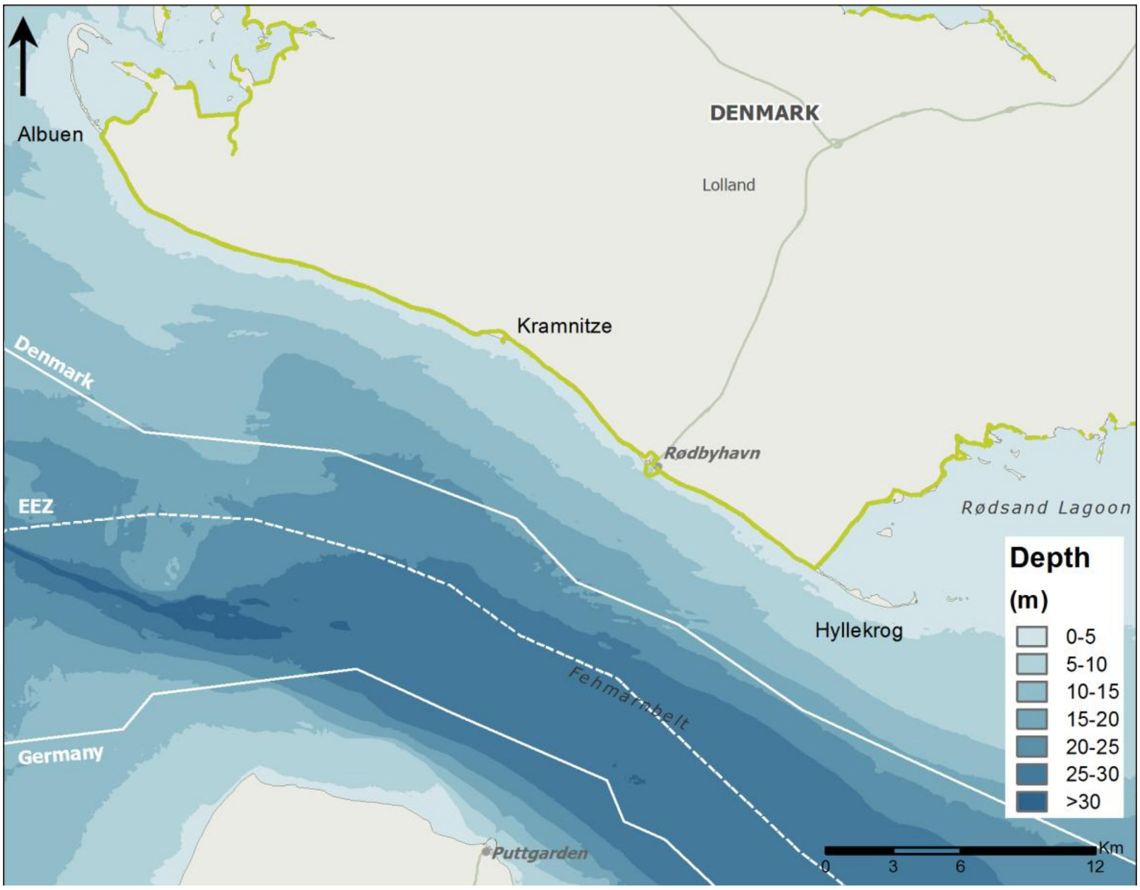


Figure 7.1 Overview over the dike along the South coast of Lolland

Figure 7.2 Overview of coastline and coastal structures from Kramnitze to Rødbyhavn. Aerial photo from 2009 (©COWI Orthophoto April 2009)

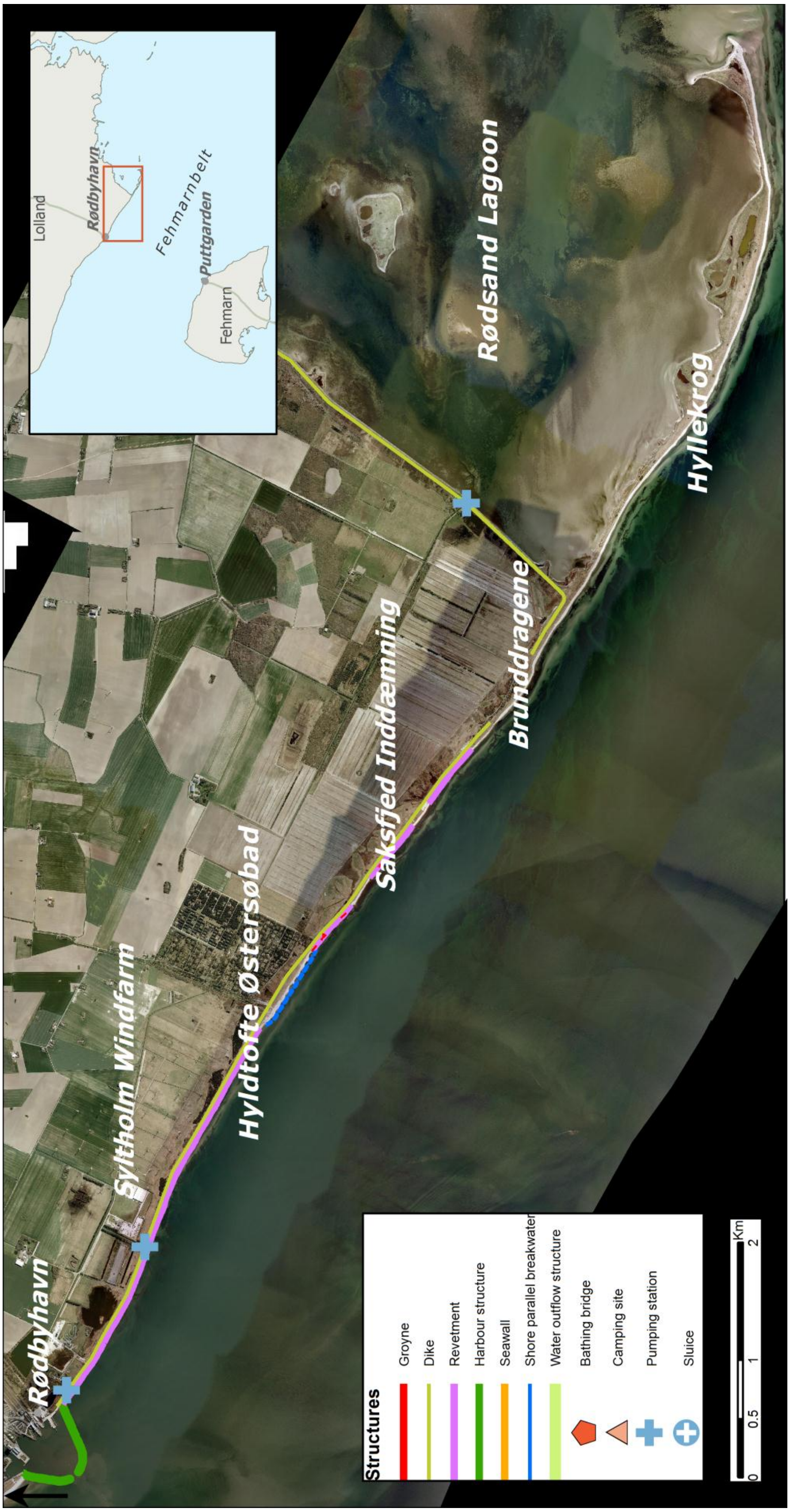


Figure 7.3 Overview of coastline and coastal structures from Rødby Ferry Harbour to Hyllekrog. Aerial photo from 2009 (©COWI Orthophoto April 2009)

7.1.1 Kramnitze fishery harbour

Kramnitze is a small town approximately 8 km west of Rødbyhavn (Figure 7.1). It has a small fishery port protected by breakwaters (Figure 7.4).

Sand accumulates west of the breakwater, see Figure 7.5, indicating a net transport of sand towards the east. The breakwaters have been extended several times to avoid the sediment from the shoreline west of the harbour to by-pass the western breakwater and deposit in the inlet to the harbour. Each time the extension caused further accumulation of sand (Fehmarnbelt Environmental Consultants 1996). The last extension of the breakwaters was performed in 1985 using three discarded steel moulds used for construction of the piers for the Farø Bridge.

The harbour is again approaching a situation where an extension of the west breakwater (possibly combined with excavation of sand from the accumulation area) is required in order to keep the harbour open for navigation. The depth in the entrance area is maintained by a propeller from a fishing vessel.

A pumping station discharging water through the harbour causes a persistent flow to the harbour breakwaters, which helps to keep the harbour entrance open. The average discharge is 1.6 m^3/s and the max discharge is in the order of 20 m^3/s. Kramnitze pumping station (Figure 7.6) is the largest pumping station in northern Europe and it drains an area of 20,000 ha = 200 mio m^2.

The former Rødby Fiord and archipelago (see Section 7.2 for historical development of the Lolland coast) have been reclaimed via the major pumping station at Kramnitze. The pumping station has been designed for a maximum capacity of 1 litre/s/ha, corresponding to a capacity of 20 m^3/s. The 1 litre/s/ha corresponds to an effective precipitation of 3154 mm per year. The average precipitation in the area is in the order of 600 mm per year, which means that the pumps are designed to cope with precipitation capacities 5 to 10 times the average precipitation intensity. The actual pumped volume is not exactly known but it has been estimated by the Lolland Municipality/the pump master on the basis of the power consumption for the years 1993 to 2010 that the average yearly pumped volume is in the order of 45 mio. m^3/year (varying between 20 and 78), corresponding to a net precipitation of 250 mm/year (precipitation – evaporation).

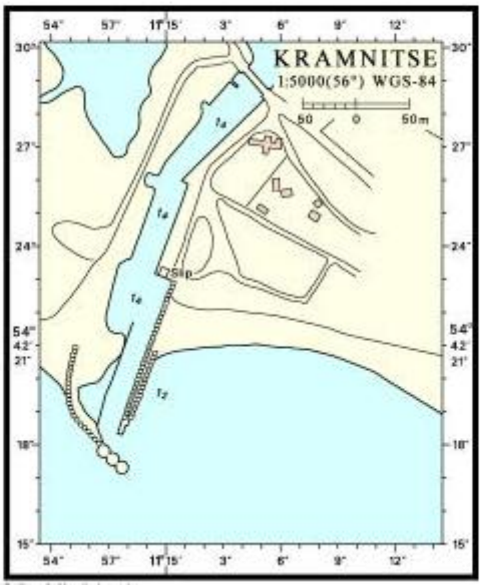


Figure 7.4 Kramnitze Fishery Harbour, sea chart and photo 1997 from "Den Danske Havnelods". @Geodatastyrelsen 2013.

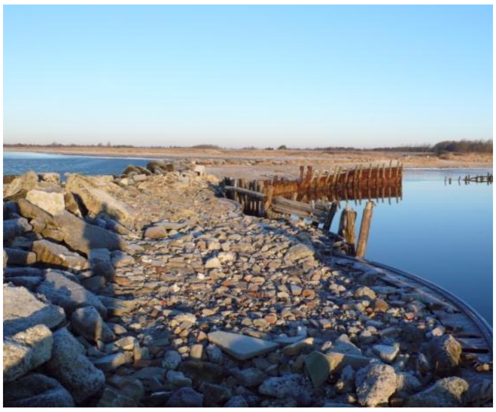


Figure 7.5 *Kramnitze Harbour. Left: sand accumulation west of western breakwater. Right: the tip of the west breakwater constructed by used steel caisson moulds filled with mixed concrete blocks and stones*

Figure 7.6 *The "new" pumping station at Kramnitze built in 1966*

7.1.2 Kramnitze to Rødby

The alignment of the coastline between the Kramnitze harbour and Rødbyhavn, a stretch of about 8.4 km, shows some minor undulations, which reflects the contour of the original landscape, which varied between islands and tidal inlets. The characteristics of this coastal section vary between sections with sandy beaches and sections, where the dike is protected by revetments, see Figure 7.2. The characteristics of the various sections are described and illustrated in the following.

Sandy stretch east of Kramnitze fishery harbour
Kramnitze harbour creates a semi-sheltered area east of the harbour which has caused a lee-side accumulation of sand in front of the western part of the town. The beach, along this about 800 m long stretch, is 15-20 m wide and high dunes are present along this section of the coast, see photo in Figure 7.7. The width of the beach decreases towards east, and off the central part of the town the shoreline is at the front of the dike.

Revetment along eastern part of Kramnitze town
From the central part of Kramnitze town and about 700 m further eastward, there is no beach in front of the dike, but the dike is partly covered by small dunes, which indicates that there has been a beach in the past along this section. The dike is protected by a revetment along this section, see photo in Figure 7.8.

Remains of wooden pile groynes are seen in this area. The seabed is covered by pebble, see photo in Figure 7.9.

Sandy beach off the Skarholm area
The area east of Kramnitze is a low-lying shallow lake/wetland area named Skarholm which stretches over about 1.4 km. This area is characterised by having a sandy beach with some gravel and a narrow dune in front of the dike, see photo in Figure 7.10.

Revetment between Skarholm and Bredfjed
The 1.1 km stretch between Skarholm and Bredfjed summerhouse area is protected by a revetment, see Figure 7.11.

Sandy beach off Bredfjed, Sandholm, Mygfjed and Lalandia
The 3 km stretch from the western part of Bredfjed to Lalandia has a fine sandy beach with some gravel. Low dunes are found along this section of the coast, see Figure 7.12. The outlet from Dragsminde Sluice at Sandholm is also seen on this figure.

There is a nice wide sandy beach off the eastern part of Lalandia, see Figure 7.13.

Revetment at headland off eastern part of Lalandia
There is a bend in the coastline forming a kind of headland off the eastern part of Lalandia. This part of the coast is protected by a 0.7 km long revetment which terminated where the sand accumulation west of Rødby Ferry Harbour starts, see Figure 7.14.

Figure 7.7 Beach conditions east of Kramnitze Harbour. Sandy beach and high dunes covering the dike

Figure 7.8 Revetment and no beach off the eastern part of Kramnitze

Figure 7.9 Seabed in front of revetment off eastern part of Kramnitze, seabed covered by pebble

Figure 7.10 Sandy beach with some gravel off Skarholm, there is a narrow dune in front of the dike

Figure 7.11 Protected section between Skarholm and Bredfjed summerhouse village, photo taken from the west end of the village

Figure 7.12 Sandy beach with gravel at the Bredfjed – Lalandia stretch, dunes in front of the dike. Photo taken at the outlet from Dragsminde Sluice in the eastern end of the stretch

Figure 7.13 Sandy beach off Lalandia with dunes in front of the dike, steel piles for bathing bridge in the foreground

Figure 7.14 Revetment off the eastern end of Lalandia. Left: west end of revetment, remains of wooden pile groynes. Right: east end of revetment, sand accumulation west of Rødbyhavn has started

7.1.3 Rødbyhavn

The first Rødbyhavn was built during the period 1900-1912, but the Ferry Harbour was not built until 1962-1963 in connection with the opening of the ferry connection between Rødby and Puttgarden. The breakwaters of the harbour extend 560 m from the coast. The layout of the harbour is seen inFigure 7.16. The dredged channel to the harbour is maintained to a depth of 8.5 m DVR90. The width of the navigation channel to Rødbyhavn was increased in 1997, see further information in (Fehmarnbelt Environmental Consultants 1998).

Rødbyhavn has blocked the natural net eastward littoral drift along the shoreline since the construction in 1900-1912 (extended in 1962-63). West of the harbour extending to the bay off the eastern part of Lalandia, a 0.9 km long sand accumulation has built up over the last about 100 years (Figure 7.17). A wide dune area is seen between the dike and the beach and seaweed accumulates at the beach. Accumulation still takes place and some sediment is by-passing the harbour breakwater. Practically all the sand bypassing the breakwater is depositing in a sedimentation reservoir constructed along the west side of the navigation channel. The reservoir is seen in Figure 7.16. The reservoir prevents sedimentation in the navigation channel.

The shoreline east of the harbour is heavily protected by a rubble mound revetment indicating erosion of the shoreline caused by the harbour blocking sediment transport from the east. The erosion has caused disappearance of the beach originally fronting the dike. No accumulation of sand is seen east of the harbour.

Figure 7.15 Rødbyhavn, consisting of the ferry harbour basin and some minor basins to the north of the ferry basin (the west basin and the north basin). Aerial photo from 2009 (©COWI Orthophoto April 2009)

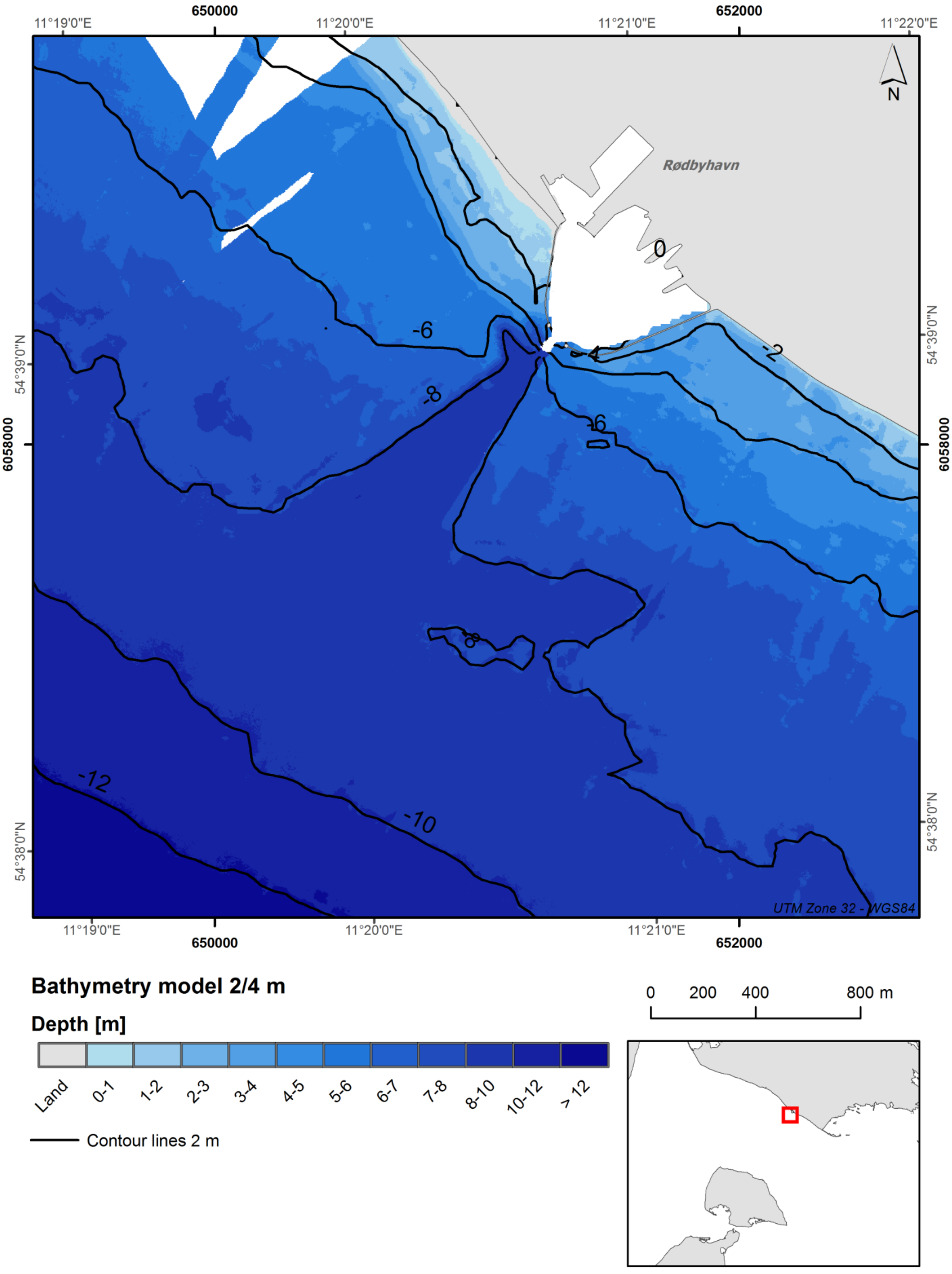


Figure 7.16 The reservoir for trapping sediment bypass from the shoreline west of Rødbyhavn is seen west of the access channel near the harbour entrance

Figure 7.17 *Sand accumulation with a wide beach and dune area west of Rødbyhavn*

Figure 7.18 *Heavily protected dike SE of Rødbyhavn. The revetment is a combined concrete cell and rubble mound structure*

7.1.4 *Rødby to Hyllekrog*

The alignment of the coastline between Rødbyhavn and Hyllekrog, a stretch of about 8.2 km, is generally a fairly straight coastline. For an overview of this section of the coastline and the coastal structures along the coast, see Figure 7.3.

The western part of the section between Rødby and Hyldtofte Østersøbad is characterised by a revetment and no beach due to the lack of supply of sediments from east caused by Rødbyhavn as described above. The scarcity of sand gradually ceases further east towards Hyllekrog, where sandy beaches appear again. Stretches of the coast between Hyldtofte Østersøbad and Hyllekrog vary between sections protected by a revetment (typically without a beach) and sections with sandy beaches. The characteristics of the various sections are described and illustrated in the following.

The section east of the breakwater protection scheme at Hyldtofte Østersøbad is also without a beach partly due to the general lack of sand due to the blocking effect of Rødbyhavn and partly due to the local blocking effect of the breakwater protection scheme. Sections protected by revetments, which are those generally without beaches, are seen in Figure 7.3.

Revetment from Rødbyhavn to Hyldtofte Østersøbad

The revetment protecting the shoreline and dike against erosion extends about 3.8 km towards the southeast from the eastern breakwater of Rødbyhavn to Hyldtofte Østersøbad. As described above no beach is seen in front of the revetment. The coastal profile is steep and the seabed is dominated by coarser sediments indicating the lack of supply of finer sediments (sand). The depth in front of the revetment is in the order of 1.5 m.

Breakwater scheme in front of Hyldtofte Østersøbad

Coastal shore-parallel breakwaters were constructed in front of the summerhouse area in 1999 to keep nourished sand in the area and prevent further erosion of the beach, see Figure 7.19. The scheme consists of ten individual breakwaters covering a stretch of 0.8 km. Small sections of beaches are suspended between the breakwaters. They are sometimes flooded. Photos from the scheme are presented in Figure 7.20. The abundant availability of sand on the beach within the scheme has caused formations of dunes in front of the dike behind the breakwaters. The breakwaters trap substantial amounts of seaweed, which according to local people from the area cause unpleasant odour in the summer period. It is not known if there is a buried revetment along the Hyldtofte Østersøbad, however, it is not active anyway.

Stretch between Hyldtofte Østersøbad and Brunddragene

Along the 1.9 km long stretch from Hyldtofte Østersøbad to Brunddragene, the dike is protected by a revetment. The area behind the dike is Saksfjed Inddæmning, which is a reclaimed area from the period of the construction of the dike.

The revetment along this section is partly exposed and partly covered in sand and low dunes are found. Sand undulations of the coastline, which most likely move in the main transport direction towards the east, and remains of small groynes are also seen, see photos in Figure 7.21.

Brunddragene to the starting point of Hyllekrog

Brunddragene is the most southeastern part of the reclaimed area, where the mainland of Lolland terminates and the spit, Hyllekrog, starts. This area was a small island before the dike was constructed; see the historical overview in Section 7.2. The height of the previous island is more than 5 m. It is characterised by sandy beaches and a dune area and there is a row of small summer cottages behind the dune. The dike continues from the easternmost termination of the previous island towards ESE for a length of 0.6 km, where the dike turns towards NE separating the Saksfjed Inddæmning from Rødsand Lagoon. The shoreline along this easternmost part of the mainland of Lolland is also sandy and small dunes are seen. This beach continues ESE-ward on Hyllekrog spit. Photos from this stretch are presented in Figure 7.22.

Figure 7.19 Hyldtofte Østersøbad. Aerial photo from 2009 (©COWI Orthophoto April 2009)

Figure 7.20 Breakwater scheme at Hyldtofte Østersøbad. Upper left: west end of scheme. Upper right: pocket beach and tombolo within the scheme. Lower left: accumulation of seaweed in the eastern end of the scheme. Lower right: revetment and no beach SE of the scheme

Figure 7.21 Stretch Hyldtofte Østersøbad to Brunddragene. Upper left: east end, breakwater scheme seen in the distant. Upper right: revetment in eastern end, remains of piled groynes. Lower left: middle part, sand undulation and buried revetment. Lower right: termination of revetment in east end of section, sandy beach takes over

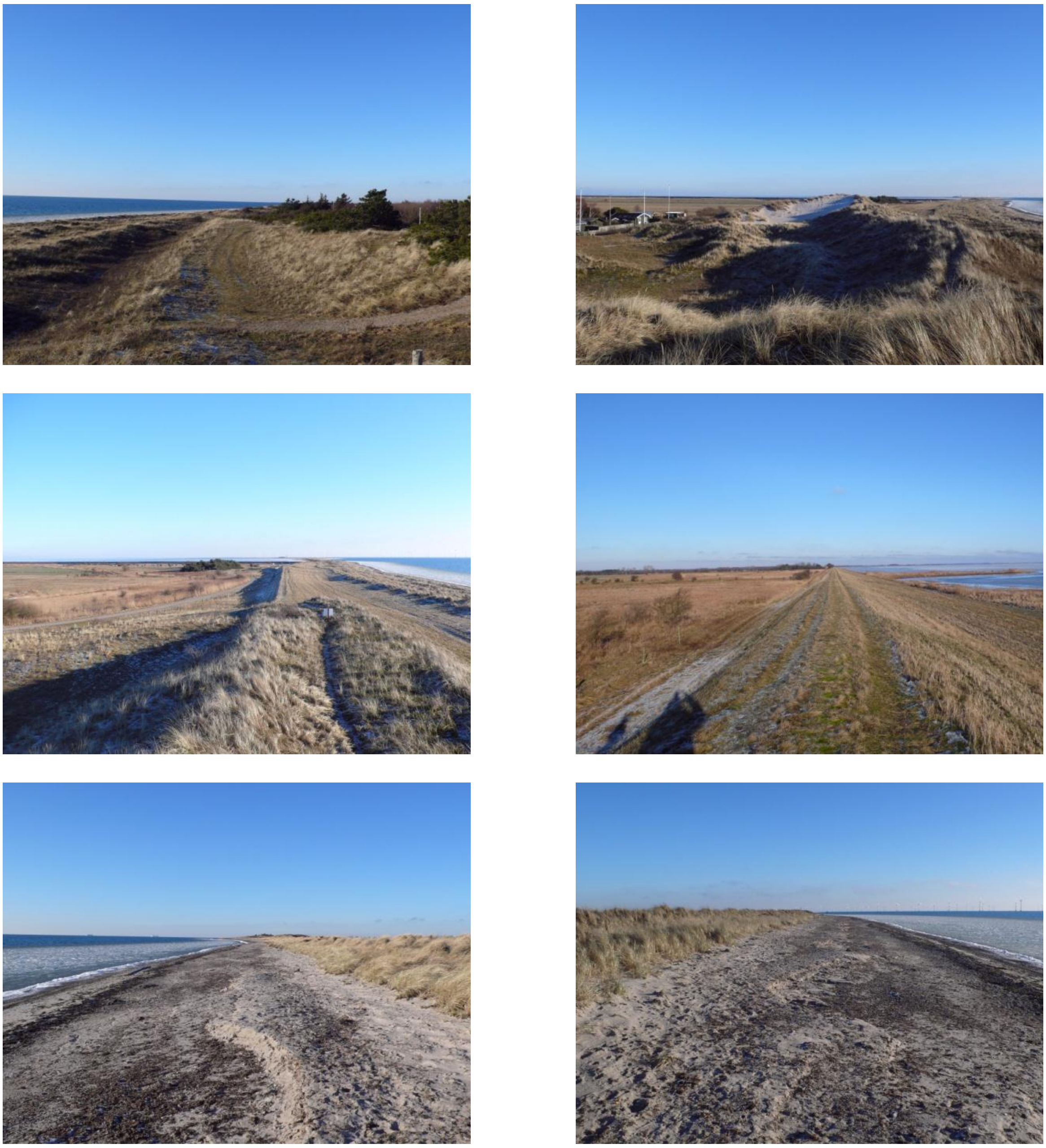


Figure 7.22 Photos from Brunddragene to Hyllekrog. Upper left: west part of Brunddragene. Upper right: east part of Brunddragene with high dunes. Middle left: transition from "island" to dike. Middle right: dike towards NE. Lower photos: beach at E end of stretch, sand with gravel and seaweed acc. and small dunes

7.1.5 Hyllekrog and Rødsand barrier islands

The Hyllekrog, Western Rødsand and Eastern Rødsand are natural barrier islands by which the Rødsand Lagoon is partly separated from the Fehmarnbelt. The gaps between the barrier islands are as such important for the water exchange between the Rødsand Lagoon and the Fehmarnbelt. Hyllekrog is connected to Lolland in its western part and does therefore have the characteristics of a spit.

The barrier islands exist as natural formations formed by a combination of onshore transport of sand from the seabed in front of the formations and supply of sand from the adjacent coasts by the littoral drift (DHI 2007b).

The Hyllekrog, nearest the area of interest, consists of moraine till overlaid with deposited loose Aeolian and marine deposits. Only small changes occur along the shoreline of Hyllekrog, except for the easternmost part, where aerial photos over the years show that the sediment transported towards the east deposits.

7.1.6 Recreational areas from Kramnitze to Hyllekrog

The entire stretch between Kramnitze and Hyllekrog is dominated by the dike, which is equipped with a gravel road open for public walking and biking. The only interruption in the dike is Rødbyhavn. This means that the entire stretch can be considered as a recreational area.

The hinterland is generally low, much of it consist of reclaimed areas, which are kept dry by pumping. Some of the drained areas are farmland and some are meadow and coastal lakes. These meadow and coastal lake areas are valuable wetlands with a lot of birds. Many of the relatively higher areas are developed with summer houses and as holiday centres. These are from west to east:

Kramnitze to Rødbyhavn

- Kramnitze village consists mainly of summerhouses
- Bredfjed is a summerhouse village
- Naturist beach east of Bredfjed (east of Dragsminde sluice)
- Lalandia is a huge holiday and amusement centre

Rødbyhavn to Hyllekrog

- Hyldtofte Østersøbad is a large summerhouse village
- Brunddragene is a cluster of small summer cottages

7.2 Historical shorelines and coastal structures

Information on the historical development of the south coast of Lolland has been collected from the literature and historical maps. Information on the coastal structures is based on maps and aerial photos and verified by coastal inspection.

7.2.1 Historical shorelines. Sea dikes and reclamations

Lolland is a low-lying area, originally prone to flooding from the sea during storm surges as well as during heavy rain due to difficult draining conditions. Figure 6.3 in the previous chapter shows a historical map from the period 1763-1805 and Figure 7.23 shows the existing situation in aerial photos from 2008.

Dikes and reclamations

For the coastal areas of Lolland, the single most important storm was an extreme event, which hit the Baltic area on 12-14 November 1872. The event caused extreme storm surges in the eastern Baltic Sea, including the Fehmarnbelt area. Major flooding on Lolland initiated construction of massive dikes to protect the hinterland. The construction of the sea-dike along Lolland's south coast was finalised in 1877.

Large shallow coastal lagoons were cut off from the sea by the construction of the dike and were reclaimed. The reclaimed areas after the construction of the dike are shown in Figure 7.24. The historic dikes and associated reclamation works are of major importance for the present-day appearance of the coastal areas and (lack of) coastal morphodynamic.

Rødby Fjord and Kramnitze areas

Before the dike was constructed, the coastal area was an archipelago consisting of a system of coast-parallel islands intersected by shallow coastal lagoons, the so-called Rødby Fjord, see a map of the area near Rødbyhavn from year 1842 in Figure 7.25 and of the Rødby/Rødsand Lagoon area in Figure 6.3 (1763-1805). The islands facing the Fehmarnbelt had the character of barrier islands, which means that they were formed by onshore transport of sand and smoothed by longshore transport processes. These outer islands were clearly different in nature from the other (more inshore) islands due to the active coastal processes. The location and shape of these islands originate from the last glaciation period, where the ice movement was from SSE, see the geological description of this phenomenon in Section 5.

The introduction of the dike along the Lolland south coast and the drainage of the land behind the dike by introduction of the large pumping station at Kramnitze and others converted vast shallow coastal lagoon areas into artificially drained low-lying farm land.

Rødby Fjord was converted into a protected coastal lagoon. Local land reclamations were gradually performed around the boundaries of the lagoon as presented in Figure 7.24. The local pumping stations at the various local reclamation dikes were closed down at the inauguration of the main pumping station at Kramnitze in August 1927. The complete drainage of the lagoon was not finalised until about 1970. A stage towards the completed drainage of Rødby Fjord is seen in the map from 1889 in Figure 7.26.

It is evident that the introduction of the main dike along the south coast of Lolland drastically changed the nature of the coastal area. The environmental quality of this area from shallow waters and wetlands into farm land was drastically reduced. The present-day shoreline along the south coast of Lolland is artificial with the most dominant element of the shoreline being the dike, which along large parts of the shoreline is protected against erosion by a revetment.

Figure 7.23 Aerial photo of the southeastern coast of Lolland (DDO® 2008, © COWI)

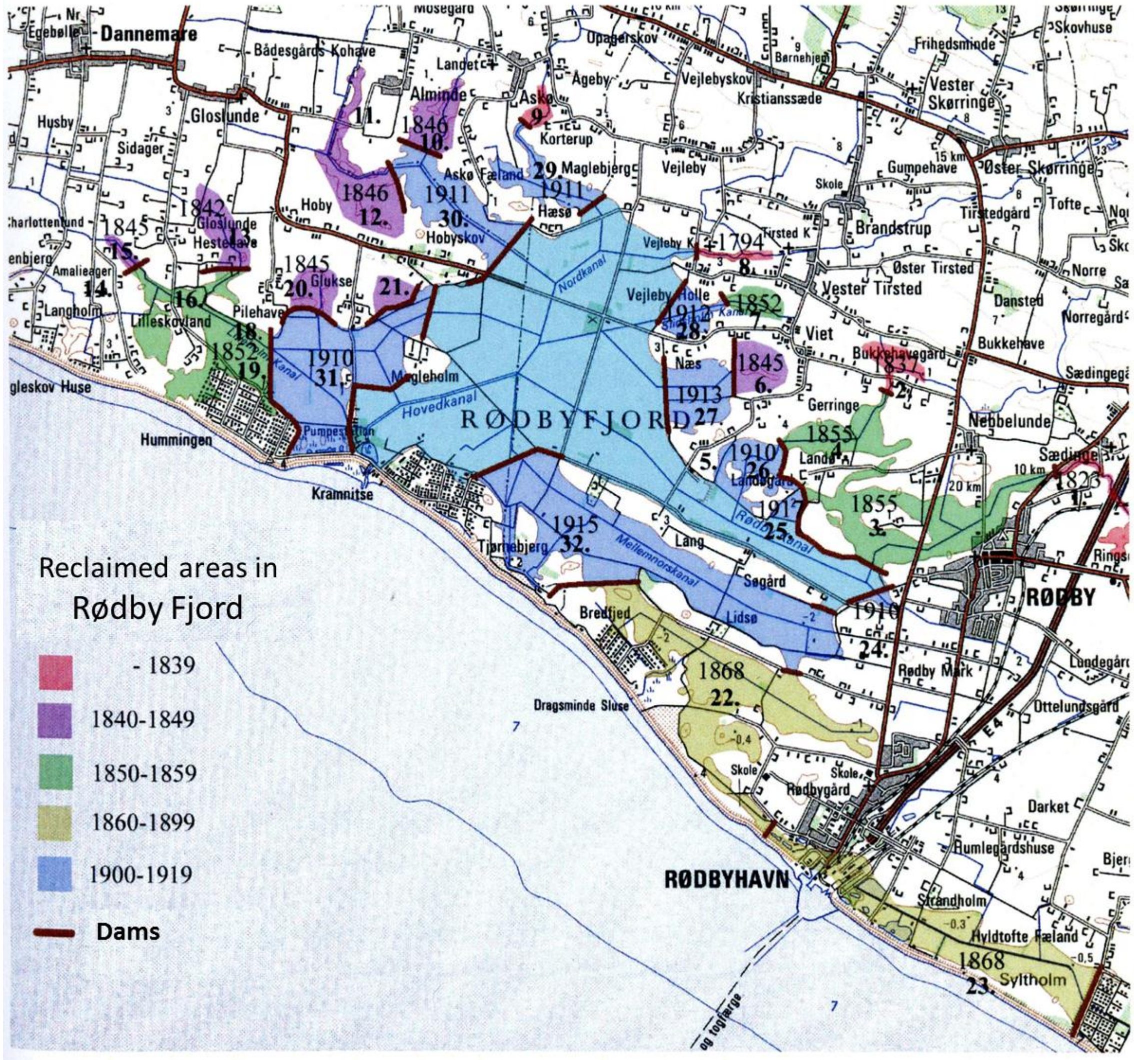


Figure 7.24 Overview of reclamations around Rødbyhavn and the year of finalisation of the reclamations (Translated to English from Hyldtoft, 2009, ©Museum Lolland-Falster)

Figure 7.25 *Map from 1842 for Rødby area, note the open Rødby Fjord (Contains data from the Danish Geodata Agency, 2010, "Generalkvartermesterstaben")*

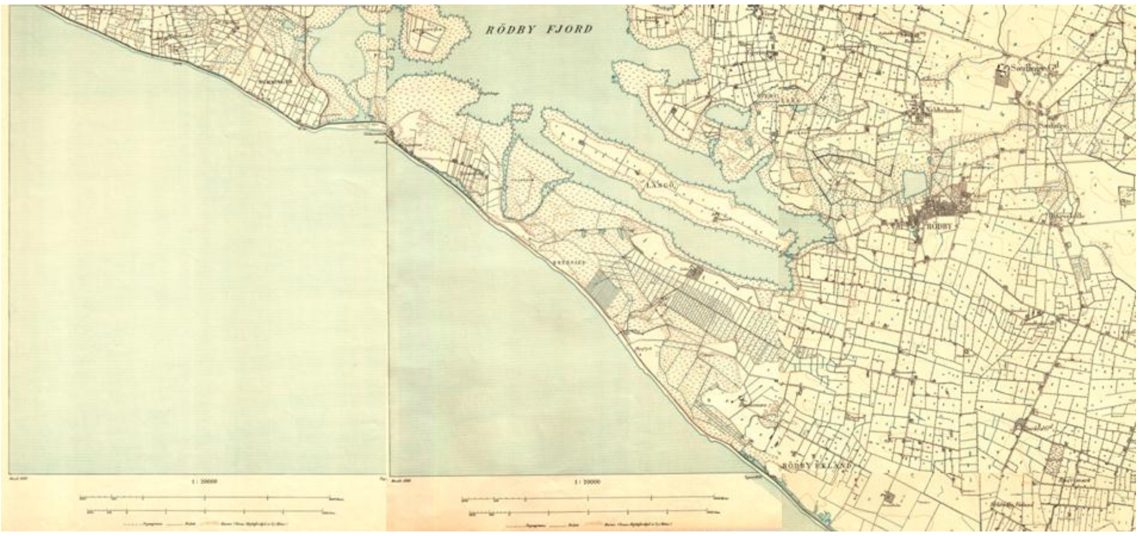


Figure 7.26 *Map of Rødby Fjord area surveyed 1889 (Contains data from the Danish Geodata Agency, 2010, "De høje målebordsblade")*

7.2.2 Rødby

The harbour breakwaters of Rødbyhavn extend to about 560 m from the shoreline and have blocked the natural net eastward littoral drift along the shoreline since the construction of the first harbour in 1900-1902 (extended in 1962-63). The layout of the new and the old harbour is shown in Figure 7.27. The old harbour extended to a water depth of about 4 m, while the present breakwaters extend to about 560 m from the shoreline to a water depth of about 5-5.5 m.

The development of the sand accumulation west of Rødbyhavn during the period 1964 to 1995 was analysed from historical maps in (Fehmarnbelt Environmental Consultants 1996). The development during this period is presented in Figure 7.27.

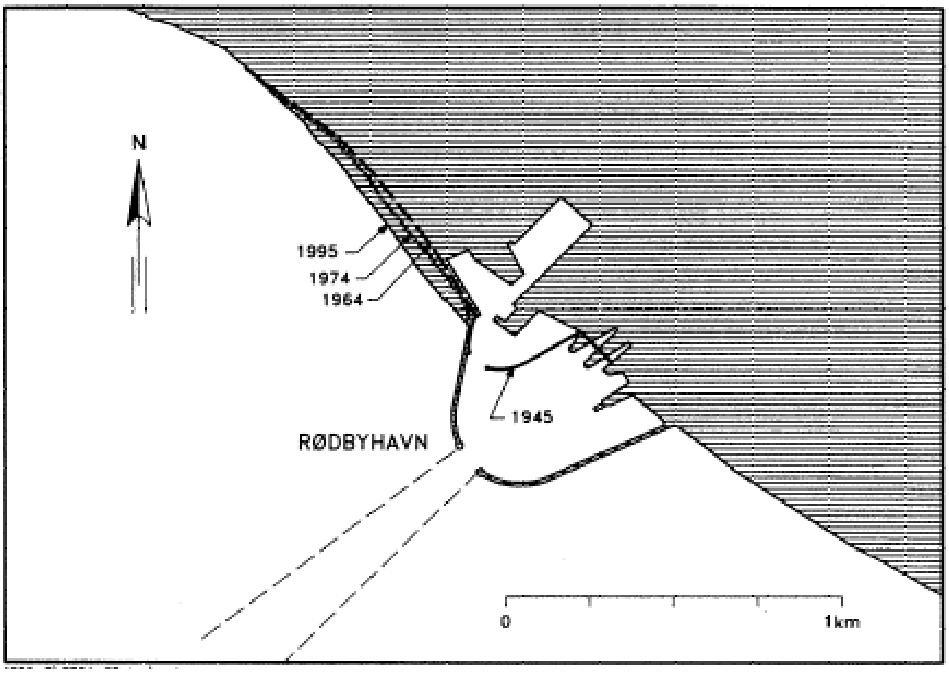


Figure 7.27 *Evolution of the shoreline west of Rødbyhavn in the period 1964 to 1995 and the old harbour in 1945 (Fehmarnbelt Environmental Consultants 1996)*

7.2.3 Hyllekrog

Hyllekrog and Rødsand are part of the row of barrier islands which existed along the south coast of Lolland prior to the reclamations and construction of the dike after the 1872 storm. Whereas the barrier islands further to the west are not present in the coastal landscape today, Hyllekrog and Rødsand still exist as such natural formations.

Detailed studies of the development Hyllekrog, nearest the area of interest, in the period 1945 to 2003 were performed in (DHI Water & Environment 2004) and (Jensen 2006) on the basis of satellite images and historical maps. The results of these studies are discussed in the following.

Hyllekrog became connected with the mainland in the period 1945-1989 (Figure 7.28) due to human interference, as the opening to the Rødsand lagoon at the western end of Hyllekrog was filled up with broken bricks to establish a road to the Hyllekrog Lighthouse located further east than the opening to the lagoon.

A satellite analysis of the western and eastern parts of Hyllekrog between 1973 and 2003 is presented in Figure 7.29 and Figure 7.30, respectively. The southern shoreline of Hyllekrog formation was generally stable in the period; however, it has been undergoing minor variations. Shifting erosion and accretion takes place along the western and middle sections, where the shoreline is orientated towards SW and SSW. Accretion takes place over the eastern section of about 1 km, where the shoreline has an orientation towards SSE. Prior to this period, between 1945 and 1967, this stretch of shoreline eroded according to (Jensen 2006), see Figure 7.28.

The development of Hyllekrog since 1945 is mainly concentrated at the eastern tip, which has changed orientation to a northern direction and at the same time it has become longer.

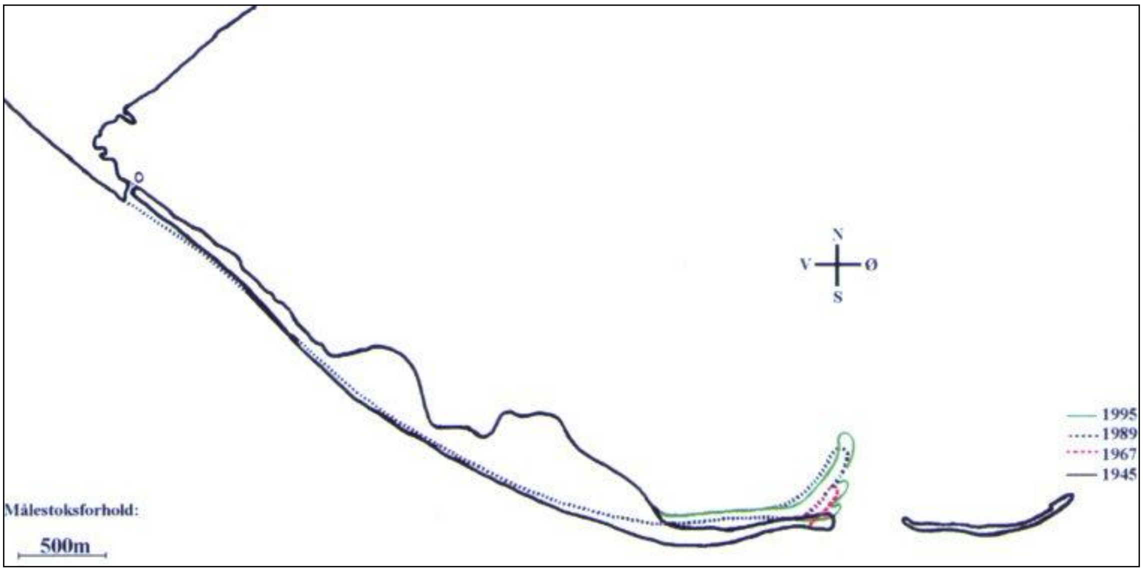


Figure 7.28 Development of the shoreline of Hyllekrog 1945-1999 (from Jensen 2006)

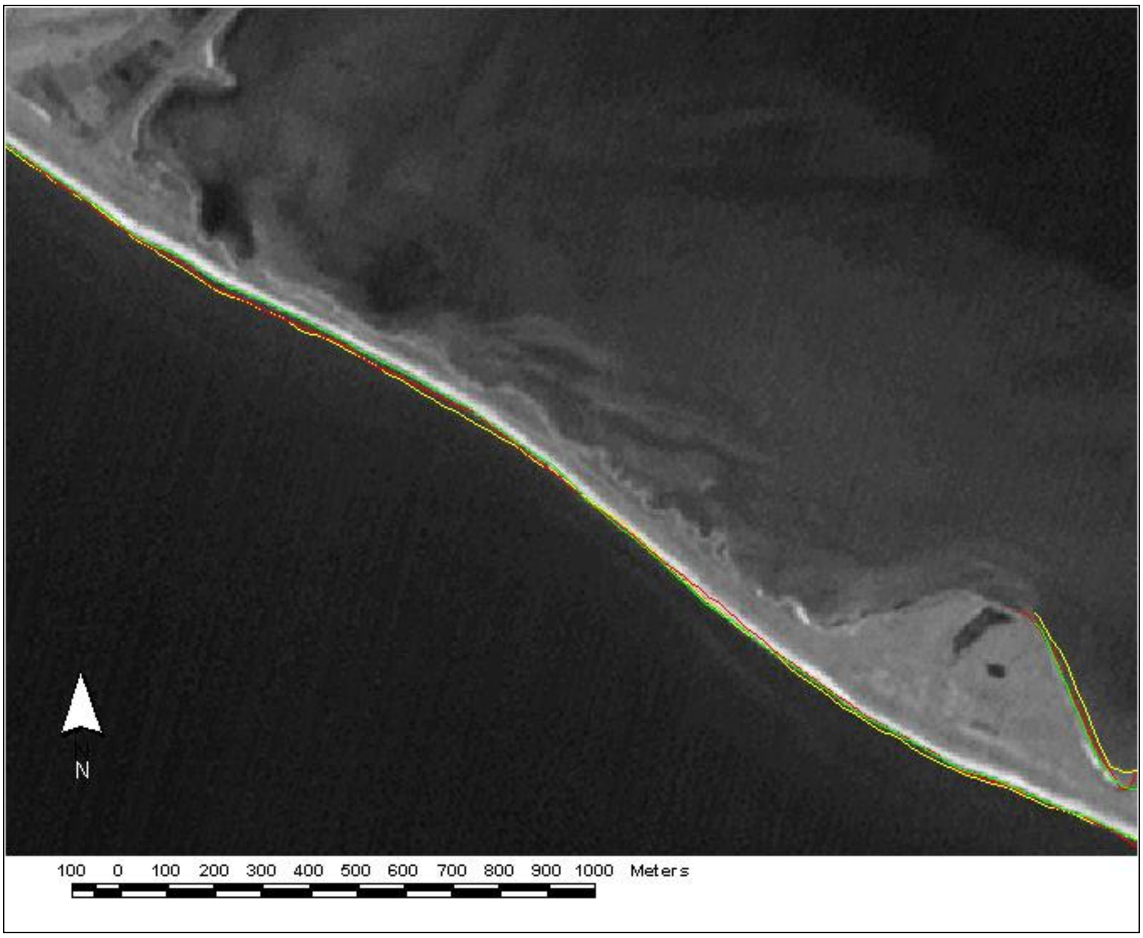


Figure 7.29 Satellite image analysis of the western part of Hyllekrog 1973-2003. Background picture dating 2003, marked shorelines: Yellow = 1973. Red = 1986. Green = 2003, from (DHI Water & Environment 2004)

Figure 7.30 Satellite image analysis of the eastern part of Hyllekrog 1973-2003. Background picture dating 2003, marked shorelines: Yellow = 1973. Red = 1986. Green = 2003, from (DHI Water & Environment 2004)

7.3 Recent Shoreline Development

The recent shoreline development between Kramnitze in the west and Hyllekrog in the east is presented below. The shoreline development is primarily analysed using aerial photos from 1999, 2004 and 2009. The only locations with significant changes are at Kramnitze, Rødbyhavn, Hyldtofte Østersøbad and Hyllekrog.. Zooms of sections along the entire stretch between Kramnitze and Hyllekrog showing the variation in the shoreline location in the three years in details can be found in Appendix A.

7.3.1 Kramnitze

Sand accumulation takes place west of Kramnitze Fishery Harbour. The accumulation happens over the nearest 400 m west of the western breakwater since 1999, see Figure 7.31. Shorelines from 1999, 2004 and 2009 indicate that a larger sand accumulation took place in the five-year period between 2004 and 2009, than in the previous period between 1999 and 2004, where the shorelines indicate only limited or no erosion/deposition.

The accumulation between 2004 and 2009 has been estimated to about 42,000 m^3, corresponding to an average accumulation of about 8,500 m^3/year, see Table 7.1.

The entrance to the harbour suffers from sedimentation, see Figure 7.4. The latest major maintenance dredging was performed about 10 years ago, but there is no exact information on the amount of sand dredged at that time. The entrance is cleaned each year. Major maintenance excavation of sand has been performed in the past, e.g. in 1994 where 31,000 m^3 of sand was excavated. The dredged material was used for beach nourishment at a beach 13 km west of Kramnitze (at Næsby) in connection with construction of 14 small coastal breakwaters (Fehmarnbelt Environmental Consultants 1996 and Det Lollandske Digelag 1994). About 5,000 m^3 sand has been nourished every year during the period 1994-2006 along the stretch between Kramnitze and Næsby. The sand for these nourishments has been taken from the sand accumulation area west of Kramnitze Harbour (personal communication with Dike Engineer S. Aa. Sørensen). The dredged volumes are estimated to 30,000 m^3 for the five-year period 1999-2004 and 15,000 m^3 for the period 2004-2006.

The total accumulated volumes are hence estimated to about 5,000-10,000 m^3/year. The accumulated volumes indicate that the net littoral transport rate along the coastline west of Kramnitze is at least of the magnitude 5,000-10,000 m^3/year in the eastward direction and probably exceed these numbers since accumulation is also known to take place in the entry area and access channel.

Table 7.1 Accumulation of sand at the beach 0-400 m west of Kramnitze Fishery Harbour

Parameter	**1999-2004**	**2004-2009**
Length of accumulation (m)	400	400
Height of active coastal profile (m)	3	3
Shoreline movement (m)	~0	+35
Accumulated volume(m^3)	~0	42,000
Dredged volume from accumulation zone (m^3)	30,000	15,000
Total accumulated volume (m^3)	30,000	57,000
Average accumulated volume (m^3/year)	**5,000 m^3/year**	**11,500 m^3/year**

Figure 7.31 Shoreline changes between 1999 and 2009 at Kramnitze. Aerial photo from 2009, (©COWI Orthophoto April 2009)

7.3.2 Lalandia

1500 m to 2000m west of Rødbyhavn off Lalandia, about 15 m of accretion of the shoreline is seen between 2004 and 2009 (Appendix A, page A-6). The technical management of Lalandia informs that no nourishment has been performed since Lalandia was inaugurated in 1988..

7.3.3 Rødbyhavn

Sand continues to accumulate west of Rødbyhavn, see Figure 7.32. Since 1999 the beach has moved forward about 35 m over a stretch of about 1 km parallel to the previous beach. Sand is transported along this beach causing sedimentation of about 15,000-20,000 m^3/year in the entrance channel to the Rødby Ferry Harbour.

The sand volume accumulated along the beach in the periods 1999 to 2004 and 2004 to 2009 has been calculated, see Table 7.2. The total accumulated volume of 20,000 m^3 (1999-2004) and 95,000 m^3 (2004-2010) in the two five-year periods indicates an average accumulation of 4,000 m^3/year in the period 1999-2004 and 19,000 m^3/year in the period 2004-2009. The average accumulation is about 14,000 m^3 during the period 1999-2009.

East of the harbour the shoreline is kept in place by a revetment and no shoreline changes are seen between 1999 and 2009.

It is noted that the tendency for the period between 2004 and 2009 to have larger accumulation near structures is seen at both Rødby and Kramnitze harbours. This indicates a larger average annual littoral drift rate along the Lolland coast in the years 2004-2009 than in the previous five years between 1999 and 2004.

Figure 7.32 Shoreline changes between 1999 and 2009 west of Rødbyhavn. Aerial photo from 2009, (©COWI Orthophoto April 2009)

Sedimentation in the access channel to Rødbyhavn

A reservoir has been excavated at the west side of the access channel in order to reduce the sedimentation in the access channel; the reservoir is clearly seen in the bathymetry in Figure 7.16. The nominal size of the reservoir is 200 m long along the channel and 100 m wide perpendicular to the channel. The reservoir is dredged to a depth of 10 m. Maintenance dredging is performed every 3 to 4 years.

Dredged volumes from the harbour basins and access channel are normally disposed at a designated disposal ground about 4-5 km WSW of the harbour, delimited by the points (WGS 84):

54°38,9'N 11°16,1'E

54°38,7'N 11°16,7'E

54°38,4'N 11°16,6'E

54°38,1'N 11°16,1'E

An exception from the normal practice occurred in 1993, where 75,000 m^3 dredged material from the entrance was disposed at a nearshore location about 500-700 m SE of the harbour (artificial bypassing).

In connection with the Fehmarnbelt Feasibility Study in 1996, see (Fehmarnbelt Environmental Consultants 1996) data on maintenance dredging were reported and new data have been obtained from Scanlines as part of the present study. The dredging volumes are presented in Table 7.3.

The dredged amounts cover maintenance dredging in the access channel and in the reservoir as well as other types of dredging in the basins. It has not been possible to obtain detailed information on the type of material dredged from the harbour and the channel. It is hence not clear if the volumes appearing in Table 7.2 are maintenance dredging due to trapping of sand or it is capital dredging or cleaning of fine harbour sediments. The distribution of the volumes of sand, fine sediments (silt, clay) or capital dredging is not known.

The sedimentation of sand (i.e. excluding the sedimentation of fines), which is assumed to be transported past the W-breakwater from the shoreline west of the harbour, has been calculated as the sum of the following contributions:

- The volume dredged in the access channel
- The volume dredged in the reservoir
- Half of the volume dredged in the ferry basin

The average volume of dredged sand is found to be 22,000 m^3/year. This number is somewhat uncertain and the variation in the dredged volumes from year to year seems large. It is estimated that the annual bypass around the W-breakwater is in the order of 15,000-25,000 m^3/year.

Table 7.2 Accumulation of sand at the beach 0-800 m west of Rødbyhavn

Parameter	**1999-2004**	**2004-2009**
Length of accumulation (m)	800	800
Height of active coastal profile (m)	4	4
Average shoreline movement (m)	+5	+30
Total accumulated volume (m^3)	16,000	95,000

Table 7.3 *Amounts of dredged material at Rødby Ferry Harbour, all volumes in m³. Data from (Fehmarnbelt Environmental Consultants 1996) and Scanlines*

Year of dredging	**Maintenance dredging of sand**		**Other types of dredging (capital and cleaning of harbour sediments/sand in basins)**		**Total maintenance dredging (Σaccess ch. + Σreser. + ½ΣFerry basin)**
	Access channel	**Reservoir**	**Ferry Basin**	**Other Basins**	
1977-78	0	64,000	110,000	0	119,000
1981	27,800	39,300	88,400	0	111,300
1985	18,000	48,500	87,400	0	110,200
1988-89	10,300	40,600	49,100	3,000	75,450
1993	36,000	63,000	85,000	28,000	141,500
2000	20,000	45,000	15,000	42,500	
2006			29,225	5,810	29,225
2007	30,000				30,000
2008	30,000				30,000
1977-2008	Total = ΣAccess ch +ΣRes. +½ΣFerry B.				**689,175 m³**
1977-2008	Average maintenance dredging 1977 to 2008 (31 years)				**~22,000 m³/year**

7.3.4 Hyldtofte Østersøbad

75,000 m³ of sand was nourished to build up beaches between the coast-parallel breakwaters (pocket beaches) as part of the construction scheme (personal communication with dike engineer S. Aa. Sørensen).

The beaches suspended between the breakwaters suffered from minor erosion between 1999 and 2004, see Figure 7.33; however, they have been stable or have even accumulated some sand since 2004.

An accumulation of sand along the coast about 2.5 km east of Rødbyhavn is seen in the 1999-shoreline (Appendix A, page A-9). The sand volume was a test nourishment of 25,000 m³, which was carried out in 1999 in connection with the construction of the coast protection scheme at Hyldtofte Østersøbad (personal communication with dike engineer S. Aa. Sørensen). The sand “disappeared” over the winter 1999-2000, but the sand was visible in the following years in the bar system eastward of the nourishment location.

Approximately 1.5-2.5 km east of Hyldtofte Østersøbad, erosion takes place and the shoreline retreats with an average rate of up to 1 m/year in the period 1999-2009.

Figure 7.33 Shoreline changes between 1999 and 2009 at Hyldtofte Østersøbad. Aerial photo from 2009 (©COWI Orthophoto April 2009)

7.3.5 Hyllekrog

The recent shoreline development at Hyllekrog (Figure 7.34) shows that the eastern tip has moved eastward by about 300 m between 1999 and 2009. This corresponds to an average of 30 m/year.

The tip of Hyllekrog shifts between two types of development:

- A northward extension of the spit during the period 1945 to 1999 (Figure 7.28 and Figure 7.30)
- An eastward extension of the spit during the period 1999 to 2009 (Figure 7.28 and Figure 7.30).

The mechanism is probably that when the northward extension becomes too long, it shifts to an eastward extension, which after some years again will shift to a northward extension.

There are no signs of recent over-wash of the formation. Hyllekrog is an active barrier island formation, which is overall stable, however, moving slowly northward and growing towards east. It is evaluated that there is a risk of local overwash/breaching in the future, especially as a result of the expected sea level rise. However, a breach during an extreme event will probably close again by natural means. It is important for the stability of the Hyllekrog formation that the supply of sand by the littoral drift from west is maintained.

Figure 7.34 Shoreline changes between 1999 and 2009 at Hyllekrog. Aerial photo from 2009 (©COWI Orthophoto April 2009)

7.4 Coastal profiles

Analysis of the profiles and changes identified to the profiles between the 1998 and the 2009 surveys are described below.

A bathymetric model has been interpolated from the 2009 profiles, see Figure 7.35 in which the names of profiles are shown. Depths from the location of the 1998 profiles have been extracted from this interpolated bathymetry for comparison with the 1998 profiles.

Outside the areas of the densely measured 2009 profiles, measured profiles are compared directly, where 1998 and 2009 coastal profiles are measured at the same location.

Selected profiles are shown below but all profiles can be found in Appendix B.

7.4.1 West of Rødbyhavn (from west to east)

The profiles RW06 to RW01 west of the harbour are all of the same type. Three profiles are shown in Figure 7.36.

The profiles show a relatively steep shoreface down to 4–6 m depth after which the slope becomes much gentler. Bar formations are seen at the shoreface in all the profiles, however, most pronounced in the area closest to the harbour (RW02 and RW03, see example in profile RW02 in Figure 7.36). There is also an indication of shoreline accretion in these two latter profiles as also seen in the shoreline evolution analysis above.

7.4.2 East of Rødbyhavn (from west to east)

Three examples of profiles east of Rødbyhavn are shown in Figure 7.37. The profiles RE01 to RE14 cover the stretch between Rødbyhavn and Hyldtofte Østersøbad, which is characterised by lack of beach. Profile RE16 is located in the middle of the segmented breakwater protection off Hyldtofte Østersøbad.

The nearshore part of the profiles RE01 to RE14 is very steep as it represents the revetment which extends to a depth of about 1.5-2.5 m. The profiles just east of Rødbyhavn are very steep indicating the erosion in this area. Gradually the profiles become flatter towards Hyldtofte Østersøbad.

There are minor variations between the profiles from 1998 and 2009; however, there are no significant changes between the profiles in 1998 and in 2009.

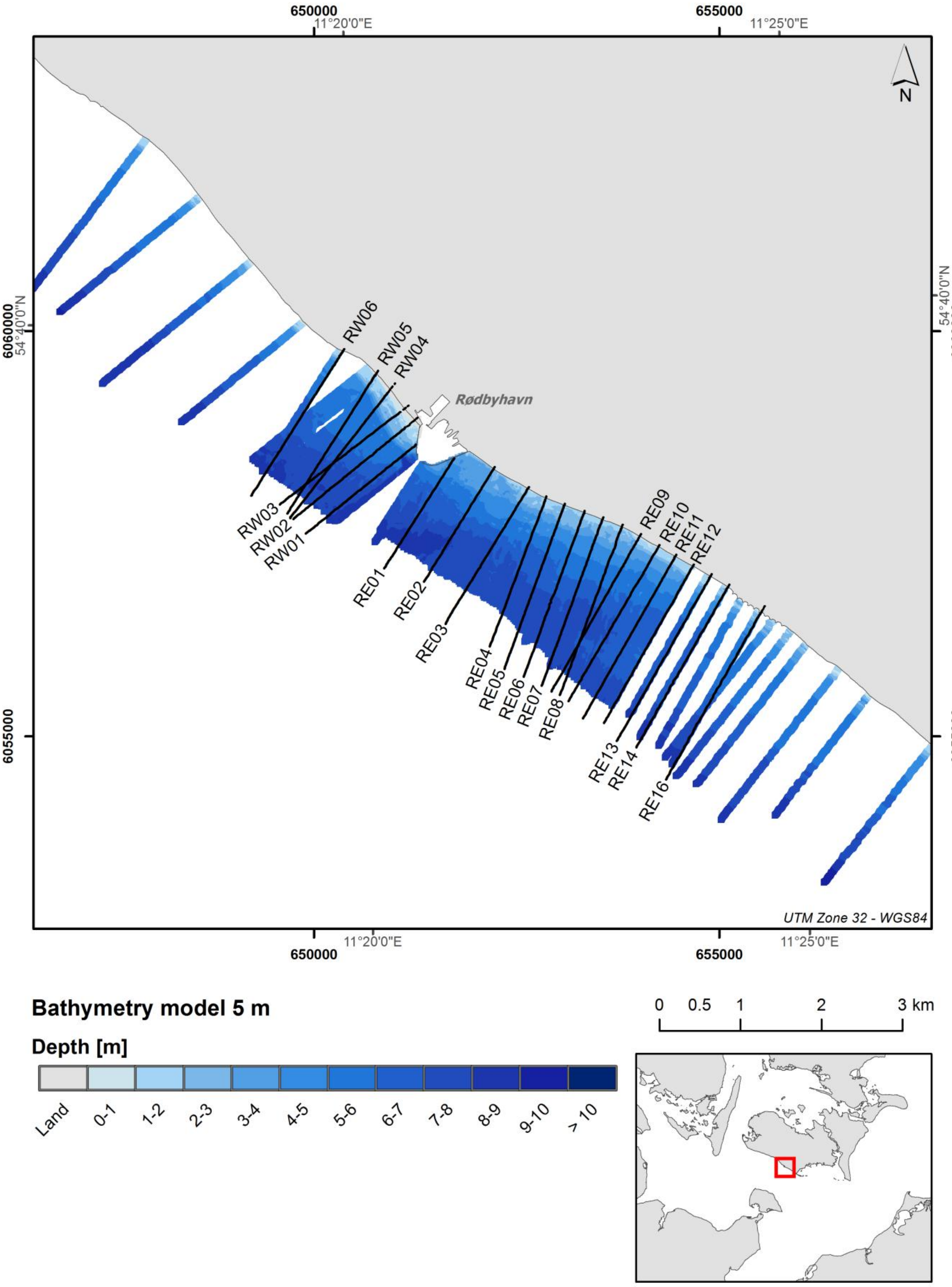


Figure 7.35 Bathymetric map for the Lolland coastal area from the 2009 survey with location of 1998 profiles indicated as black lines

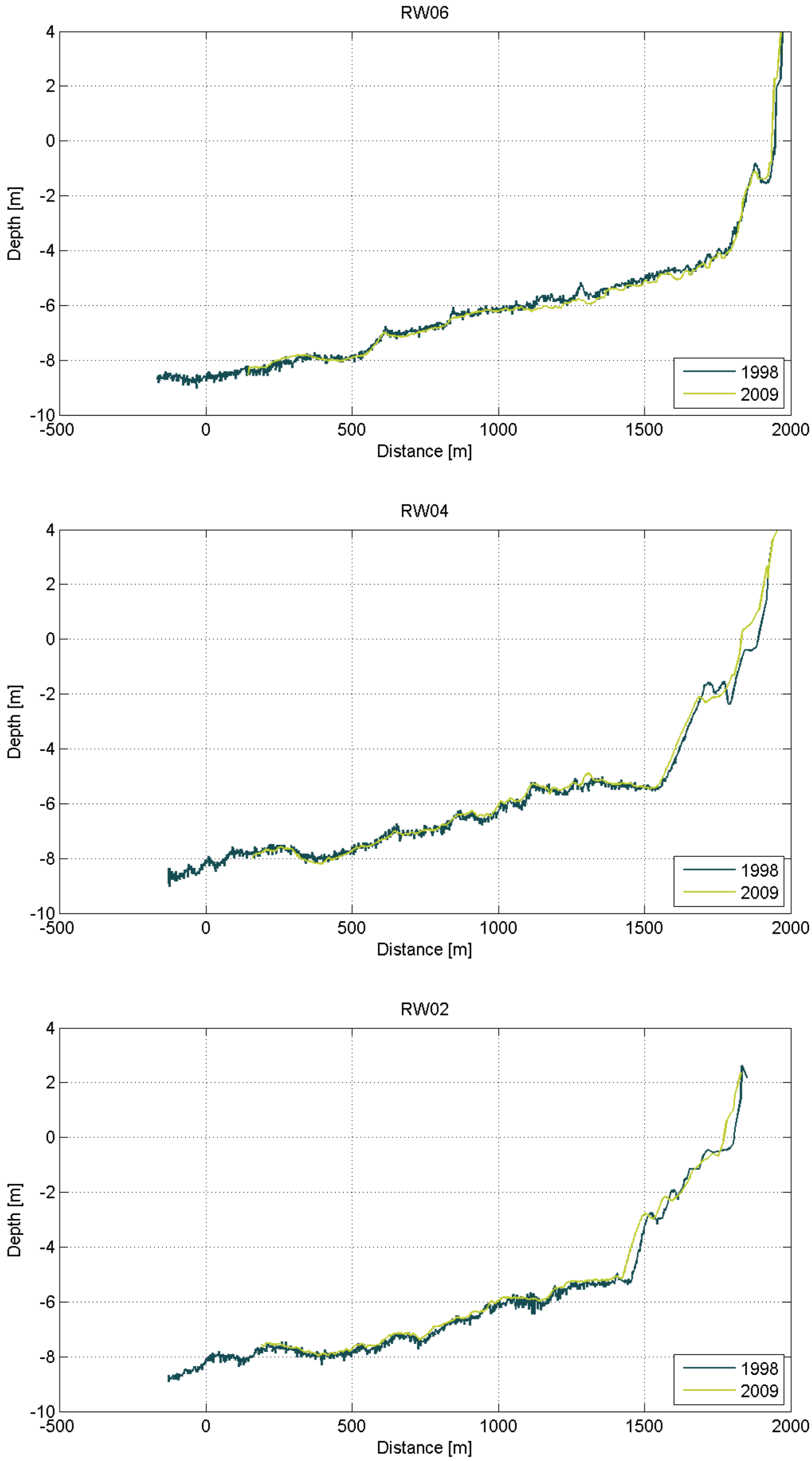


Figure 7.36 Coastal profiles RW06, RW04 and RW02 west of Rødbyhavn, 1998 and 2009. Depths relative to DVR90

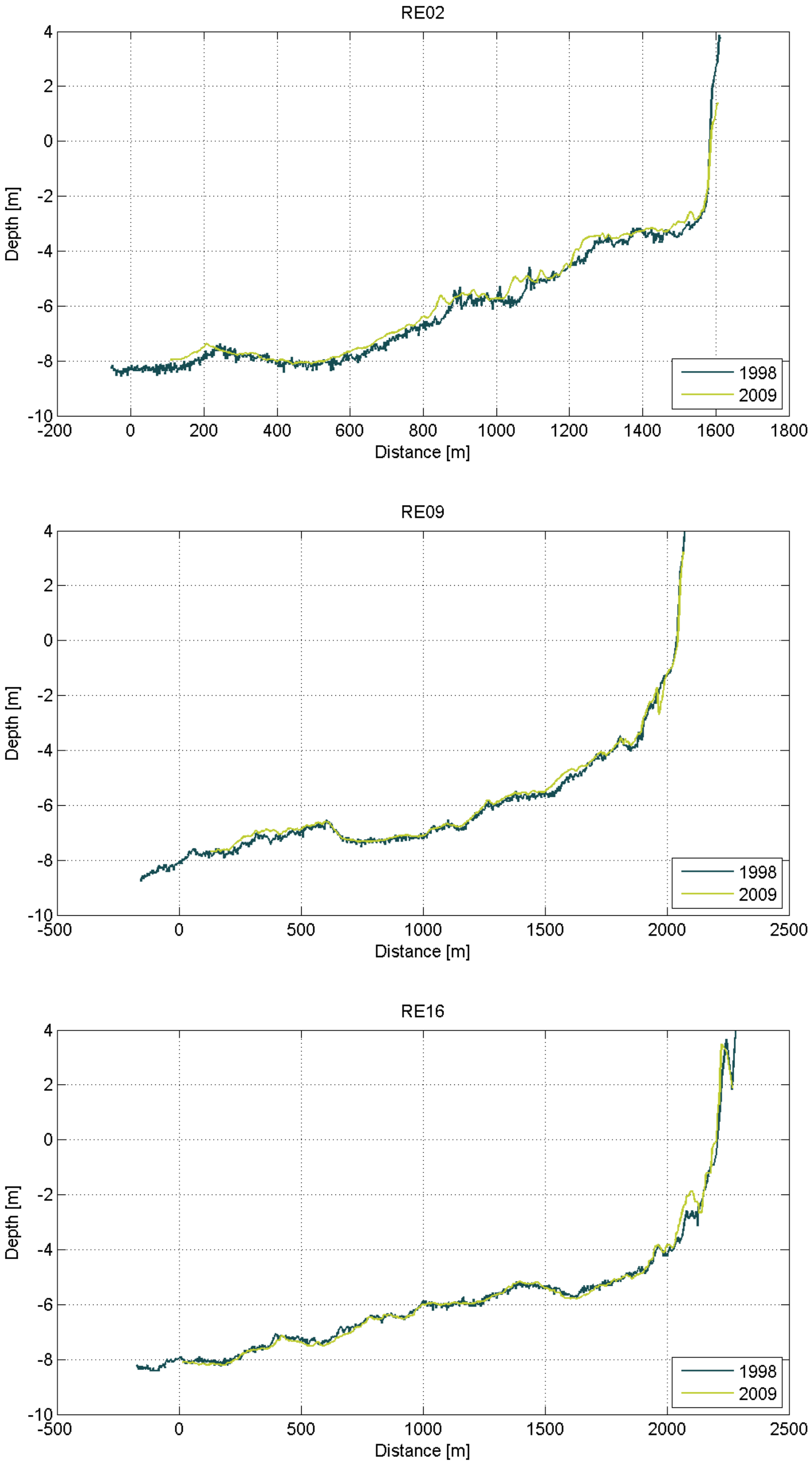


Figure 7.37 Coastal profiles RE02, RE09 and RE16 east of Rødbyhavn, 1998 and 2009. Depths relative to DVR90

7.5 Sea bed conditions near the coast

The conditions and the grain size distribution of the surface sea bed material in the Fehmarnbelt are described by analysed grab samples. A large number of grab samples were collected in 2009 in the entire Fehmarnbelt area and some grab samples were collected in 1998 along some of the measured profiles described above. Diver observations of sand and vegetation-cover, aerial photos and substrate mapping are also included in the interpretation of the sea bed conditions along the coast; see further information on the data material in Section 4.6 and in Appendix C which includes detailed figures with information on the sea bed conditions along the stretch from Kramnitze to Hyllekrog.

Figure 7.38 shows the median grain size, d_{50}, from grab samples collected along the coast of Lolland. The samples collected very near the coastline (at water depths less than approximate 3-4 m) show that the sea bed material is sand. West of Rødbyhavn the sea bed consists of fine-medium sand, mostly with grain sizes between 0.15 and 0.3 mm. Samples with higher grain sizes of 0.5-2 mm are found among these. Samples collected in the accumulation area west of Rødbyhavn indicate slightly finer material (about 0.2 mm) and higher homogeneity. East of Rødbyhavn, the sea bed material is slightly coarser with samples indicating medium to coarse sand but some stretches have samples with fine-medium sand. Just east of the eastern breakwater a few samples with fine sand are found. In general, the sediment is graded with a geometric standard deviation ($\sigma = \sqrt{d_{84}/d_{16}}$) of 1.4 or higher. No differences in the grain size distribution can be identified between samples from 1998 and 2009.

At water depths greater than 3-4 m extending to about 10 m, coarser material is found and only few samples with fine-medium sand. At some sample locations, sampling was not possible due to hard bottom indicating scarcity in fine material; these locations are marked with black markers in Figure 7.38.

The results show a narrow band of mobile sediment near the coast which is confirmed by aerial photos, where a lighter colour near the coast gives evidence of finer sea bed material and little vegetation. An example is shown in Figure 7.39. Similar figures for the coast of Lolland can be found in Appendix C. Diver observations of the percentage of sea bed covered by vegetation (macroalgaes) are included in the figure. Vegetation on the sea bed indicates that hard substrate such as larger stones are present on the sea bed. In areas with a high cover of vegetation, the sea bed can therefore be assumed to be relatively hard and contain little mobile sediment.

The substrate map created by FEMA (FEMA 2013a), see Figure 6.5, shows the same picture, see example in Figure 7.40. Similar figures for the coast of Lolland can be found in Appendix C. A narrow band along the coast has been interpreted as sand, while coarser sediments with patches of sand are seen at greater water depths.

The band of fine material is identified to have a width of less than a few hundred metres along the Lolland coast, except for the accumulation zone west of Rødbyhavn where fine material extends about 500 m from the shoreline.

The general picture of the sea bed conditions is consistent with the geological conditions (Section 5) at the coast of Lolland. The sea bed consists of moraine till with sporadic areas of marine sand. A thin layer of reworked glacial sediments (lag sediment) on top of the till bed is characteristic, a so-called residual seabed. This layer, about 0.10 m thick, consists mainly of gravel and coarser material as seen in the above analysis. The nearshore band of finer material origins from transported material along the coast and a supply of material from offshore.

An overview of the sediment conditions in the nearshore zone along the Lolland coast is presented in Table 7.4.

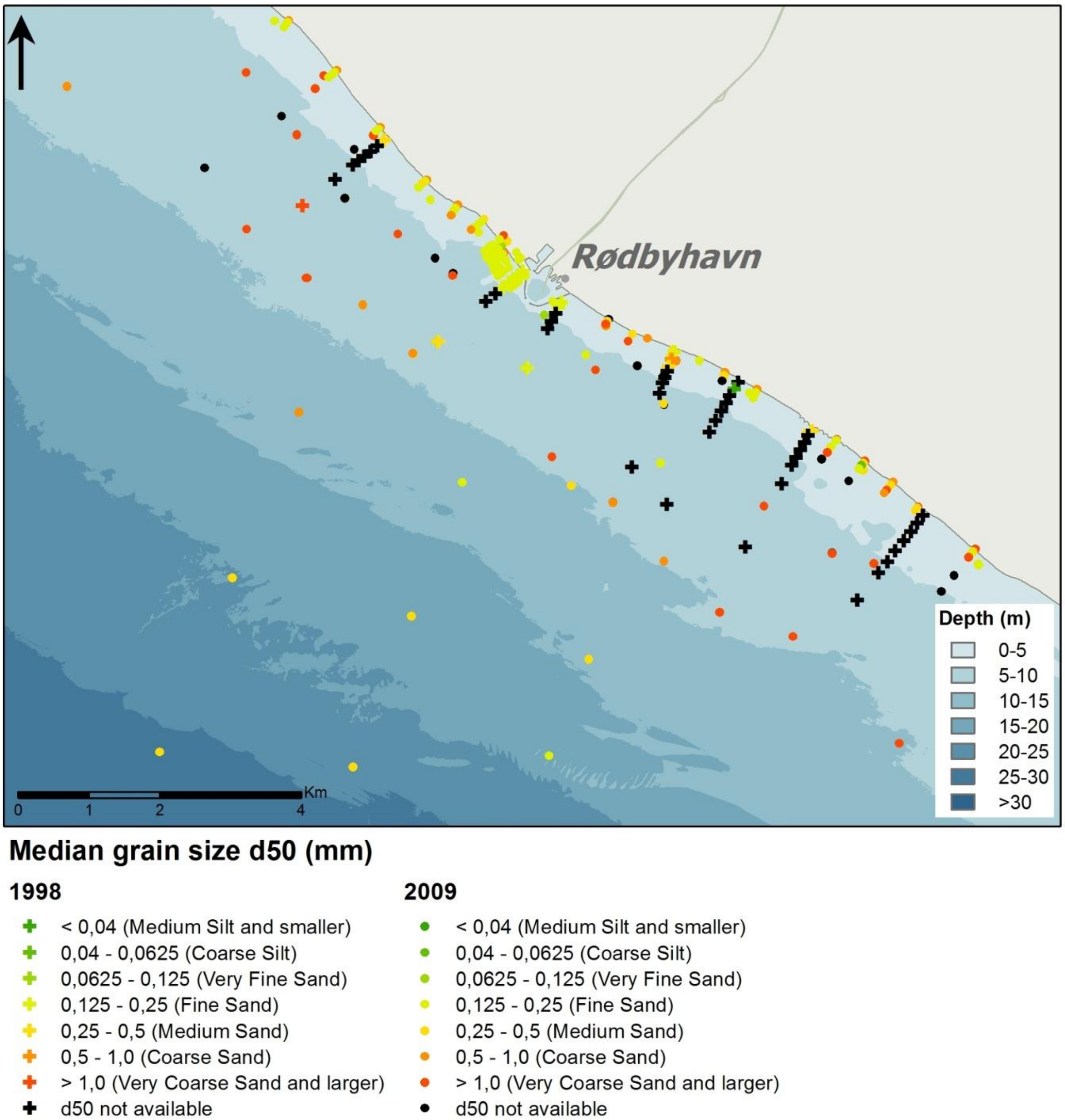


Figure 7.38 Median grain size in grab samples collected along the Lolland coast

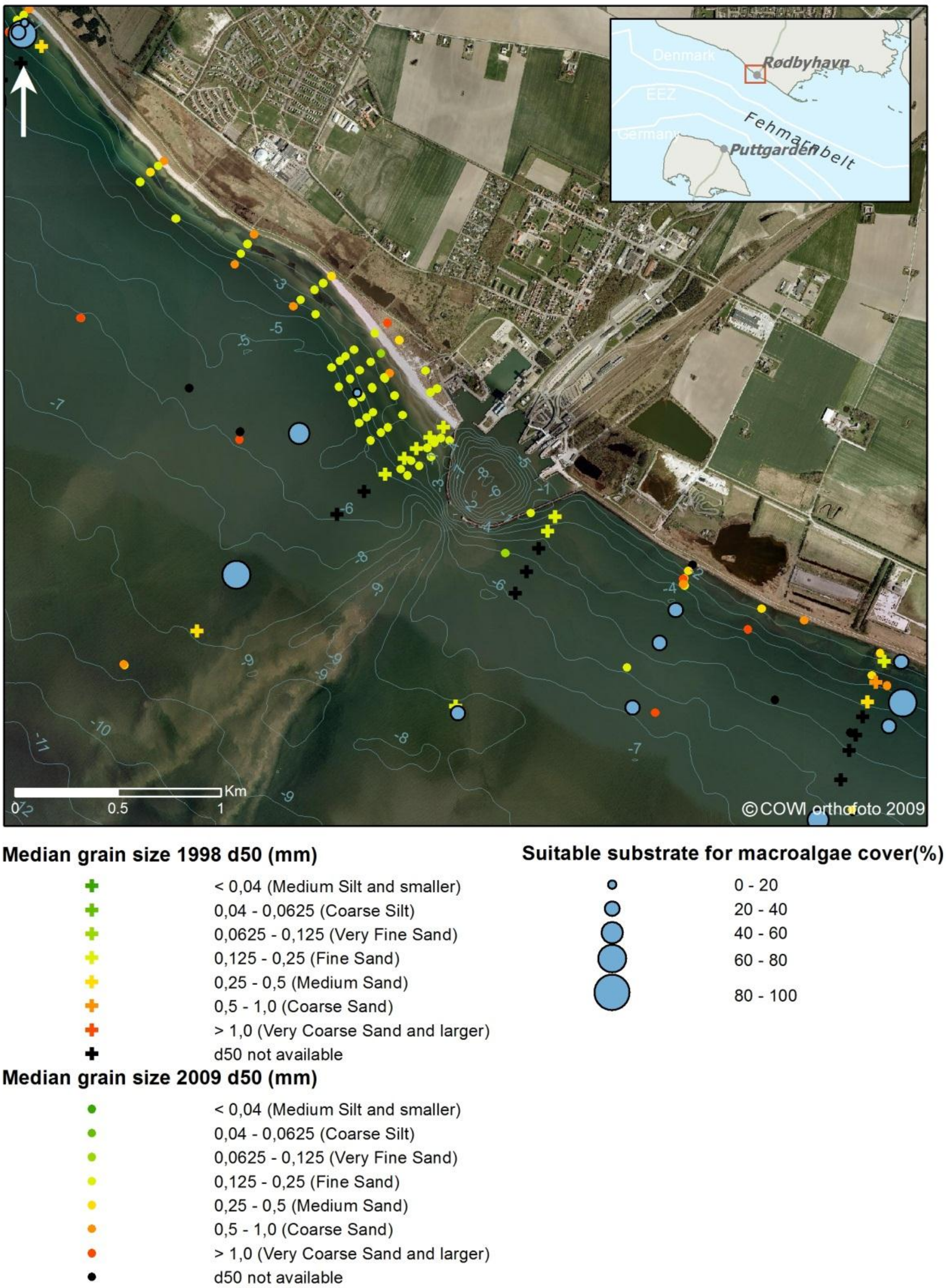


Figure 7.39 Aerial photo of the nearshore zone near Rødbyhavn. The median grain size from grab samples and diver observations of vegetation cover are also shown. Aerial photo from 2009 (©COWI Orthophoto April 2009)

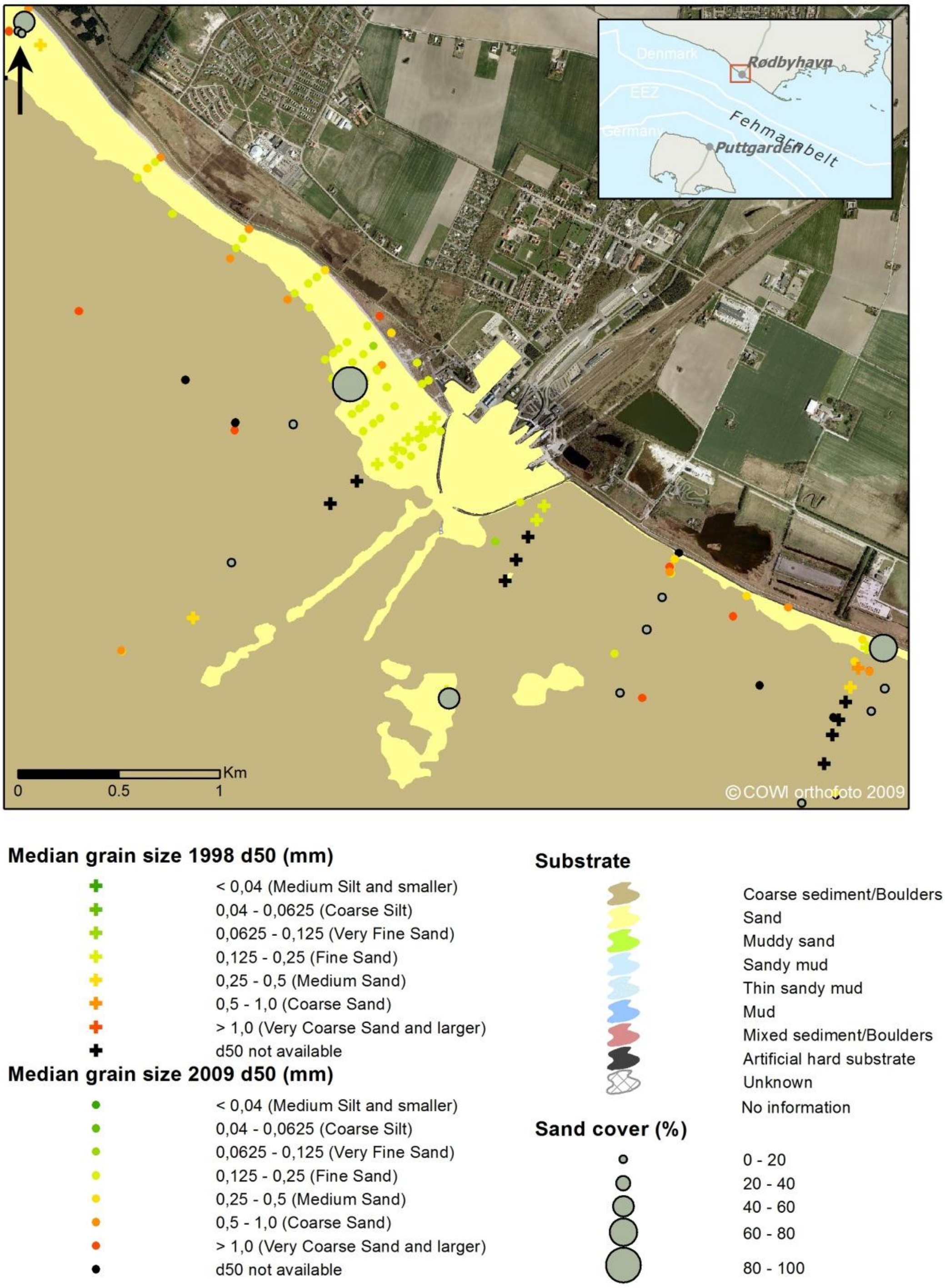


Figure 7.40 Substrate map for the nearshore zone near Rødbyhavn. Median grain size from grab samples and diver observations of the percentage of sand at test locations are also shown. Aerial photo from 2009 (©COWI Orthophoto April 2009)

Table 7.4 *Overview of sediment in the nearshore zone at water depths less than about 3-4 m at the coast of Lolland*

West of Rødbyhavn		**East of Rødbyhavn**
Generally fine-medium sand, but some samples with coarse sand, fine sand in the accumulation zone close to Rødby. No changes 1998 to 2009	Rødby-havn	Generally medium to coarse sand, but some samples with fine sand close to east breakwater. Many unsuccessful sampling attempts indicating hard seabed without movable sand. No changes from 1998 to 2009

7.6 Nearshore Waves and Currents

The waves are the primary driving force for the littoral transport in the nearshore zone. Currents - in excess of the wave-driven longshore currents – are less important, but have some influence on the transport rates.

The overall hydrodynamic conditions were described in the previous Section 5. The nearshore wave- and current conditions for the south coast of Lolland are described below.

7.6.1 Establishment of wave conditions

Calculations of the time-varying wave conditions in the larger Fehmarnbelt area, including the entire Baltic Sea and the Danish Straits, have been carried out by numerical modelling. A refined numerical model has been established for the Fehmarnbelt area and has been used to simulate the 21-year period, 1. Jan. 1989 – 30. April 2010. In each calculation point, wave parameters such as wave height, wave direction and wave period, are calculated with hourly intervals. Distances between calculation points are typically small along the sections of coast (about 50-100 m), and increases further offshore and further away from the area of interest. Details of the wave modelling are given in (FEHY 2013b).

Comparison of modelled and measured wave conditions

The results from the wave calculations have (mainly) been calibrated and validated against measurements of wave conditions at two measuring stations in the central part of Fehmarnbelt, MS01 and MS02. MS01 is located approximately 7 km south of Rødbyhavn at a water depth of -20 m DVR90. MS02 is located approximately 6 km north-northeast of Puttgarden at a water depth of -29 m DVR90. Both of the measuring stations were deployed in March 2009, see further information in Section 4.7. The period available for comparison of measurements and calculated wave conditions is March 2009 - April 2010.

The comparisons between modelled and observed wave conditions show some deviations between measured and modelled wave directions and heights.

Wave roses for measured are shown in Figure 7.41. The wave roses represent the measured wave conditions in the period March 2009 – April 2010 at the two measuring stations.

The magnitudes of the deviations were found to vary with the directions from which the waves approach the Fehmarnbelt area. The deviations in the modelled wave directions at the measuring stations, MS01 and MS02, are shown in Figure 7.42. The mean deviations for some directional sectors (of 10 degrees each) reach about 25 degrees, but for the main wave directions (W-WNW and SE at MS01, see Figure 7.41) the deviations are below 10-15 degrees. A similar picture is seen at MS02 closer to the German coast. The tendencies for the deviations to vary with the wave direction are the same, but slightly shifted in the directions. Figure 7.43 shows that although a clear variation with the wave directions is seen, a large scatter appears in the comparison between measured and modelled wave direction. The wave heights deviate also with the wave directions, see Figure 7.44.

The deviations have their origin in the wind field applied as forcing for the wave generation mechanism in the wave modelling. The deviations seem to be related to the presence of 'upstream' land areas. A comparison of measured conditions against the applied wind forcing in the wave model shows similar tendencies at a wind measuring station just 25 km east of MS01 (Nysted). According to DMI (the provider of the wind data) the observed differences between modelled and measured wind directions may origin from uncertainties in the applied 'air-land' resistance parameters over land areas in the applied meteorological model. The resolution of the (many) land areas surrounding Fehmarnbelt in the meteorological model or the modelled static stability over land areas as well as the coastal resolution of the wind fields of 10 km are also possible explanations.

The wave directions as well as the wave heights in the 21-year timeseries of wave conditions applied in the littoral drift calculations have been adjusted using the findings described above. The adjusted wave roses at the measuring points are seen in Figure 7.41.

It should be mentioned that the adjustments of the nearshore wave directions are significantly smaller than at the offshore locations. The reason is the fact that waves turn when propagating towards shallower water if they approach the coast with an angle to the normal of the bed contours. Waves propagate fastest on deeper water and the wave direction will therefore tend to approach the normal to the beach orientation (defined as the normal to the depth contours at the beach). 'Errors' in the offshore wave directions will due to this mechanism reduce to somewhat smaller errors in the nearshore wave directions.

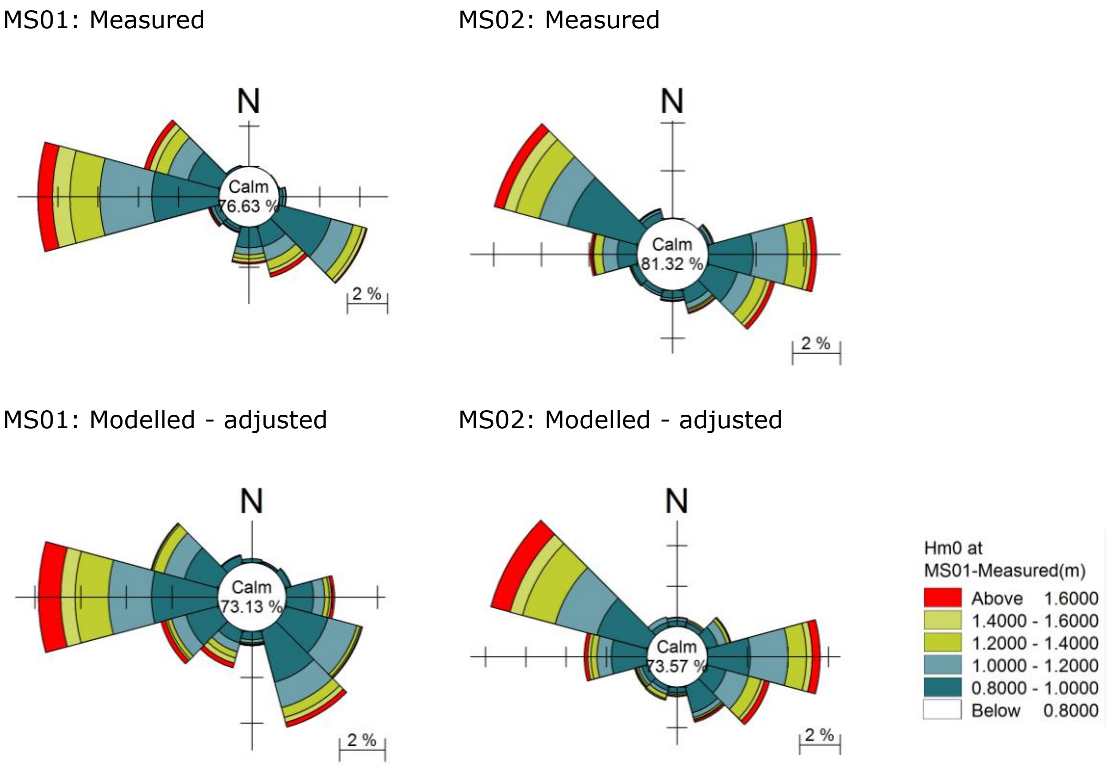


Figure 7.41 Wave roses for wave heights>0.8m for the measured wave conditions (upper figure), modelled wave conditions (middle) and adjusted modelled wave conditions at measuring station MS01 (left, 7 March 2009 - 30 April 2010) and MS02 (right, 30 March 2009 - 30 April 2010). The locations of the measuring stations are shown in Figure 4.9

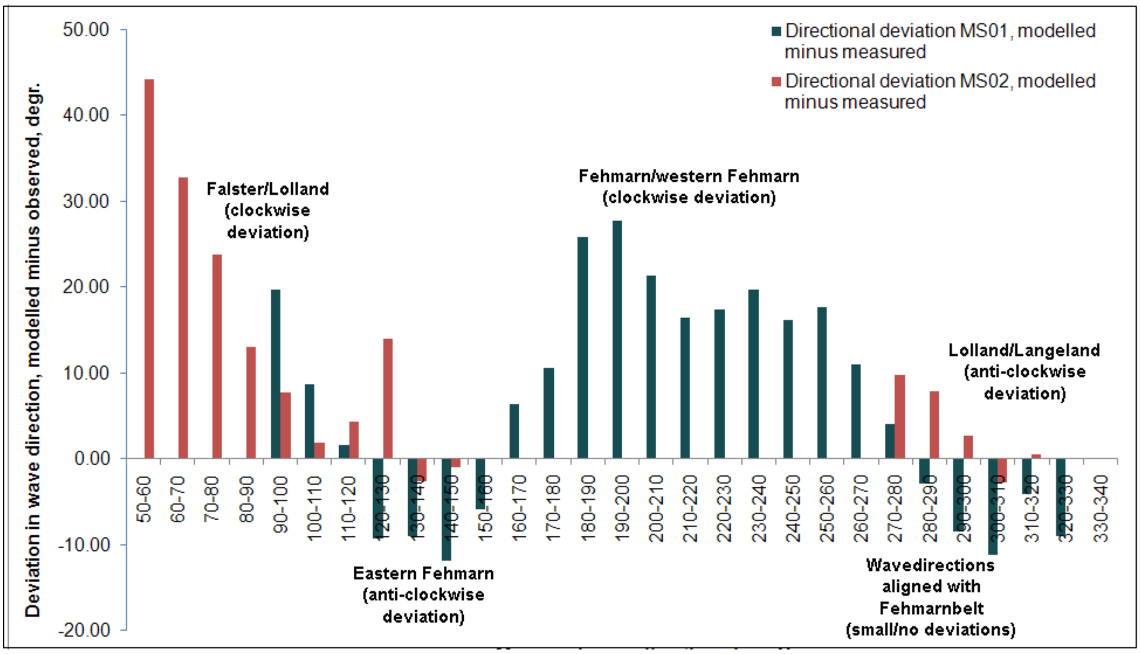


Figure 7.42 Deviations between modelled and measured wave directions at measuring station MS01 and MS02. The analysis is made for measured wave heights >0.8 m at MS01 and >1 m at MS02

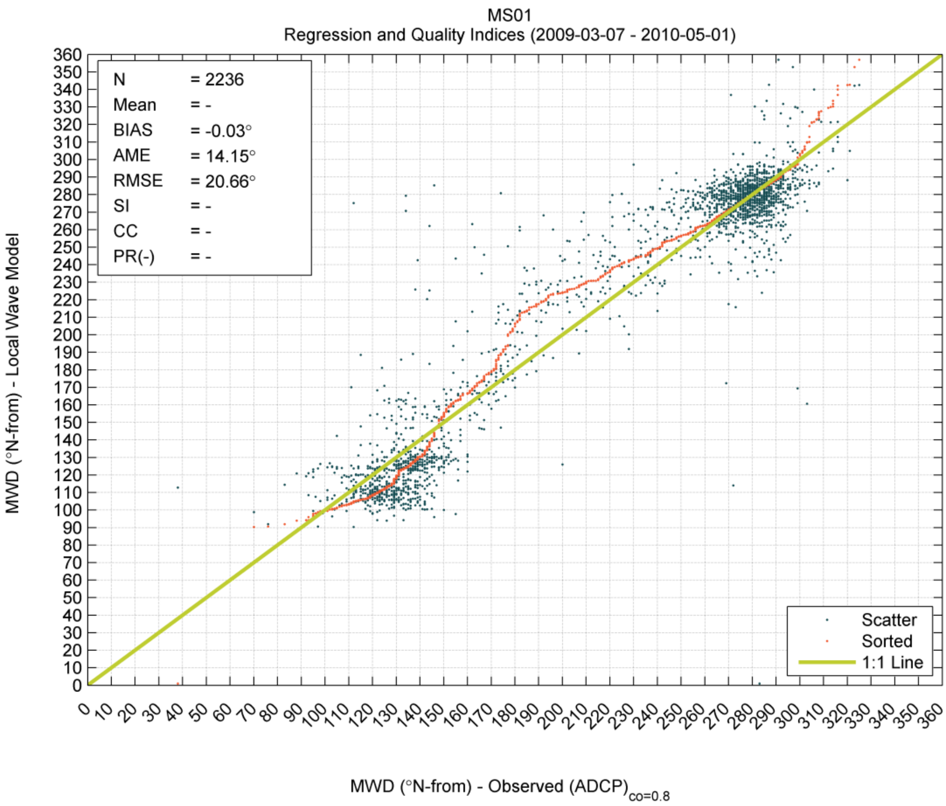


Figure 7.43 Correlation between measured and modelled wave directions at MS01 nearest to the Lolland coast ('Scatter': simultaneous directions. 'Sorted': lowest direction modelled versus lowest direction measured, second lowest direction modelled versus second lowest direction measured etc.)

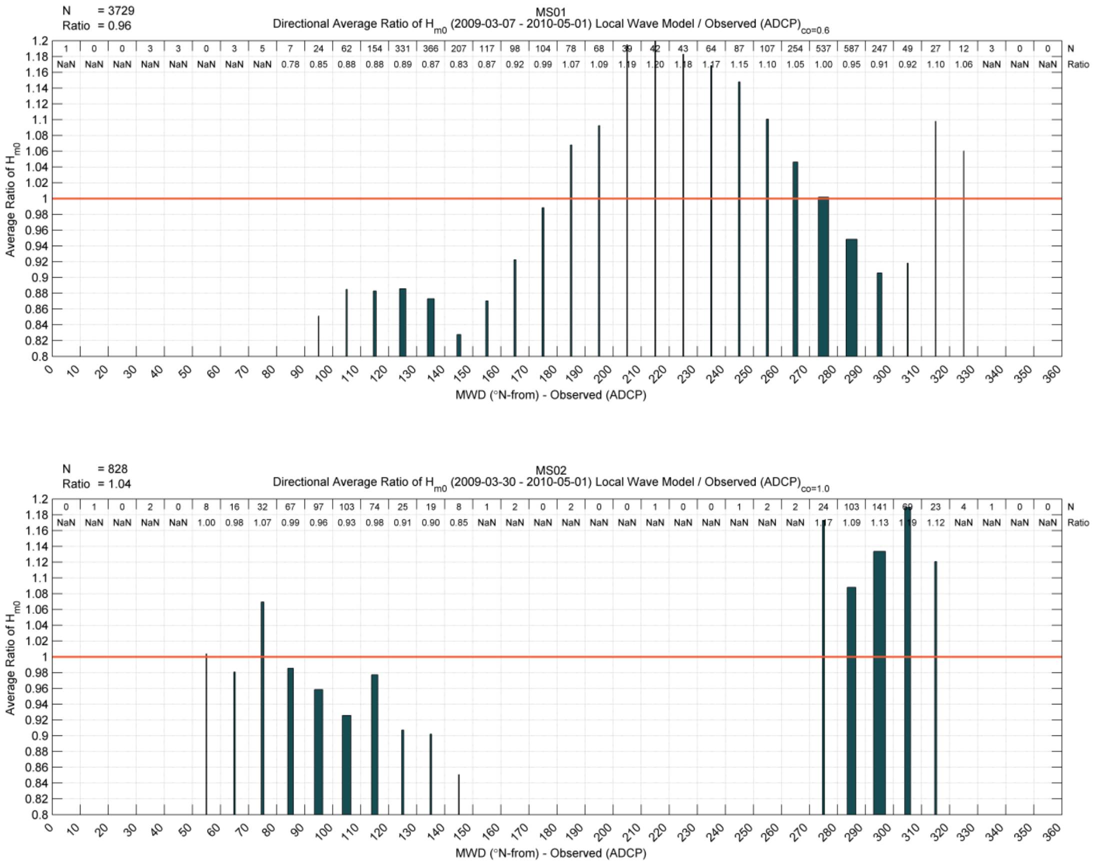


Figure 7.44 Deviations between modelled and measured wave heights at measuring station MS01 and MS02. The analysis is made for measured waves >0.8 m at MS01 and >1 m at MS02

7.6.2 Nearshore current conditions

Current conditions in excess of the wave-generated current have a minor influence on the littoral drift transport rates compared with the effect from the waves. For this reason the current is often excluded in calculations of the littoral drift. The effect of the currents is included in the calculations carried out for this report.

Nearshore current conditions are obtained from a local 3D flow model carried out by FEHY for Femern A/S (FEHY 2013b). The model is operated for the year 2005 only and the current conditions for this year are therefore assumed representative for the average current conditions in the 21-year period, 1989-2011, required for the littoral drift calculations. The representativeness of the year 2005 is analysed in FEHY(2013c).

Nearshore current conditions are obtained at each of the same locations where the nearshore wave conditions are established. The grid applied in the flow model is, however, relatively coarse in the nearshore area. The water depth at the location where the nearshore conditions are established may therefore differ from the correct water depth at this location. To ensure that the current conditions are representative for the correct water depth, the current speeds are transformed to the correct depth. The current speed for the correct water depth is found by assuming a local balance between the pressure gradient and the friction between the sea bed and the flowing water. This is done by assuming that the pressure gradient for a given time step is constant along a coastal profile.

7.6.3 Nearshore wave conditions

Nearshore wave conditions have been established for about every 1 km along the south coast of Lolland, in most cases at a water depth of 4 m. This extraction depth for the waves is selected to be just offshore of the active littoral zone to benefit from the modelled two-dimensional wave field in the one-dimensional calculations of the littoral drift (in LITDRIFT). At certain locations, such as in the lee of harbour breakwaters, the wave roses have been extracted closer to the shoreline. This has been done in order to include the sheltering effect of the feature/structure in the local wave conditions. The locations of the extracted wave roses as well as the wave roses are presented in Figure 7.49 and Figure 7.54, and the locations are tabulated in Table 7.5.

West of Rødbyhavn

The wave roses along the coast west of Rødbyhavn are presented in Figure 7.45. The wave roses along this shoreline show a double peaked directional distribution with the predominant waves from SW-erly directions and the secondary waves from SE-erly directions. Typical wave patterns for the dominant and secondary wave direction are shown in Figure 7.50 Figure 7.51, respectively and the nearshore bathymetry is presented in Figure 7.48. The secondary SE-erly waves along the stretch west of Rødby are much smaller than the predominant waves from SW, see Figure 7.47. The angle of incidence between the waves and the beach is defined as the angle between the incoming wave angle (‘coming from’ direction) and the normal to the depth contours (the beach or shoreline orientation). The shoreline west of Rødby curves around to face a slightly more western direction close to the harbour. It is seen that the predominant waves west of the west breakwater at Rødbyhavn form an angle with the shoreline orientation. This angle and the direction of the waves indicate that there is an eastward transport along this beach leading to the accumulation along the beach and sedimentation in the entrance as described in Section 8.3.

Wave roses from location D6 (west of Bredfjed) and location D9B (east of Lalandia) show dominant wave directions which are slightly more southerly than wave roses from the adjacent locations. D6 and D9B are both located in areas where the shoreline forms a small ‘bay’. The depth contours in the area are therefore turned slightly in these areas. As described in the section above the waves turn and approach the normal to the depth contours when propagating towards shallower water depths.

East of Rødbyhavn

The nearshore wave roses east of Rødbyhavn are presented in Figure 7.49. Typical wave patterns are shown in Figure 7.50 and Figure 7.51, respectively. The bathymetry is illustrated in Figure 7.52. It is seen that there is a double peaked directional distribution of the waves with predominant waves from WSW and secondary waves from SE. The angle of incidence between the dominating waves and the beach orientation is slightly larger than west of Rødby as the shoreline east of Rødby curves around to face a slightly more southern direction. This wave climate results in a net littoral transport towards ESE. This fits well with the fact that no sand is bypassing Rødbyhavn for which reason there is no beach in front of the dike east of the harbour (see Section 8.3).

Between D11 and D18, the direction of the dominant westerly waves turns toward WNW. This origins partly from a change in the bathymetry and partly from the fact that the coast becomes more exposed to waves from directions between west and north when moving further east of Rødbyhavn.

Along Hyllekrog, the shoreline curves towards a more southerly direction and the angle between incoming waves and the beach orientation is very large.

The angle of incidence is relatively large along Hyllekrog, which gives an eroding but not unstable coast. However, the angle of incidence of the predominant waves east of the bend in the shoreline some kilometres into the Hyllekrog formation is relatively large, which means that this section of shoreline is in principle unstable, which fits well with the fact, that undulations have been observed along this eastern section of the Hyllekrog formation.

The current roses at both sides show current speeds up to about 0.3-0.4 m/s.

Table 7.5 Locations along the south coast of Lolland where nearshore wave and current conditions were established

Location	Position (UTM-32 WGS 84)		Bathymetry (m DVR90)
	Easting	Northing	
D1	643090	6064498	-4.40
D2	644203	6064121	-4.57
D3	645111	6063716	-4.54
D4	645718	6063422	-4.40
D5	646562	6062952	-4.05
D6	647735	6062113	-4.13
D7	648265	6061436	-4.44
D8	648829	6060530	-4.25
D9	649601	6059901	-4.23
D9B	650347	6059498	-4.03
D10	650763	6059012	-4.84
D11	651821	6058320	-4.05
D12	653197	6057456	-4.3
D13	653895	6057165	-4.31
D14	654706	6056724	-4.16
D15	656059	6055503	-4.16
D16	656686	6055071	-4.63
D17	657287	6054448	-4.24
D18	658098	6054012	-4.14
D19	659223	6053163	-4.18
D20	659900	6052685	-4.46
D21	661318	6052186	-4.63
D22	662620	6052038	-4.10

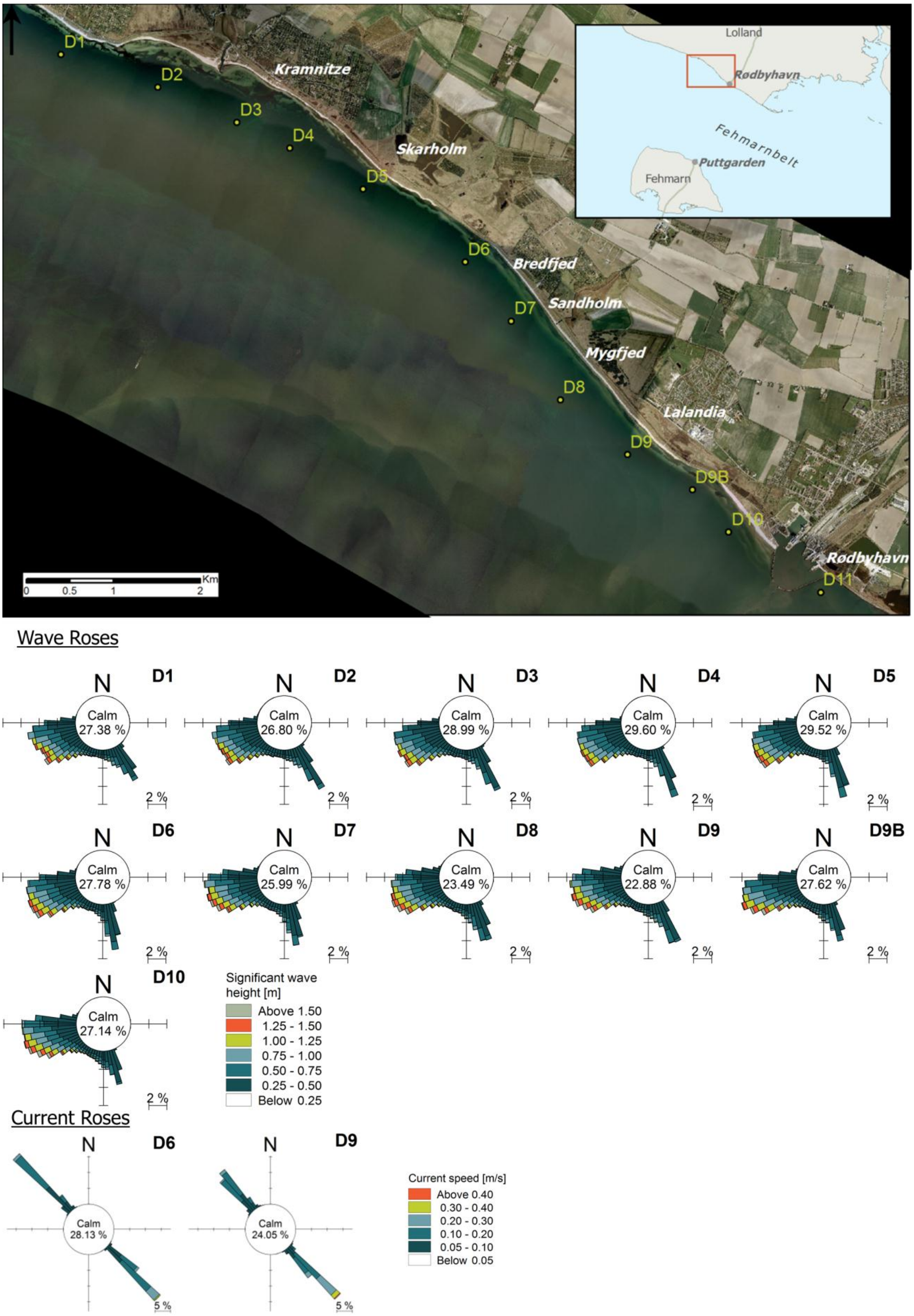


Figure 7.45 *Nearshore wave roses west of Rødby. Time of calm wave conditions (Hs below 0.25 m) given for each wave rose in % of time. Aerial photo from 2009 (©COWI Orthophoto April 2009)*

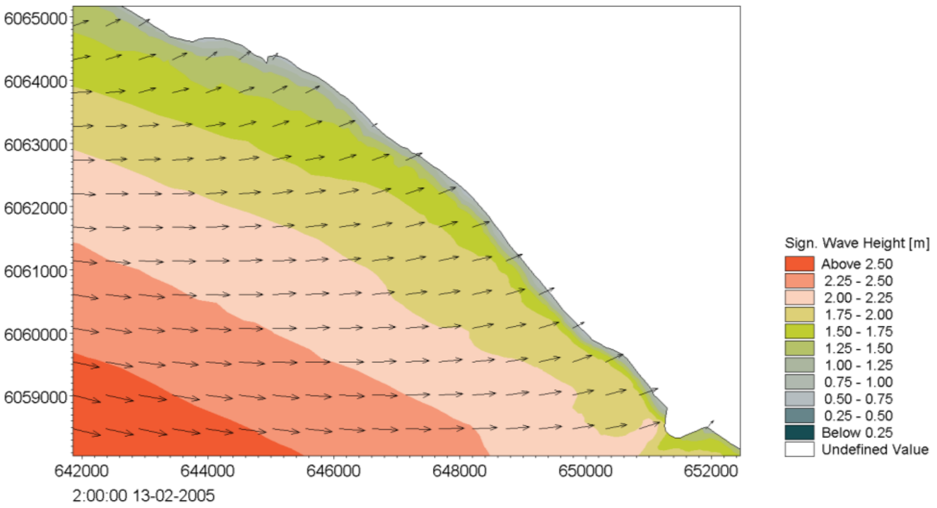


Figure 7.46 Typical wave pattern west of Rødby for westerly waves. Date of situation: 13.02.2005

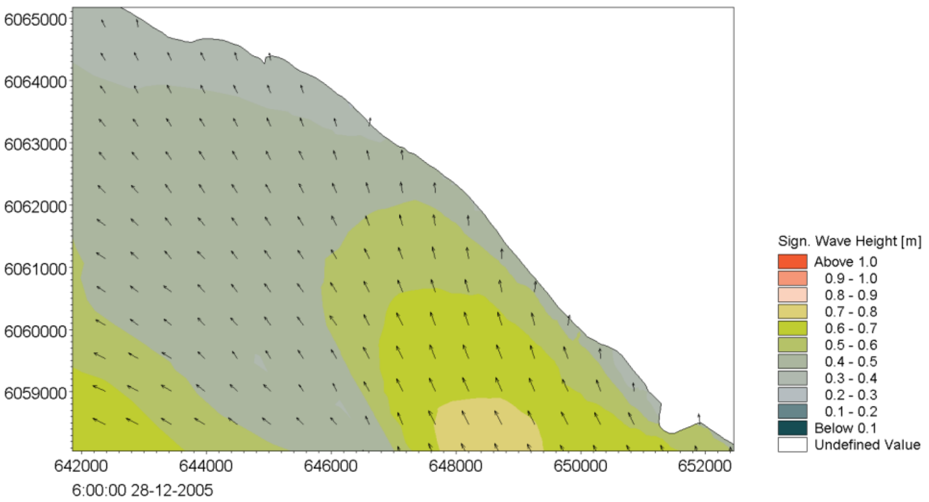


Figure 7.47 Typical wave pattern west of Rødby for SE-erly waves. Date of situation: 28.12.2005

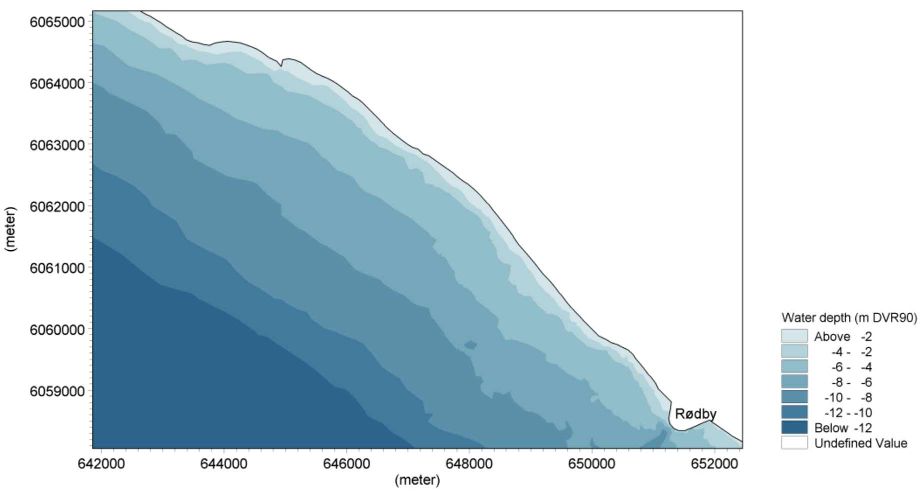


Figure 7.48 Bathymetry west of Rødbyhavn

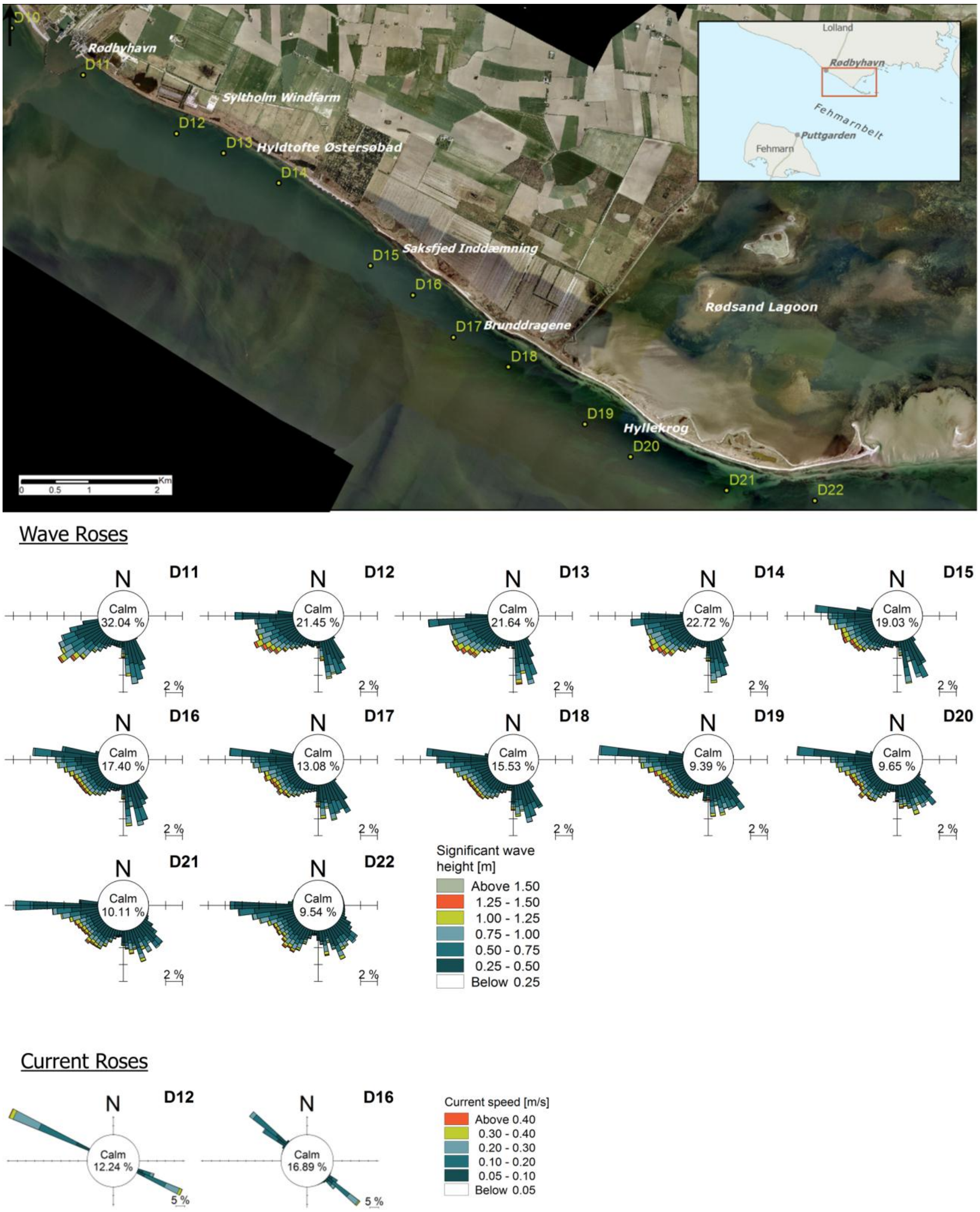


Figure 7.49 Nearshore wave roses east of Rødbyhavn. Time of calm wave conditions (Hs below 0.25 m) given for each wave rose in % of time. Aerial photo from 2009 (©COWI Orthophoto April 2009)

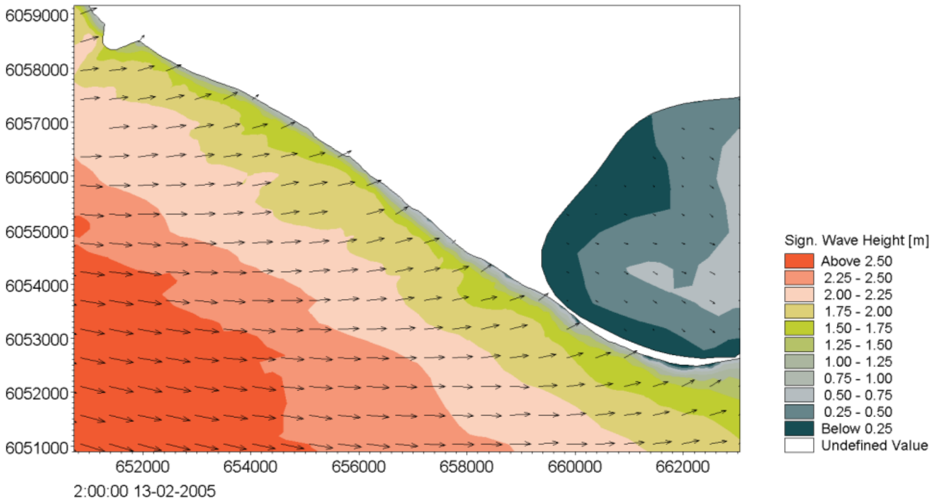


Figure 7.50 Typical wave pattern east of Rødby for WNW-erly waves. Date of situation: 13.02.2005

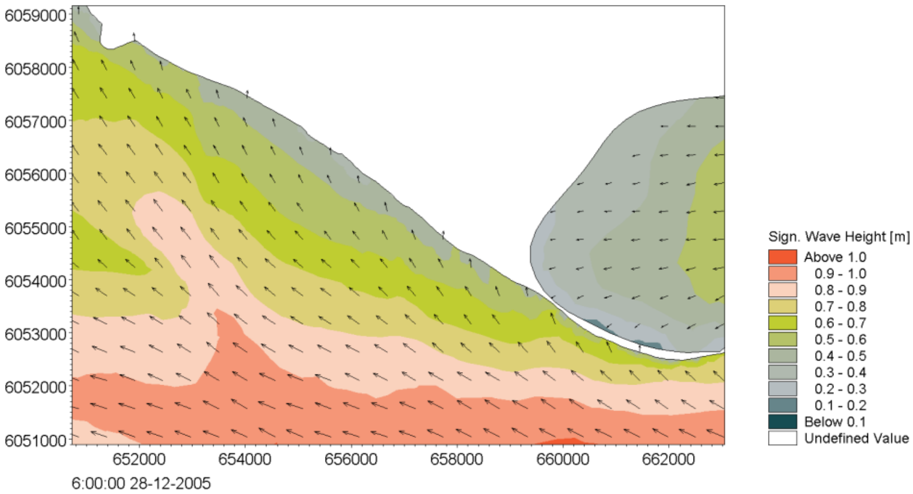


Figure 7.51 Typical wave pattern east of Rødby for SE-erly waves. Date of situation: 28.12.2005

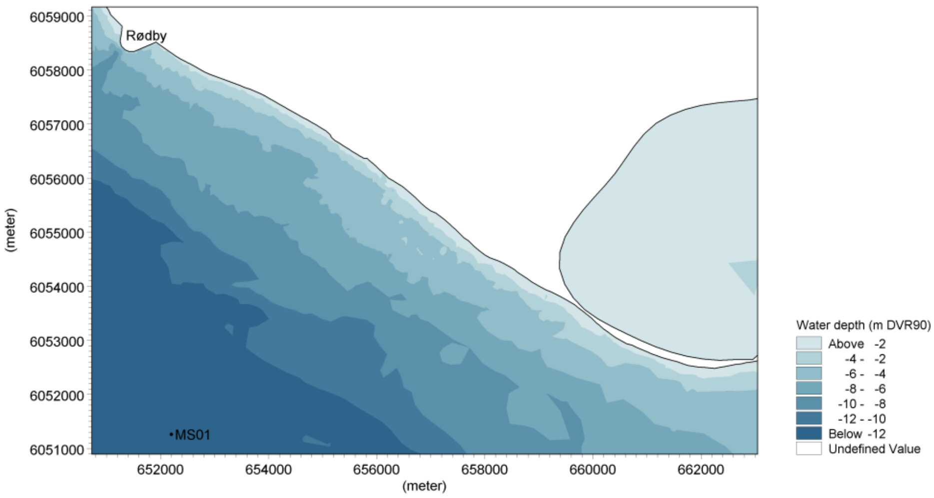


Figure 7.52 Bathymetry east of Rødbyhavn

7.7 *Sediment budget and shoreline evolution*

The littoral drift budget has been established along the south coast of Lolland for coastal stretches of about 5 to 6 km length at each side of Rødbyhavn, i.e. extending from the coastal section west of Bredfjed to Brunddragene.

The littoral drift budget is described below. The variability of the littoral drift rates along the coast causes erosion or accumulation at the beach, i.e. an increasing or decreasing transport rate along the coast. This makes the shoreline retreat or advance with time.

A model to predict the littoral transport rates and the associated accumulation and erosion has been set up. The model is capable of reproducing the observed tendencies for shoreline retreat and advance along the coast of Lolland.

The results described in this chapter are:

- **Littoral drift rates:** net transport, gross transport and east- and westgoing transport components of the sediment transport along the coast in the littoral zone. These rates are compared to the accumulated volumes at specific locations such as the accumulation zone west of Rødbyhavn and the maintenance dredging volumes in the harbour and access channel

- **Shoreline evolution. Shoreline advance and retreat**: the observed tendencies are compared with results from the model

- **Equilibrium beach orientations**: the equilibrium beach orientation is the beach orientation that gives a net annual littoral drift of zero. Along a shoreline with a dominant incident wave direction, the equilibrium orientation is reached when the coastline is facing this direction. If a new beach is designed such that it faces the equilibrium orientation, the average net transport is zero leading to a stable shoreline. The difference between the equilibrium orientation and the present orientation is a measure of the transport capacity at a given location

The methodology in the littoral transport calculations is described in Section 7.7.1 and the results are described in Sections 7.7.4 and 7.7.5.

7.7.1 *Performance of littoral drift calculations*

Littoral drift computations have been performed along coastal stretches of about 5 to 6 km length at each side of Rødbyhavn extending from west of Bredfjed to Brunddragene.

A two-step approach has been applied in calculating the variability of the littoral drift rates along the coast:

- **Step 1:** Establishment of the overall sediment budget

- **Step 2:** Refined calculation of the variability along the coast

Step 1: Establishment of the overall sediment budget.
Sediment transport computations have been performed at selected profiles with about 1 km distance along coastal stretches of 5 km length at each side of Rødbyhavn. The locations of the profiles, for which the littoral drift rates are calculated along the Lolland coast, are D6-D17 shown in Figure 7.45 and Figure 7.49. Nearshore and current conditions for the selected profiles are presented in the previous Section 7.6.

The littoral transports in the profiles have been computed by the LITDRIFT module of LITPACK. The LITDRIFT module is used to determine the annual littoral drift at a given section of the coast. It simulates the cross-shore distribution of wave height, set-up and set-down, longshore current and sediment transport for an arbitrary coastal profile. The model is based on a quasi-3D approach, where the vertical velocity profile used in the sediment transport is calculated based on input from the 2D flow and wave fields on an intra-wave period time scale. The orientations of the profiles are perpendicular to the depth contours in the main transport zone, which is typical in the depth interval 0.0 to 2.0 m.

In general the littoral drift modelling is based on the physical parameters described in the previous sections of this report (Sections 7.4-7.6). Their representation in the model is summarised in Table 7.6. Model parameters are also summarised in the same table.

The composition of the seabed material is complicated in many of the profiles. The seabed conditions along the Lolland coast are dominated by coarse sediments as documented in Section 7.5 with only a narrow nearshore zone with movable sand. Where sand is present it is generally relatively fine sand. The grain size distribution in the littoral zones shows large variations, typically between 0.15 mm and up to several millimetres. These coarse sediments do not contribute significantly to the littoral transport. At each location a median grain size and spreading factor (describing the homogeneity of the sediment) is chosen to represent the sediment characteristic of the movable sediments in the coastal profile. These conditions are summarised in Table 7.7.

In some of the profiles there is no beach but an exposed revetment. The extension of the revetment in terms of depth has been estimated on basis of the measured coastal profiles.

It is evident from the above discussion of the bathymetric conditions and of the sediment characteristics in the coastal areas that most of the stretches are fairly complicated, which constitutes a challenge for performing reliable littoral transport computations. The littoral transport rates have therefore been assessed as described in the following:

1. Calculation of the littoral transport capacity: it is assumed that movable sediment is available in the entire profile. This method provides an *upper* estimate of the actual transport and the potential distribution of the transport in the coastal profile

2. Adjustment of transport capacity: the zone of movable beach sand is restricted due to the occurrence of hard seabed/seabed with coarse sediments and occupancy of part of the profile by revetments as described in Table 7.7.

The occurrence of hard seabed/seabed with coarse sediments is estimated based on the analysis of the sea bed conditions in Section 7.5 and Appendix C.

The littoral drift rates give input to the overall sediment budget for the coastal stretches and are the basis for analysis of the overall tendency for the coastline to retreat or advance between the calculation locations.

Step 2: Refined calculation
The small-scale variabilities within these locations are not captured in Step 1. The littoral drift is very sensitive to the incident angle formed between the beach orien-

tation and the incoming waves. In some configurations, changing the coastline orientation by a few degrees can have a significant impact on the sediment transport rates. Consequently if - between two locations where the sediment transport has been calculated - the shoreline orientation varies this variation should be taken into account to capture the right variation of the littoral transport. This is taken into account in Step 2 which is therefore a refinement of the sediment budget obtained in Step 1.

In Step 2, it is considered that for a point, P, located between two points, where the littoral drift transport has been calculated in Step 1, the littoral drift rate can be estimated by interpolation in the transport rates for the adjacent locations, both of which computed with the actual beach orientation at point P. The transport rates to be interpolated to give the transport at P are obtained from the so-called 'q-alpha'-relations for the two adjacent points with the beach orientation at point P. The 'q-alpha'-curves define at a given location (with specified wave conditions, coastal profile and sea bed conditions as described for Step 1) the relationship between the net littoral drift and the beach orientation at the location. For the actual beach orientation, this curve gives the net littoral transport rate at this location.

The resulting shoreline evolution, the shoreline advance or retreat, is calculated from the gradient of the transport rates.

The calculation methodology, Step 1 and Step 2, described above has as a precondition that the transport conditions are in equilibrium with wave conditions. This implies that the alongshore variations in the coastal profile, wave and sea bed conditions should be limited and slowly varying. The method is considered applicable along the majority of the Lolland coastline. In the area just east of Rødbyhavn, however, this is not the case. The wave driven current is not expected to be fully developed near the harbour. The transport rates in this area are, however, expected to have the correct order of magnitude.

Table 7.6 Physical and model parameters entering the littoral drift model

Model parameter	Parameter setting	Comments
Nearshore wave and water level conditions	Statistical representation of 1989-2010[1] wave conditions for each location D6-D17	See Section 7.6 for description of nearshore wave conditions
Nearshore current conditions	Statistical representation of 2005 current conditions for each location D6-D17	See Section 7.6 for description of nearshore current conditions
Coastal profiles	Varies along the coast. In general measured profiles from 2009 are used	Measured profiles (described in Section 7.4) at the location, where transport is calculated, are used in the model. Exceptions for this is: D9B: Coastal profile measured at location D9 is used D15-D17: Coastal profile measured at location D17 is used
Sediment conditions	One representative grain size (d_{50}) and spreading median factor (σ) selected for each location/profile. The applied sediment characteristics are summarised in Table 7.7. Graded sediment with 10 fractions.	The sediment conditions are applied based on findings in Section 7.5.
Width of littoral zone	A nearshore and offshore limit is applied according to sea bed conditions at each location. A summary of the conditions is supplied in Table 7.7	The width of the littoral zone is estimated based on findings in Section 7.5.
Beach orientation	Varies along the coastal section, see result section.	Estimated based on shoreline orientation and the orientation of depth contours in the active littoral zone (typically with the 1-2m depth contour)
Active beach profile	West of Rødbyhavn: D6-D9B: 3m D9B-D10: 4m East of Rødbyhavn: D11-D17: 2.5m	Active part of the beach profile is estimated from the measured coastal profiles, see Section 7.4.
Bed roughness	Apparent bed roughness (for wave-driven current): $20d_{50}$ Bed roughness for skin friction (for littoral drift transport): $2.5d_{50}$. Porosity of deposited/eroded sediment: 0.4	
Critical Shields parameter	$\theta_c = 0.045$	
Water temperature	10°C	
Grid spacing	0.1m	
Statistical represention of wave and current condition	ΔH_{rms}=0.1m ΔT_{02}=0.5m ΔMWD=5degr ΔWL=0.1m ΔV=0.1m/s	

[1] During the calibration process the statistical representation for the years 1999-2004 and 2004-2010, were applied to validate the transport conditions in the accumulation zone west of Rødbyhavn since the shoreline movements in this area varied significantly during the two periods

Table 7.7 Sea bed characteristic applied in the littoral transport model. The cut-off levels indicate the limits for the littoral zone

Loca-tion	Grain size, d_{50} (mm)	Geometrical standard de-viation (-)	Loose sedi-ment on the sea bed	Offshore cut-off level for transport
			Upper level (m DVR90)	Lower level (m DVR90)
D6	0.25	1.4	-0.4	-2
D7	0.25	1.4	-	-2
D8	0.25	1.4	-	-4.5
D9	0.25	1.4	-	-2
D10	0.2	1.3	-	-5
D11	0.3	1.5	-1	-2
D12	0.3	1.5	-1	-2
D13	0.25	1.3	-0.2	-2.5
D14	0.25	1.4	-1	-2.5
D15	0.25	1.3	-0.75	-2.5
D16	0.25	1.3	-	-2.5
D17	0.25	1.3	-	-2.5

7.7.2 Summary of significant shoreline changes

The littoral transport rates along the Lolland coast are calibrated based on the following information:

- The total accumulated volume of sediment west of Rødbyhavn in the period between 1999 and 2009 was approximately 110,000 m^3 or in average about 11,000 m^3/year

- The accumulated volume was less during the first half of the period (between 1999 and 2004), approximately 16,000 m^3 or about 3,000 m^3/year, than during the last five years between 2004 and 2009, where the accumulated volume was approximately 95,000 m^3 or about 19,000 m^3/year

- The sedimentation in the harbour basins and access channel to Rødbyhavn was in the order of 15,000-20,000 m^3/year

- Shoreline changes along the coastal stretch between the beach west of Bredfjed (location D6) to Brunddragene (location D17) in the period 1999-2009 (excluding the area immediately west of Rødbyhavn) using the information on the shoreline positions from the aerial photos

Observed changes to the coastlines for the two five-year periods 1999-2004 and 2004-2009 are shown in Figure 7.53. Persistent changes are seen at:

- Bredfjed to Lalandia: shoreline advance of about 0.5-1 m/year in average

- Immediately west of Hyldtofte Østersøbad: shoreline advance of about 0.5-1m/year in average

- 0-800 m east of Hyldtofte Østersøbad: shoreline advance of about 0.5-1 m/year in average

- In front of Saxfjed Inddæmning: shoreline retreat of about 0.5-1 m/year in average

The above accumulated volumes and shoreline changes are derived from shoreline changes between the years 1999 to 2004 and 2004 to 2009, respectively, and information on maintenance dredging in Rødbyhavn, see further information in Section 7.3.

An annual accumulation of 11,000 m^3/year for an average year west of Rødbyhavn and the sedimentation of 15,000-20,000 m^3/year in the harbour area, indicates a net transport rate in the order of 25,000-35,000 m^3/year eastwards for average conditions.

The accumulation area west of Rødbyhavn, which shows distinct differences in the two five-year periods, the littoral transport rates and budget at the relevant locations (D9, D9B and D10) have been calculated based on wave statistics corresponding to the periods 1999-2004 and 2004-2009.

However, along the remaining part of the Lolland coastline, the shoreline changes are relatively small. The shoreline retreat/advance is in the order of about 5-10 m during 10 years. For these areas the calibration has aimed at reproducing the overall tendency for erosion/deposition during 10 years. The wave statistics for the average year in the period 1989-2010 has been taken to apply also for the average wave conditions during the period 1999-2009.

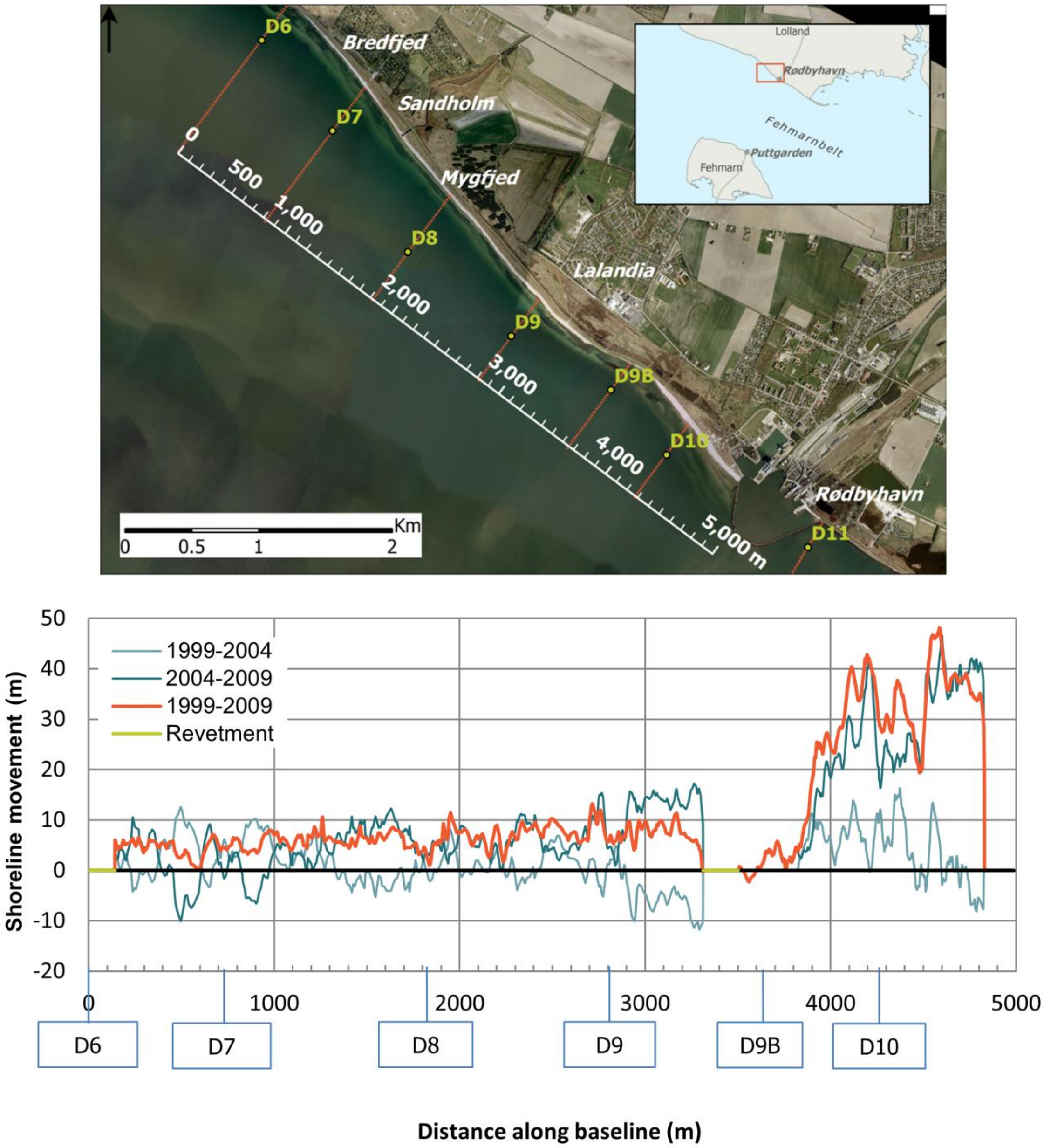
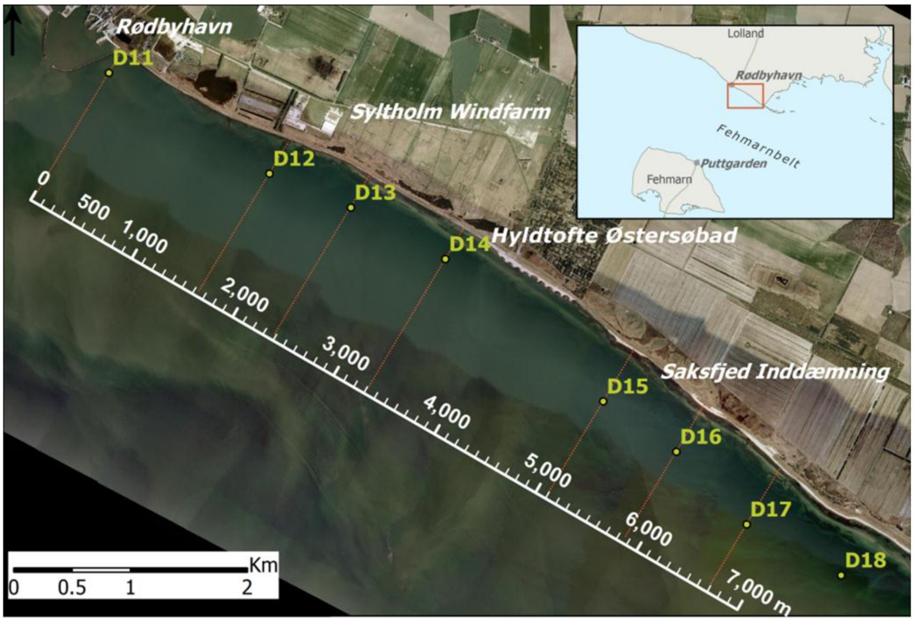


Figure 7.53 *Shoreline retreat (negative) or advance (positive) west of Rødbyhavn between Bredfjed and Rødbyhavn. 1999-2004 (light blue curve), 2004-2009 (dark blue curve) and 1999-2009 (red curve). Aerial photo from 2009 (©COWI Orthophoto April 2009)*



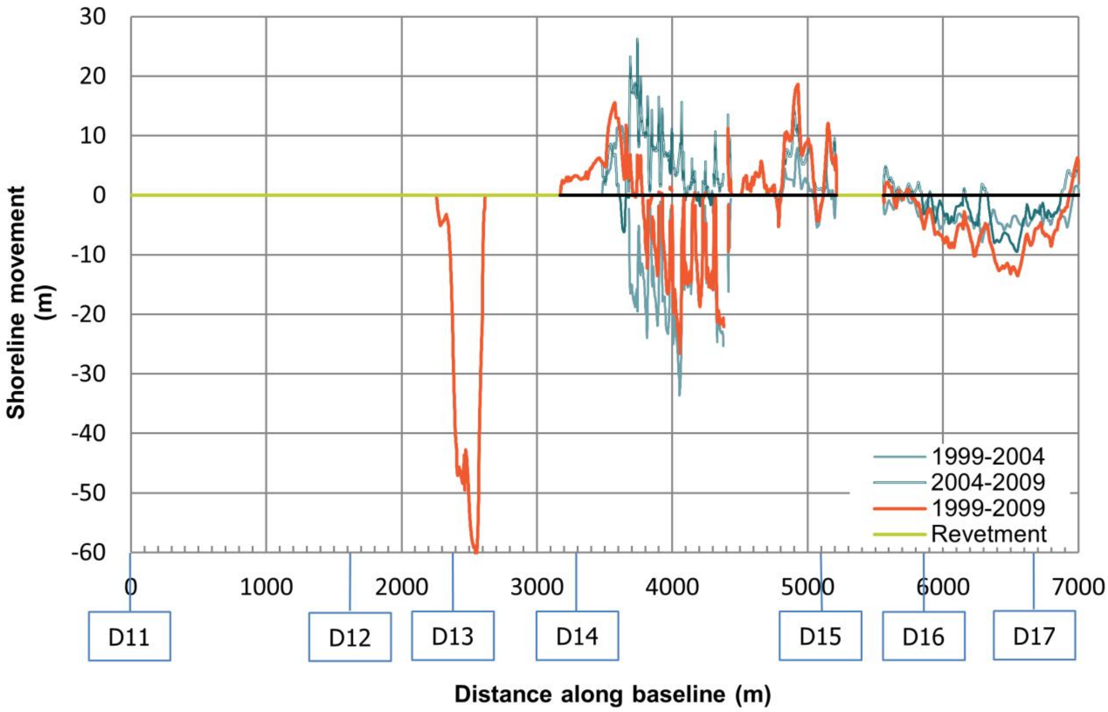


Figure 7.54 Shoreline retreat (negative) or advance (positive) east of Rødbyhavn between the harbour and Brunddragene.1999-2004 (light blue curve), 2004-2009 (dark blue curve) and 1999-2009 (red curve). Aerial photo from 2009 (©COWI Orthophoto April 2009)

7.7.3 Calibration of littoral drift and shoreline evolution model

The calibration of the modelling complex has been undertaken from the accumulation area west of Rødbyhavn. Initially the overall budget, corresponding to **Step 1**, has been calibrated to fit the observations. The littoral drift has been calculated at the locations D6 to D10 using wave statistics corresponding to the periods 1999-2004 and 2004-2009. Afterwards **Step 2**, refined calculations of littoral drift and shoreline evolution have been undertaken for the two periods and compared with detailed observed shoreline evolution.

The calibrated shoreline evolutions (outcome of Step 2) are shown in Figure 7.55. The calibrated overall sediment budgets for the two periods are shown in Table 7.8, where “sand being transported into the accumulation area” is the simulated littoral drift 200 m east of D9B and “sand transported around western breakwater” is the simulated littoral drift 600 m east of D10. The latter is compared with the observed sedimentation in the reservoir and in the harbour basin, as previously described. The difference between the two simulated transport rates is compared with the volumetric change due to accretion of the shoreline. The main calibration parameters are the bed roughness and the exact information about the various physical parameters such as sediment properties and width of the band in the profile which is covered by movable sand, exact orientation of the beach. The final physical parameters are presented in Table 7.6. The calibration is found to be satisfactory.

Finally, the long term average wave conditions, representing the period 1989 to 2010, have been used to simulate long term average littoral drift and 10 years of shoreline evolution. The 10-year simulated shoreline evolution from D6 to Rødbyhavn has been compared with the total observed shoreline evolution, see Figure 7.56. The calibrated littoral drift model run with the long term average wave climate is seen to reproduce the main features in the observed evolution and provides the correct order of magnitudes of shoreline changes.

The calibrated model setup and methodology have been validated by comparing the observed shoreline evolution over the period 1999-2009 with the simulated shoreline evolution corresponding to the 10 years with long term average wave conditions, see Figure 7.56. (It is noted that the first 3.2 km east of Rødby is eroding and there is no beach in front of the revetment, which protects the dike along this stretch. Therefore shoreline evolution cannot be observed along this stretch). The simulation of 10 years of shoreline evolution using the long term average wave climate is seen to reproduce the main features in the observed evolution and provides correct orders of magnitude of shoreline changes.

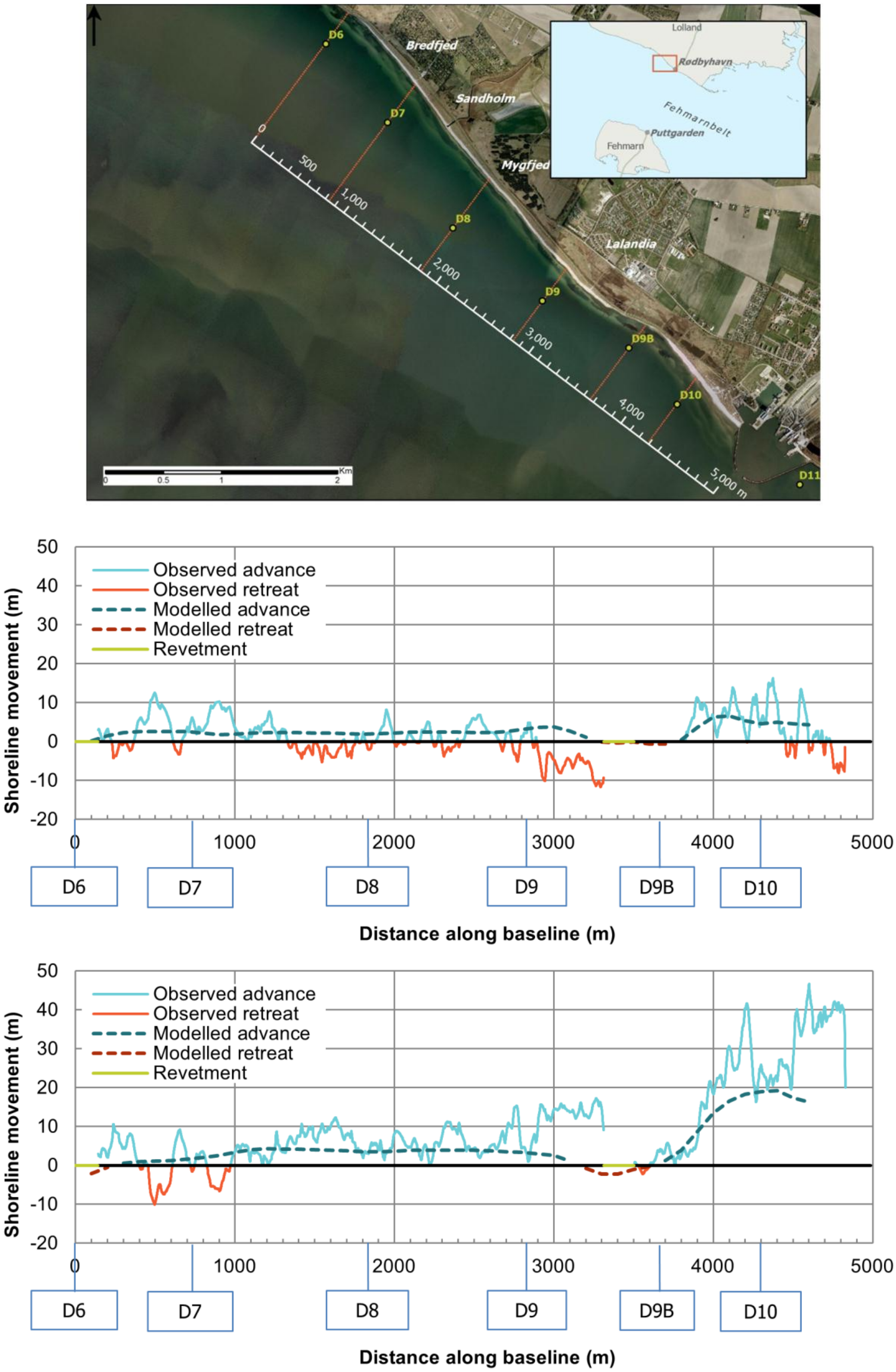


Figure 7.55 Upper panel: baseline and locations of overall sediment budget calculation points. Aerial photo from 2009 (©COWI Orthophoto April 2009)

Middle panel: simulated and observed shoreline evolution, 1999-2004
Lower panel: simulated and observed shoreline evolution, 2004-2009

Table 7.8 Comparison of modelled littoral drift budget for the accumulation area west of Rødbyhavn with observed accumulation and estimated sedimentation in the harbour for the periods 1999-2004 and 2004-2009. Average annual volumes (m^3/year)

Year: 1999-2004	**Model (m^3/year)**	**Observation (m^3/year)**
Sand being transported into the accumulation area	21,500	-
Sand accumulated in the accumulation zone	4,000	4,000
Sand transported around western breakwater	17500	15,000-20,000
Year: 2004-2009	**Model (m^3/year)**	**Observation (m^3/year)**
Sand being transported into the accumulation area	31,500	-
Sand accumulated in the accumulation zone	12,500	19,000
Sand transported around western breakwater	19,000	15,000-20,000

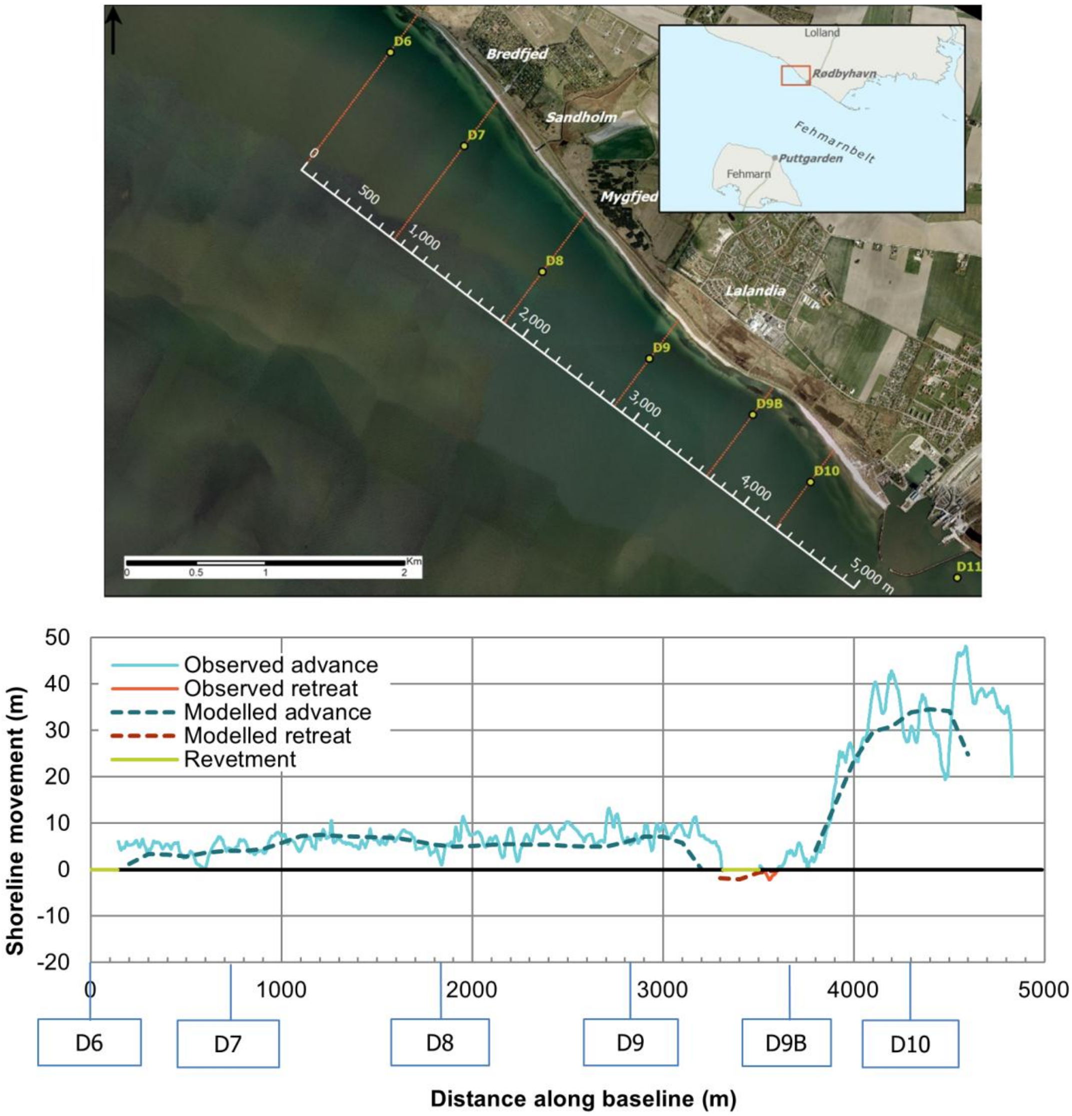
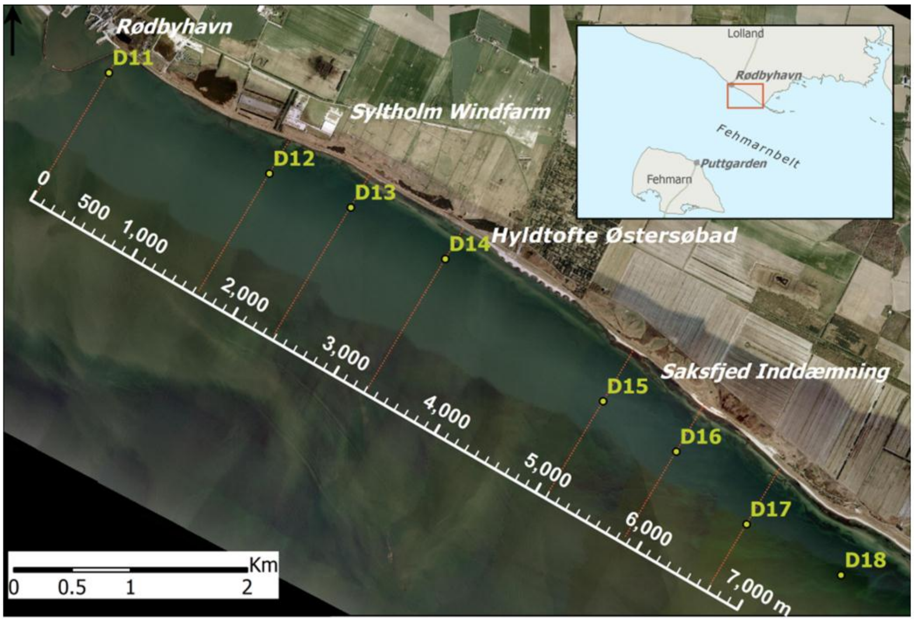


Figure 7.56 Simulated shoreline evolution over 10 years using the long term average wave climate, 1989-2010, compared with the observed shoreline evolution 1999-2009, west of Rødby-havn. Aerial photo from 2009 (©COWI Orthophoto April 2009)



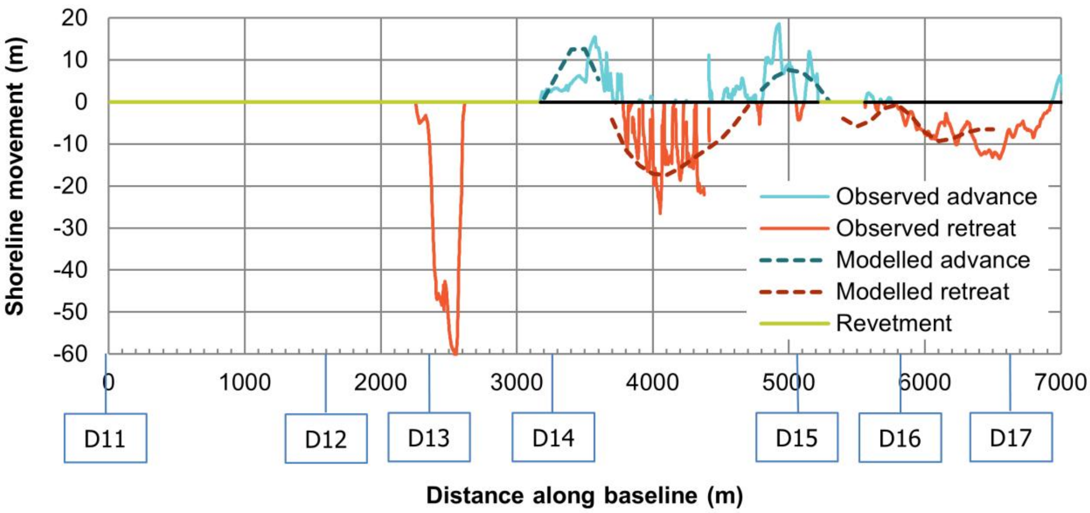


Figure 7.57 Simulated shoreline evolution over 10 years using the long term average wave climate, 1989-2010, compared with the observed shoreline evolution 1999-2009 east of Rødbyhavn. Aerial photo from 2009 (©COWI Orthophoto April 2009)

7.7.4 Littoral drift budget west of Rødbyhavn

The annual littoral drift rates along the coastal section west of Rødbyhavn have been calculated using the average wave conditions (1989-2010), see Figure 7.58.

A net eastwards transport rate of 17,000-32,000 m^3/year is found along this section. The net transport rate decreases from about 32,000 m^3/year west of Bredfjed (D6) to about 17,000 m^3/year at the harbour for the average year conditions. This indicates a net input of about 15,000 m^3/year to this coastal section from the east. The majority of this volume is predicted to deposit in the accumulation area west of Rødbyhavn, where the transport rate decreases rapidly. The gross transport rates along the coastal section are in the order of 50,000-70,000 m^3/year.

Accumulation zone west of Rødby
The sediment budget immediately west of Rødbyhavn is in average:

- Sand being transported into the accumulation area: about 27,500 m^3/year

- Sand accumulated on the beach in the accumulation zone: about 10,500 m^3/year

- Sand transported along the accumulation zone and around the western break-water: 17,000 m^3/year

Lalandia
In the bay east of Lalandia, the shoreline curves around to have a larger angle with the dominant incoming waves. This gives a tendency for the net littoral transport to increase, and erosion to take place from this area. A revetment has been constructed to protect the coast at this section. The erosion from this area may be slightly larger than indicated in the model. Measured profiles from 1998 and 2009 indicate that erosion takes place at water depths 3-6 m (profile RW06, see Appendix B).

Bredfjed to Lalandia
Between Bredfjed (D7) and Lalandia (D9) there is a tendency for persistent deposition of about 0.5-1.0 m/year, Figure 7.57. The deposition corresponds to the reduction in the net transport caused primarily by the gradual change in the beach orientation.

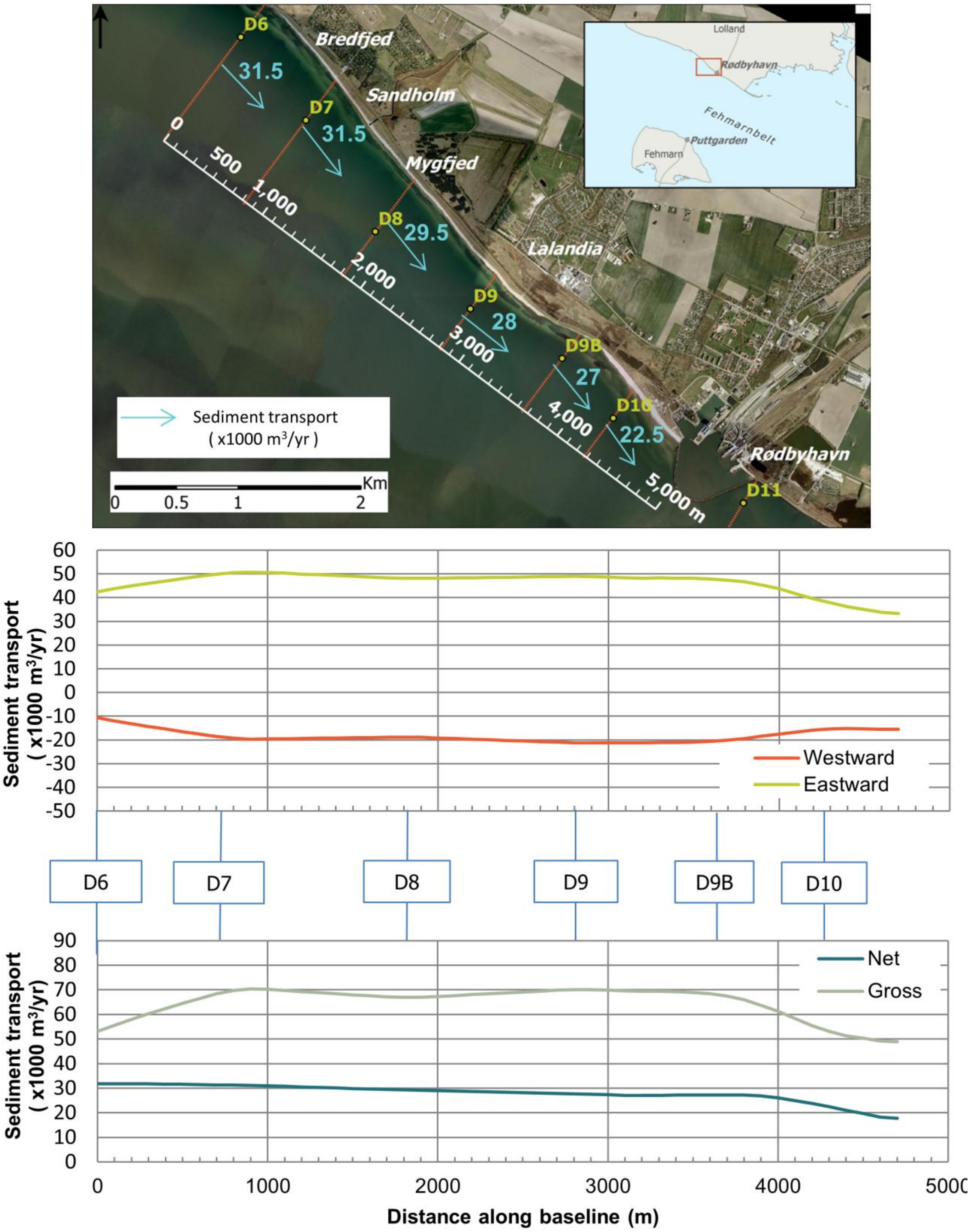


Figure 7.58 Average Littoral drift transport rates west of Rødbyhavn. Middle figure: West and east going transport components, lower figure: Net and gross transport rates. Aerial photo from 2009 (©COWI Orthophoto April 2009)

The average equilibrium beach orientations are shown in Figure 7.60 together with the present beach orientations. The equilibrium orientation is the alignment of the shoreline which corresponds to zero net littoral drift. The littoral drift increases with increasing angle between shore normal and the angle of incoming waves until the angle reaches approx. 45. This is valid for all combinations of wave height and direction. The equilibrium orientation is found by calculating the total net littoral drift for a given wave climate assuming different shoreline orientations. The orientation where the net littoral drift is zero is the equilibrium orientation. The so-called Q–alpha curve, which is the relationship between net littoral drift and shoreline orientation is shown for position D10 as an example in Figure 7.59.

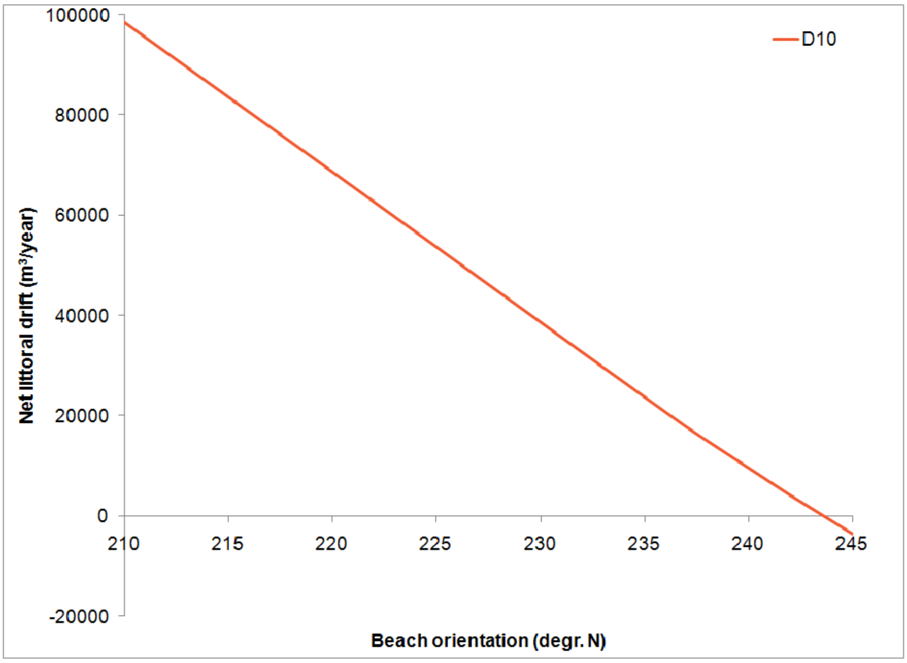


Figure 7.59 "Q-alpha" relation(relation between net littoral drift and shoreline orientation) for D10

The net and gross transport rates are tabulated in Table 7.9. The beach orientations and the equilibrium orientations are tabulated in Table 7.10Table 7.10.

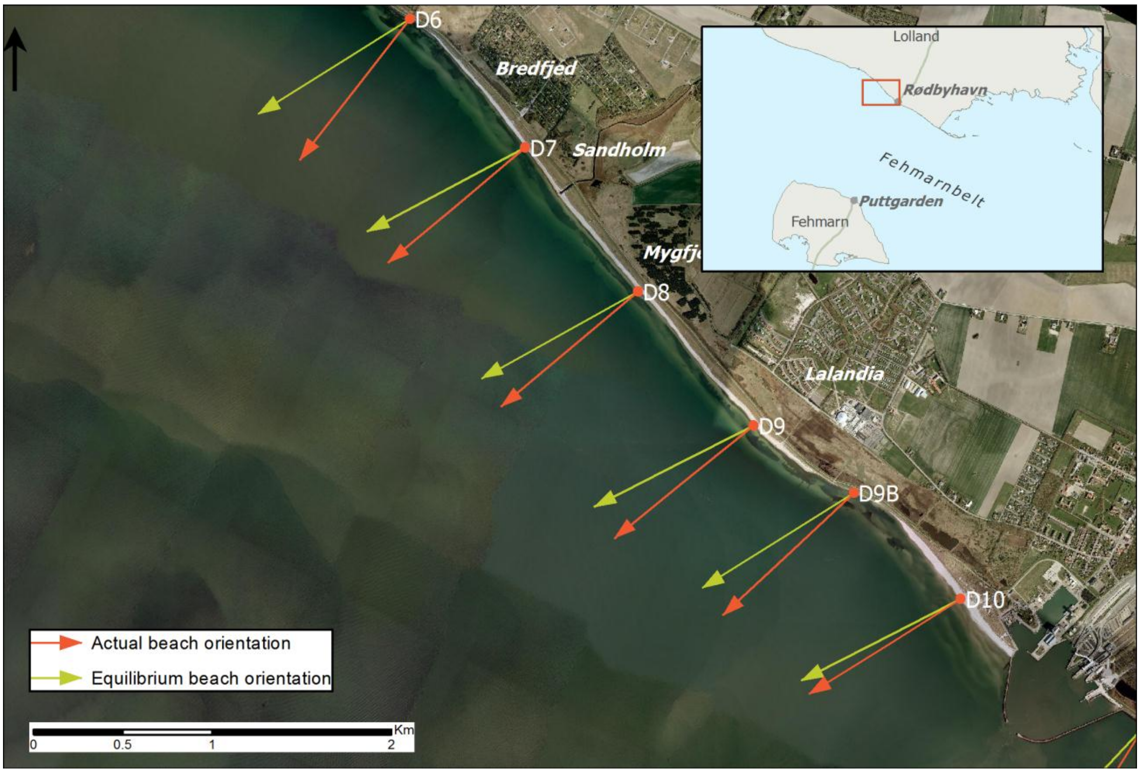


Figure 7.60 Equilibrium beach orientations west of Rødbyhavn. Aerial photo from 2009 (©COWI Orthophoto April 2009)

Table 7.9 Average littoral transport rates west of Rødbyhavn

Location	Net littoral transport rate (m^3/year)	Gross littoral transport rate (m^3/year)
D6	31,500	53,000
D7	31,500	68,500
D8	29,500	67,000
D9	28,000	70,000
D9B	27,000	68,500
D10	22,500	53,000

Table 7.10 Equilibrium beach orientations west of Rødbyhavn

Location	Beach orientation (degr. N)	Equilibrium beach orientation (degr. N)
D6	218	238
D7	230	242
D8	230	241
D9	231	243
D9B	227	238
D10	238	243

7.7.5 *Littoral drift budget east of Rødbyhavn*

The calculated average annual littoral drift rates along the coastal section east of Rødbyhavn are presented in Figure 7.61 for the average wave conditions in the period 1989-2010.

The net eastwards transport rates gradually increase from being zero at the harbour (D11) to about 22,000 m^3/year at Brunddragene (D17) indicating an overall erosion of the beach east of Rødbyhavn. Small variations in the net transport rate cause the relatively small shoreline changes observed.

The gross transport rates increase from about 15,000 m^3/year at the harbour to about 80,000 m^3/year off Brunddragene.

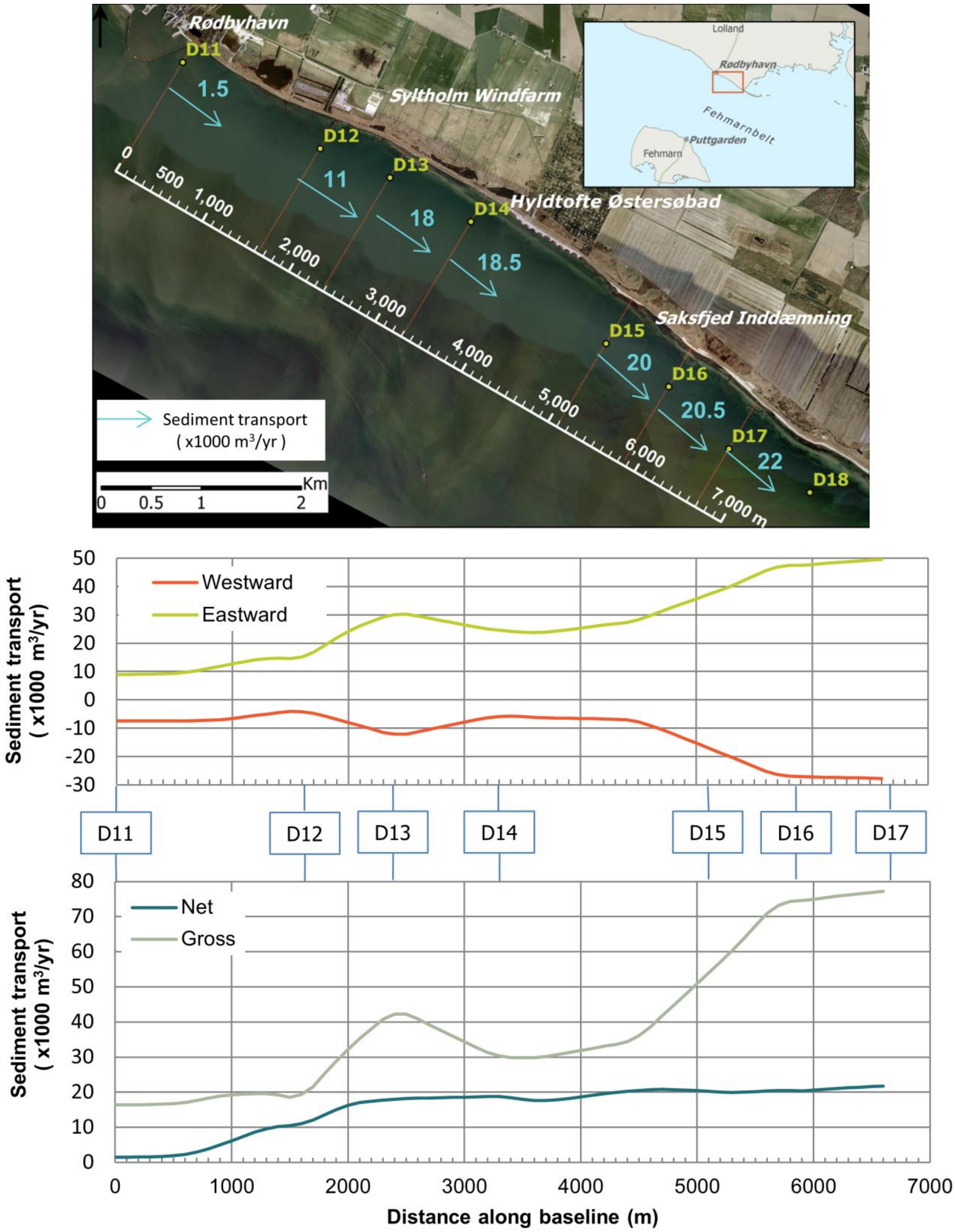


Figure 7.61 Average littoral drift transport rates east of Rødbyhavn. Middle figure: East- and west going transport conditions, Lower figures: net and gross transport rates. Aerial photo from 2009 (©COWI Orthophoto April 2009)

East of Rødbyhavn to Hyldtofte Østersøbad

The net transport rate is small at the harbour. No by-pass around the harbour breakwaters takes place. The net transport gradually increases east of the harbour to be about 15,000-20,000 m^3/year west of Hyldtofte Østersøbad. The beach orientation shifts slightly anti-clockwise off Syltholm Windfarm facilitating an increase in the transport rates as the angle between the dominant wave direction and beach orientation increases.

The increase in the net transport along this stretch is reflected in the situation with no sandy beaches east of the harbour and a hard seabed with coarse sediments which has been starved from finer sediments. The width of the littoral zone is very limited in front of the revetment covering the entire stretch. The deficit in the littoral budget is in the order of 15,000-20,000 m^3/year along this stretch. Parts of this volume have come from the nourishment along this section (75,000 m^3 in 1993 and 25,000 m^3 in 1999, see Section 8.3) and the remaining volume has eroded from the coastal profile. The 1999 nourishment shows up in Figure 7.57 as a large shoreline retreat, since the majority of the volume was eroded from the coast between 1999 and 2004.

The shoreline model is capable of catching the overall tendencies in the transport variation along this section.

Near Hyldtofte Østersøbad
Within the breakwater scheme a net shoreline retreat has taken place in the period 1999-2009. The net transport rates increase slightly in this area although the beach orientation is nearly constant. This is due to the waves turning slightly clockwise as the coast gets more exposed to waves from west and west-northwest. It is also noticed that the angle between the equilibrium orientations and the beach orientations increases along this stretch, see Figure 7.62.

The small beaches between the breakwaters actually advanced slightly between 2004 and 2009 (Figure 7.54) indicating that the breakwater scheme is presently stable.

Southeast of Hyldtofte Østersøbad the beach curves clockwise and the net transport rates reduce slightly causing the small accumulation area east of the breakwater scheme.

Saksfjed Inddæmning to Brunddragene
Further east of Hyldtofte Østersøbad in front of Saksfjed Inddæmning and towards Brunddragene a slightly increasing net transport rate is found. This corresponds well with the observed shoreline retreat in front of Saksfjed Inddæmning and Brunddragene.

The slight increase of the net transport is a balance between several physical mechanisms. The eastward as well as the westward transport rates increase along this section as the coast becomes more exposed to westerly and northwesterly waves as well as the south-easterly waves, which become more important. The beach orientation turns slightly anti-clockwise (between D16 to D17) increasing the eastward transport rates. On the other hand the beach gradually becomes less steep from about Hyldtofte Østersøbad and eastwards. The littoral drift decreases for decreasing profile steepness.

The equilibrium beach orientations for the period 1989-2010 are shown in Figure 7.62 together with the present beach orientations.

The net and gross transport rates are tabulated in Table 7.11. The beach orientations and the equilibrium orientations are tabulated in Table 7.12.

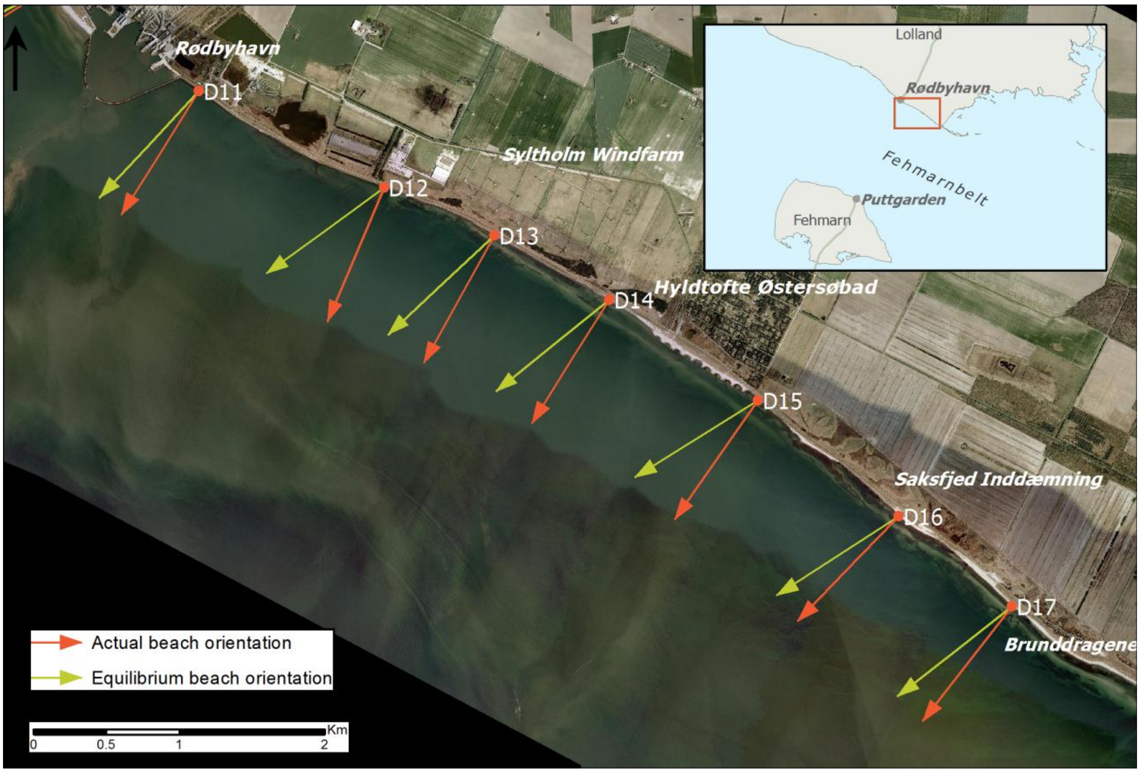


Figure 7.62 Equilibrium beach orientations east of Rødbyhavn. Aerial photo from 2009 (©COWI Ortho-photo April 2009)

Table 7.11 Average littoral transport rates east of Rødbyhavn

Location	**Net littoral transport rate (m^3/year)**	**Gross littoral transport rate (m^3/year)**
D11	1,500	16,500
D12	5,000	19,500
D13	11,000	42,000
D14	18,000	30,500
D15	20,000	54,000
D16	20,500	74,500
D17	22,000	77,500

Table 7.12 Equilibrium beach orientations west of Rødbyhavn

Location	**Beach orientation (degr. N)**	**Equilibrium beach orientation (degr. N)**
D11	212	223
D12	203	234
D13	209	227
D14	212	231
D15	215	238
D16	224	237
D17	218	232

7.7.6 *Remarks on littoral drift budget along the coast of Lolland*

The littoral drift budget along the south coast of Lolland has been calculated between Bredfjed west of Rødbyhavn and Brunddragene east of the harbour.

Net transport rates in the order of 0-30,000 m^3/year and gross transport rates in the order of 15,000-70,000 m^3/year have been obtained for the average.

The wave conditions are one of the primary parameters for estimating littoral drift conditions. The modelled wave conditions were found to deviate from the measured wave conditions. The main source of uncertainty is identified to be due to inaccuracies in the applied wind fields. The modelled nearshore wave conditions have been adjusted to account for the discrepancies between modelled and measured waves. The uncertainty in the waves will be reflected as an uncertainty in the predicted transport rates. The uncertainty of the littoral drift calculations is estimated at +/- 50%. However, with the adjusted nearshore waves a satisfactory calibration against observed shoreline evolution has been obtained.

8 FEHMARN COAST

8.1 General description of Fehmarn coast

The northwest coastal stretch from Markelsdorfer Huk to Puttgarden is low-lying land characterised by storm beaches, sand spits, coastal lagoons, dune areas, meadows and salt marches, which have been formed by the natural coastal dynamics. This stretch belongs to the most important coastal landscape in Schleswig-Holstein with Grüner Brink as the most prominent natural coastal formation.

The entire north coast of Fehmarn is protected by a dike constructed after the 1872-storm. The dike extends along the west- and north coasts from south of Markelsdorfer Huk (the northwest ‘corner' of Fehmarn) to Puttgarden and along the northeastern coast from Ohlensborgs Huk, located about 1 km southeast of Puttgarden, to the cliff off the village Klausdorf about 4-5 km southeast of Puttgarden. The dike is in general located close to the shoreline apart from the stretch covered by Markelsdorfer Huk and Grüner Brink where the dike runs landwards of these formations, see Figure 8.1.

The present coastline and the coastal structures between Markelsdorfer Huk and Klausdorf are described below. The coastline was inspected on 27th January 2011. The photos shown in the following are from this site inspection. An overview of the coastline and the structures is presented in Figure 8.2 (Markelsdorfer Huk to Puttgarden) and Figure 8.3 (Puttgarden to Klausdorf).

Aerial photos of sections along the entire stretch between Markelsdorfer Huk and Klausdorf showing details of the shoreline and the structures can be found in Appendix D.

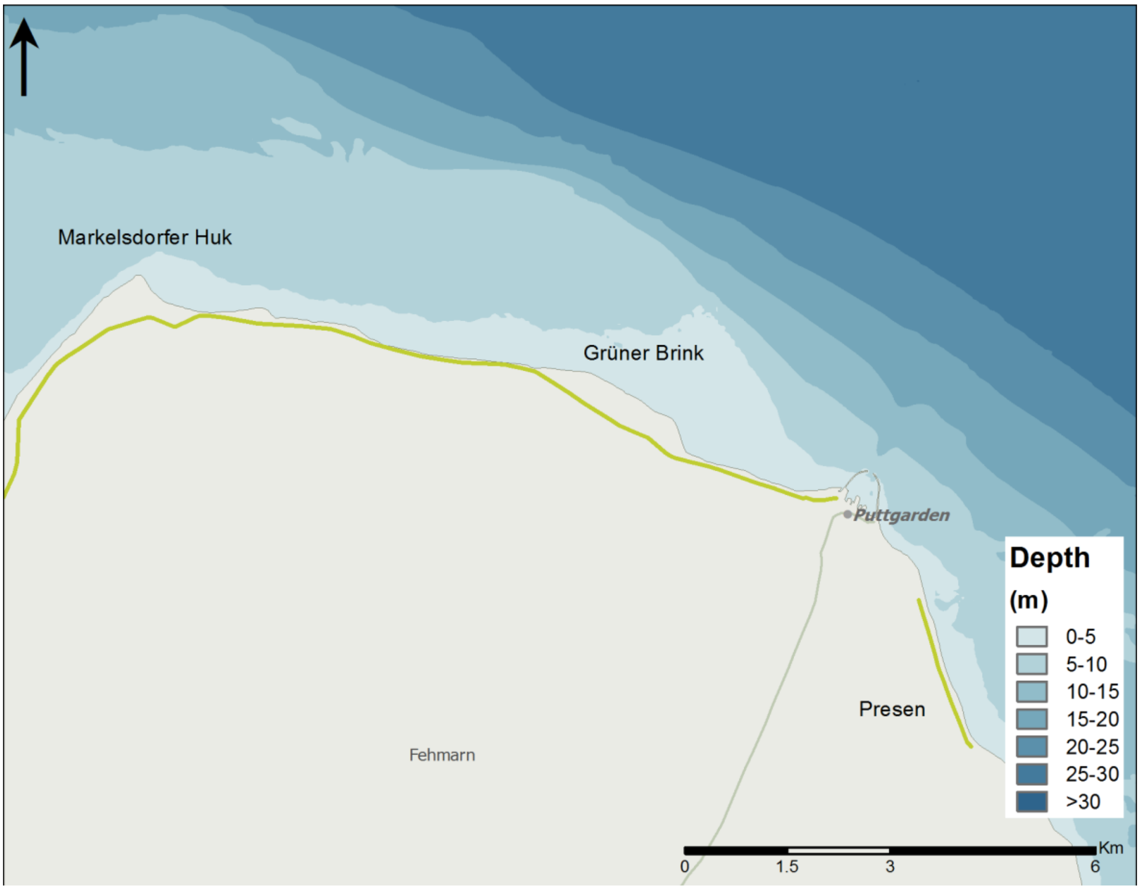


Figure 8.1 Overview over the dike along the west, north and northeast coasts of Fehmarn

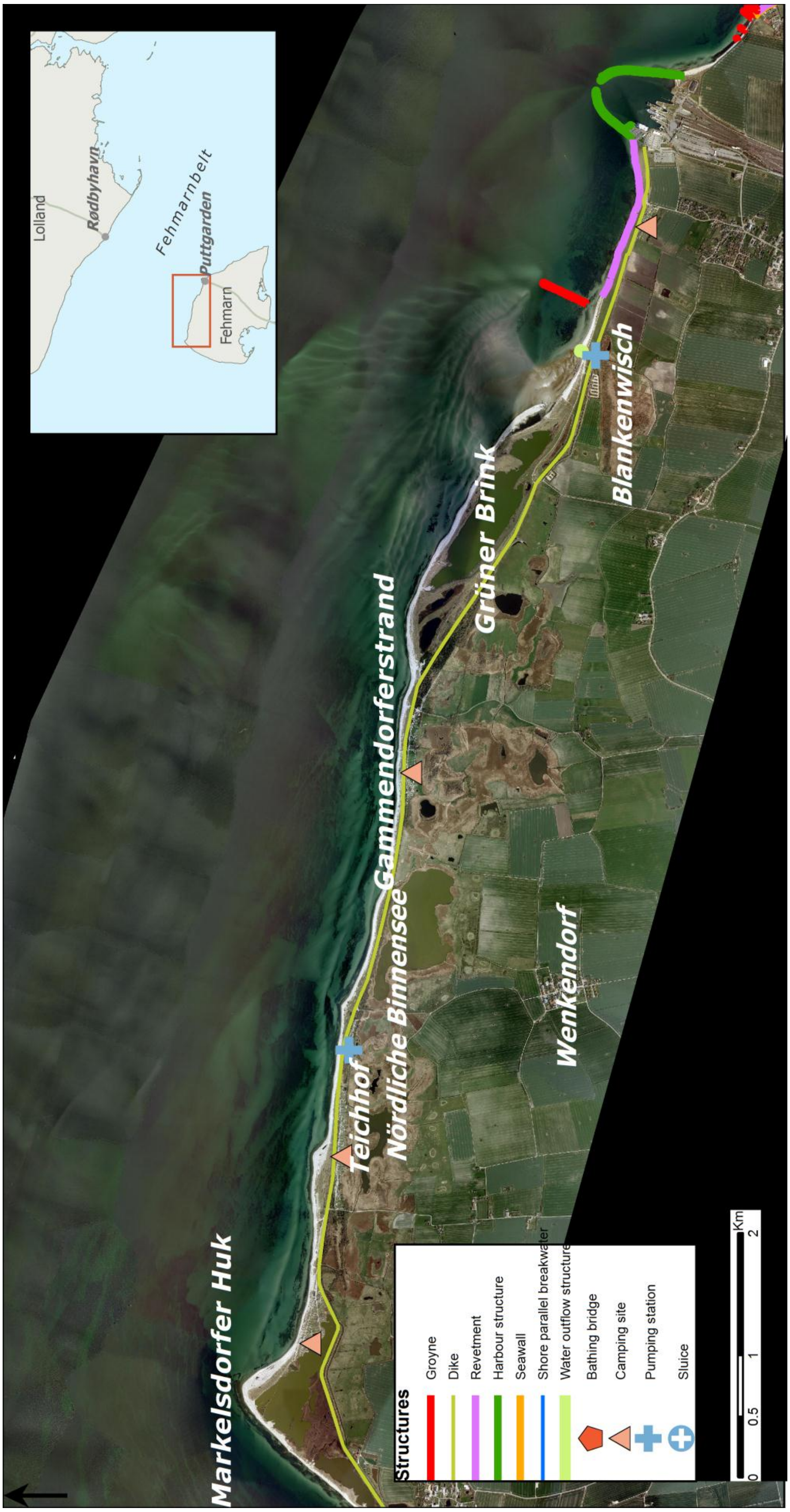


Figure 8.2 Overview of coastline and coastal structures from Markelsdorfer Huk to Puttgarden. Aerial photo from 2009 (©COWI Orthophoto April 2009)

Figure 8.3 *Overview of coastline and coastal structures from Puttgarden and Klausdorf. Aerial photo from 2009 (©COWI Orthophoto April 2009). Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen.*

8.1.1 *West of Puttgarden – from Markelsdorfer Huk to Grüner Brink*

The northwestern corner of Fehmarn, Markelsdorfer Huk, is a marine foreland. Waves from SW-WNW'ern directions cause erosion of the west coast of Fehmarn and a net littoral transport towards the north causing formation of the cuspate marine forland Markelsdorfer Huk. The predominant waves from WNW - NW-erly directions along the north coast of Fehmarn cause transport of some of the material deposited at Markelsdorfer Huk further eastward. This sediment is the main source for the formation of Grüner Brink.

The cuspate marine foreland at Markelsdorfer Huk is composed of a system of spits and barrier island formations consisting of sand, gravel and shingle. The system of sand spits has formed some coastal lagoons, which are referred to as Nördlicher Binnensee, which actually consists of three separate lakes separated by meadows. The westernmost of these is part of the Markelsdorfer Huk foreland, see photos in Figure 8.4.

The dike runs south of the Markelsdorfer Huk foreland, the westernmost part of Nördlicher Binnensee. There is consequently no connection between the lake and the Binnensee lakes further east. The dike cutting off the connection between the lakes is seen in Figure 8.5.

There is a large caravan site on the spit formation at the eastern end of the western Nördlicher Binnensee and another one east of the access road to the sea. There are two more caravan sites along this section of beach, a small one at Teichhof and a big one at Gammendorf Beach, see Figure 8.2.

Along the stretch from Markeksdorfer Huk to Gammendorf a series of irregular beach undulations is present. The width of the beach varies along this stretch and some places a relatively wide coastal area can be seen with dunes in front of the dike, see Figure 8.6.

Figure 8.4 *Markendorfer Huk cuspate foreland. Upper: spit and tidal meadow formations near the Huk. Lower left: westernmost part of Nördlicher Binnensee. Lower right: sand/gravel beach at north coast of Markendorfer Huk*

Figure 8.5 Dike at the east end of the westernmost of the three Binnensee lakes




Figure 8.6 *Teichhof off Wenkandorf. Upper: sand/gravel beach. Lower left: wide dune area off the dike. Lower right: part of the easternmost Binnensee, photo taken from the road towards east*


Figure 8.7 *Gammendorf beach. Left: wide foreland in front of dike, Grüner Brink in the background. Right: sand/gravel beach, typical for the area*

8.1.2 Grüner Brink

Grüner Brink is a special coastal morphological feature, which stretches along the coast from 2.4 km to 4.7 km west of Puttgarden. The Grüner Brink is a system of coastal lagoons created by the formation of natural sand spits which have developed as a result of the special wave conditions in the area. The coastal morphological processes in the area are still active and new lagoon sections are under formation due to growth of new sand spits towards SE.

The alignment of the coastline between the Markelsdorfer Huk and Puttgarden, a stretch of about 10.6 km, can be divided in two characteristic sections:

- Western section between Markelsdorfer Huk and Gammendorf Beach (East end of Grüner brink) with an orientation of about 12.5° (orientation is defined as the direction of the normal to the coastline)

- Eastern section between Gammendorf Beach and Puttgarden with an orientation of about 27°

The shift in orientation at Gammendorf Beach is the reason for the formation of Grüner Brink, as this shift in the orientation of the original coastline initiated the formation of the sand spits detached from the coastline of which Grüner Brink is formed.

The wave climate off Grüner Brink is dominated by very oblique waves from WNW - NW-erly directions. This means that the shoreline in principle is unstable (any perturbation in the shoreline has a tendency to grow) and there is a tendency to the formation of sand spits separated from the coast, as in the case of Grüner Brink.

The morphological development of Grüner Brink is sketched in Figure 8.8. It appears that a system of nearly shore-parallel bar like formations is present along the Grüner Brink complex. The shoreface area has a width of 300 m at the west end and about 600 m at the east end; the bar formations terminate in a sand flat north and east of the spit. These formations indicate the littoral transport zone. The wave climate at this location causes a net transport towards the east. The alongshore transport of sand feeds the spit, but also an 'offshore front' of Grüner Brink.

The sand spits gradually grow in length and approaches the coastline and eventually a new spit is formed along the previous spit. These spits have formed coastal lagoons landward of the outer perimeter of Grüner Brink over the years. The presently growing spit is marked in Figure 8.8 with a green arrow. Remains of 'old' spits can be identified in the area of the coastal lagoon/lake; these are marked with red arrows on Figure 8.8.

The offshore part of Grüner Brink terminates abruptly at the eastern end with a steep slope resting on the residual seabed. This slope is the 'offshore front' of the Grüner Brink. The sand transported along the northern coastline of Grüner Brink deposits on this steep slope or 'front' and is not transported further onto the coastline, see Figure 8.8.

The Grüner Brink has a total length along the coast of 2.3 km and a width perpendicular to the shoreline of about 400 m. Photos in Figure 8.9 - Figure 8.11 illustrate the coastline at the Grüner Brink. Photos from the west and mid part of Grüner Brink are presented in Figure 8.9.

The present sand spit, which is nearly connected to land and encloses a new small coastal lagoon, is seen in the photos in Figure 8.10. A lot of seaweed accumulates in the lagoon.

The dike runs on the landward side of the Grüner Brink Lagoon, see the photos in Figure 8.11.

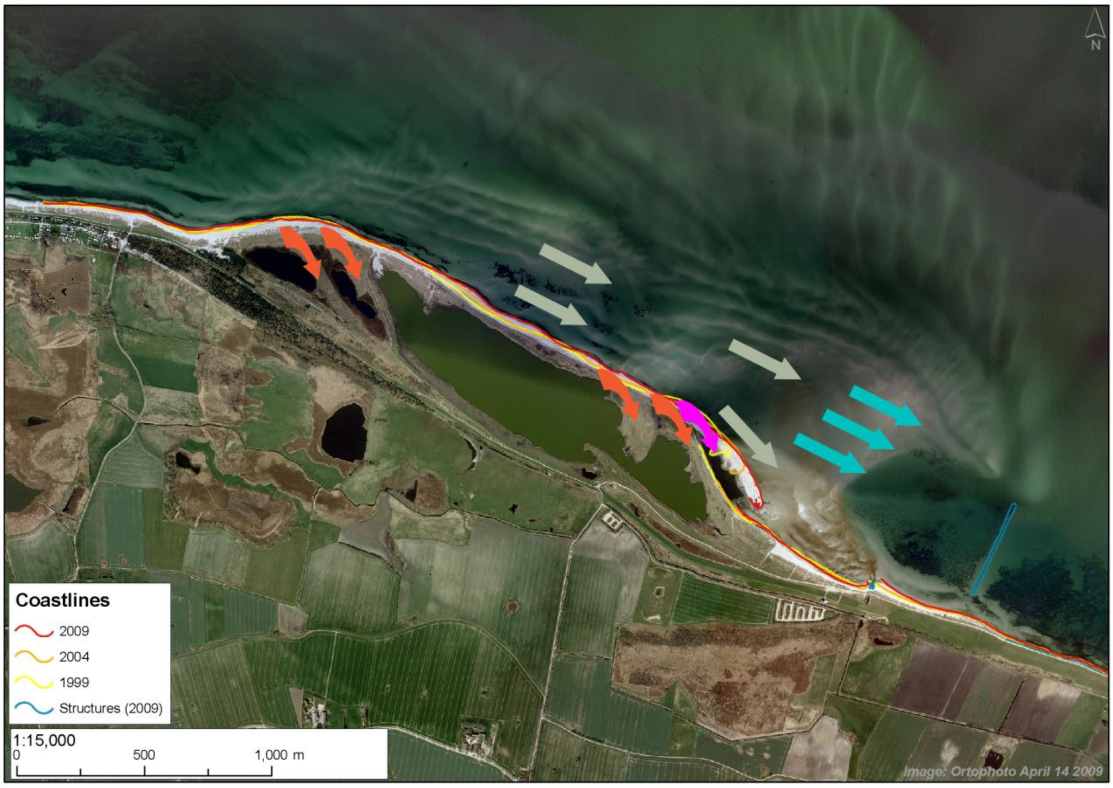


Figure 8.8 *Grüner Brink formation with coastlines from 1999, 2004 and 2009., see Section 4.3. Overall morphological development of Grüner Brink indicated with arrows: red arrows indicate remains of old spits. Green arrow indicates present day movement of the spit. Blue arrows indicate progression of the formation below the water level. Grey arrows indicate transport of sediment which deposits on the steep slope or offshore front. Aerial photo from 2009 (©COWI Orthophoto April 2009)*

Figure 8.9 *Grüner Brink. Upper left: western end of GB where it departs from the original shoreline. Upper right: overwash fan at the north facing part of GB. Lower left: mid part of GB, coastal lagoon, dunes and backshore. Lower right: Mid part of GB, sandy beach with gravel and seabed berms*

Figure 8.10 *Brüner Brink, eastern part. Upper left: root of sand spit towards NW. Upper right: along the sand spit, towards SE. Lower left: overwash fan at NW end of sand spit. Lower right: coastal lagoon behind sand spit with seaweed accumulations*

Figure 8.11 *Dike landwards of Grüner Brink and the coastal lagoon. Left: the dike. Right: the coastal lagoon of Grüner Brink*

8.1.3 *Grüner Brink to Puttgarden*

This section of the coastline is characterised by a lack of supply of sand. The lack of loose sediments at the section is caused by the transport conditions around Grüner Brink described above: the sediment transported along the shoreface of Grüner Brink deposits either at the spit or deposits at the steep offshore front of Grüner Brink. The consequence of these conditions is that no sand is bypassed to the shoreface and beach further towards east. Furthermore, there is hardly any wave exposure along the section immediately east of the spit and the shallow shoreface as these formations shelter for the waves.

The stretch between Grüner Brink and Puttgarden has the following main coastal elements:

Sandy beach at Grüner Brink

There is a sandy beach from the eastern end of Grüner Brink and about 1 km towards east, see photos in Figure 8.12. The beach is a public beach with parking facilities and a restaurant available behind the dike. The backshore is artificially cleaned for vegetation, see left photo in Figure 8.12 and aerial photo in Figure 8.2.

Long groyne

A 350 m long groyne 1.4 m west of Puttgarden was constructed in 1960 at the same time as Puttgarden. The groyne is detached from the shoreline with a gap between the groyne and the shoreline of about 90 m.

The groyne was built to prevent sedimentation in the navigation channel. However, the trapping of the sediment at the termination slope of Grüner Brink causes a very sparse supply of sediments to the area between Grüner Brink and Puttgarden. This is the reason why no sand has accumulated at the west side of the long groyne.

The migration of the offshore front of Grüner Brink causes sediment to by-pass the end of the long groyne. The by-passing has started within the last approximately 10 years and as Grüner Brink migrates further east, more sediment will deposit in the area around the long groyne. The sedimentation will be experienced as an increase in the sea bed level in the area. With time (several decades) the long groyne will be covered with sand.

There is a salient in the shoreline landward of the long detached groyne, see photos in Figure 8.13, indicating a local westward net transport east of the groyne. The beach consists mainly of shingle at this location.

Drainage outlet

There is a drainage outlet in the middle of this section from the Blankenwisch wetland, which is protected by two 30 m long rubble mound jetties, see photos in Figure 8.14.

Sand has accumulated east of the drainage structures indicating a local westward littoral transport in the area east of the outlet structure, see photos in Figure 8.15.

Shingle beach west of Puttgarden

There is only a very narrow shingle beach along the dike between the salient at the long groyne and Puttgarden; the dike is protected by a revetment along this stretch, see photos in Figure 8.16. No natural development of the shoreline has taken place along this stretch the last 100 years. A caravan site is located behind the dike approximately 0.5 km west of Puttgarden.

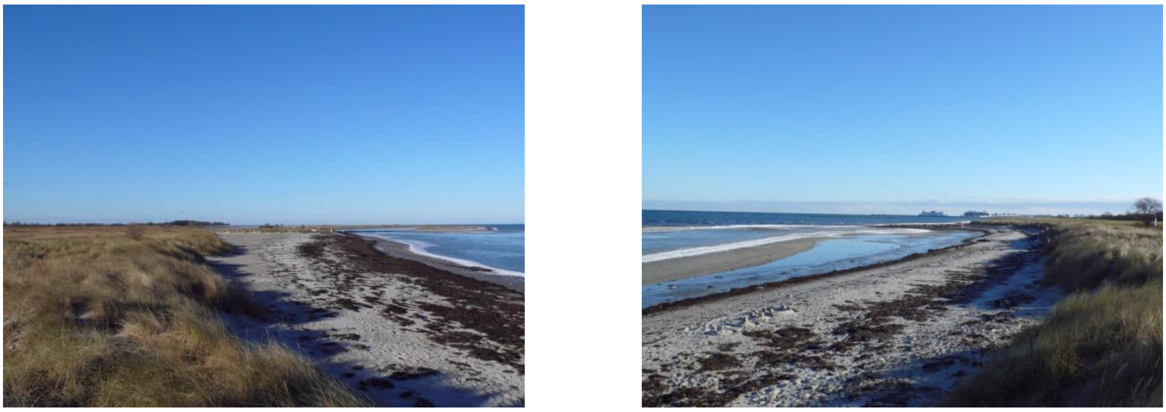


Figure 8.12 *Beach east of Grüner Brink. Left: towards NE, sand spit of GB in the background. Right: towards ESE, outlet structure in the background*

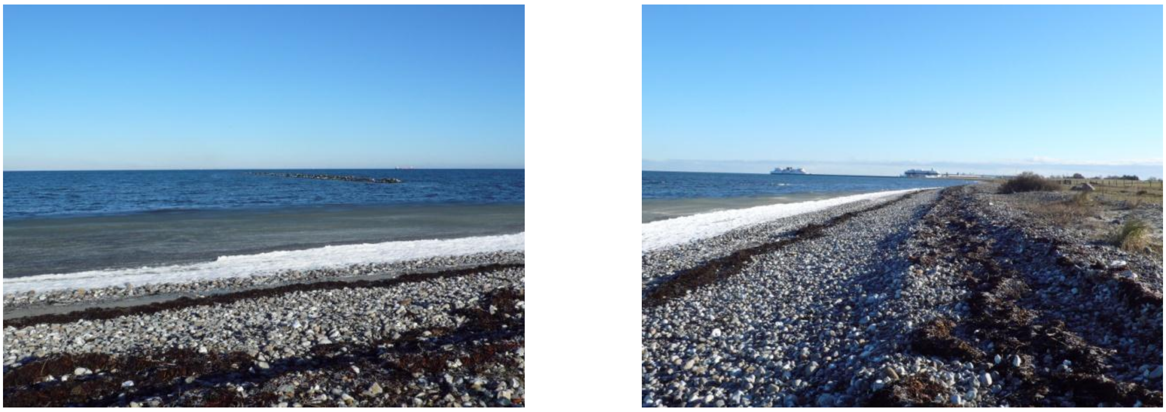


Figure 8.13 *Shingle beach landward of the long groyne. Left: shingle beach at salient, groyne in the background. Right: eastern part of the salient, shingle beach*

Figure 8.14 *Drain outlet for the Blankwish wetland. Left: outlet protected by rubble mound jetties. Right: channel from pumping station leading to outlet*

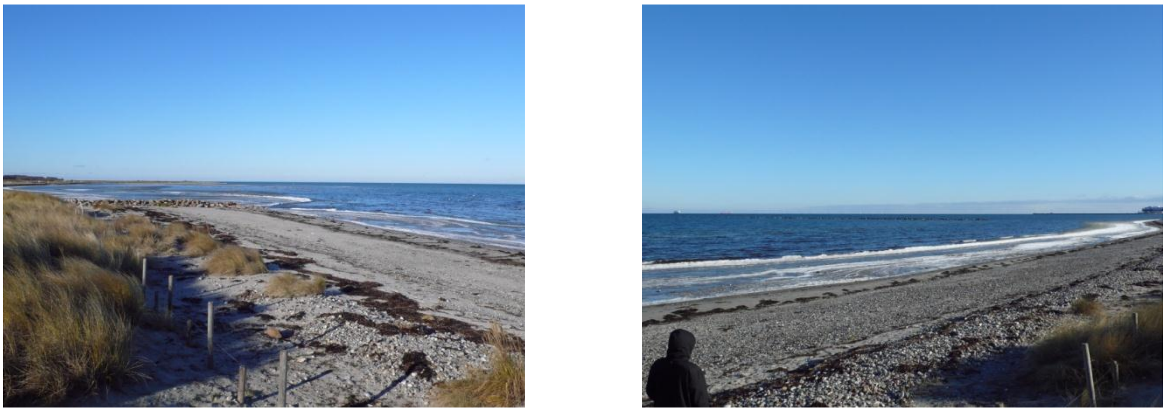


Figure 8.15 Beach east of outlet for the Blankenwish wetland, sandy beach with shingle berms. Left: beach east of the outlet supported by the outlet structure. Right: view towards E, the long detached groyne is seen in the background

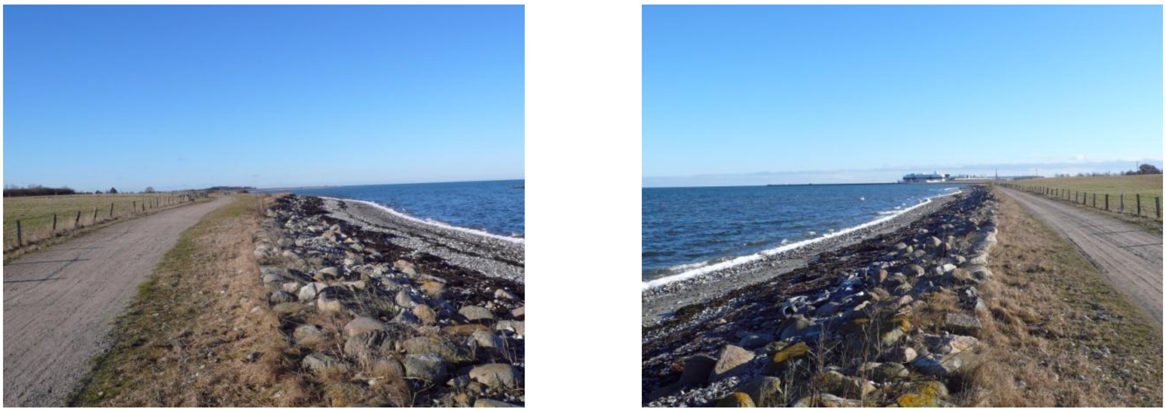


Figure 8.16 Revetment starting about 100 m east of the long groyne. Left: towards west, revetment and shingle beach, long groyne is seen in the background. Right: towards east, revetment and very narrow shingle beach in front of the dike

8.1.4 Puttgarden

Puttgarden (Figure 8.17) was constructed in 1962-63, and at the same time a long groyne (approximately 350 m) detached from the shoreline was built about 1.4 km west of the harbour as described above.

The harbour extends to about 520 m from the shoreline. The navigation channel leading to the harbour has a depth of 8.5 m. The width of the navigation channel was increased in 1997 to allow for half-hour departures requiring the ferries to pass each other close to the harbour, see further information in (COWI-Lahmeyer 1998).

There is no sedimentation in the navigation channel.

It is also noted that there is hardly any sand accumulation west of Puttgarden (Figure 8.2), which indicates that there is limited supply of sediment to this area.

A small sand accumulation is located SE of the east breakwater of Puttgarden, in the corner between the breakwater and the coastline. The very small sand accumulation indicates that the supply of sand to the area is very small since sand has accumulated over a period of about 50 years. Photos from the accumulated beach are presented in Figure 8.20.

Figure 8.17 Puttgarden (©COWI Orthophoto April 2009)

Figure 8.18 Sand accumulation SE of Puttgarden

8.1.5 East of Puttgarden – from Puttgarden to Klausdorf

The coastline between Puttgarden and the area off Klausdorf is presented in the following. For an overview of the stretch, see Figure 8.3.

The coastline between Puttgarden and StaberHuk (the south-eastern promontory of Fehmarn) is in general characterised by low cliff formations. A low grass-covered dike, however, protects the low lying land in the area off the village Presen from just south of Marienleuchte to the cliff east of Klausdorf.

The main coastal elements at this section of the coast are described below.

Small groynes and a sea wall at Ohlenborgs Huk and Marienleuchte

The village of Marienleuchte is located about 700 m SE of Puttgarden immediately south of the headland Ohlenborgs Huk, which is an about 5 m high till formation. The northern part of the town is occupied by the naval coastal station Marienleuchte ("Marineküstenstation Marienleuchte") with a lighthouse, see Figure 8.19.

There are three small groynes immediately north of Marienleuchte. Accumulation of sediment occurs at the southeastern side of these small groynes indicating a net transport of sand towards northwest in this area (Figure 8.20). The accumulated material in the groynes is mainly shingle.

The naval coastal station Marienleuchte is protected by a massive vertical seawall fronted by a stone glacis/revetment and there are remains of some groynes near the southern end of the seawall, see photos in Figure 8.21.

Aerial photos indicate also submerged groynes protecting cables in this area (Figure 8.3).

The village of Marienleuchte has a cliff towards the sea which is only partially protected by a revetment, see photo in Figure 8.22.

Dike off the village Presen
Immediately south of Marineleuchte, the level of the hinterland falls. A low grass covered dike protects the low-lying land in the area of the village of Presen from just south of the village of Marienleuchte to the cliff east of Klausdorf. There is a pumping station off Presen. The beach in front of the dike is sandy with some gravel, see photos in Figure 8.23.

Drainage outlet at Presen
The drainage outlet in the northern part of Presen is protected by rubble mound jetties, which act as groynes, see left photo in Figure 8.24. There is sand accumulation south of the southern jetty, see right photo in Figure 8.24, and erosion north of the northern jetty. The erosion area is protected by an asphalt revetment, see Figure 8.23.

Low cliffs and shingle beach off Klausdorf
The dike terminates towards south where it meets the high till formation off Klausdorf. The shoreline along the Klausdorf coast is an open till cliff in front of which is a shingle beach with boulders, see photos in Figure 8.25.

The cliff and shingle/boulder type of beach continues further SSE-ward. There is a caravan site, Klausdorf Strand Camping site, 2 km further down the coast at a local headland. The access road to the beach at this location is protected by a revetment and some groynes; there is also a small boat ramp, see photos in Figure 8.26.

Figure 8.19 New Lighthouse at Marienleuchte. The old lighthouse is seen (partly behind the cliff) to the right in the photo.

Figure 8.20 Stretch between Puttgarden and Marienleuchte. Shingle accumulation at groyne located NW of Marineleuchte

Figure 8.21 Seawall at naval coastal station Marienleuchte. Left: Southern part of seawall at naval coastal station with remains of groynes. Right: vertical seawall fronted by glacis

Figure 8.22 Cliff off Marienleuchte village, seawall at naval coastal station seen in the background. Shingle beach and a low revetment

Figure 8.23 Dike between Marienleuchte and the till cliff off Klausdorf, protecting the low lying land around Presen. Upper left: northern end of dike immediately south of Marienleuchte. Upper right: southern part of dike north of pumping station off Presen. Lower left: asphalt revetment of dike north of drainage outlet at Presen, sandy/shingle beach off the dike. Lower right: dike from pumping station towards SSE, drainage canal along dike

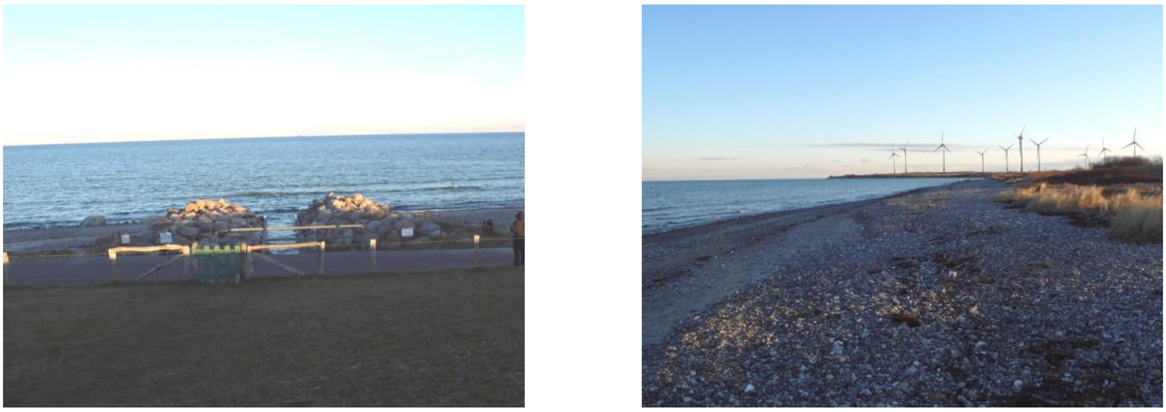


Figure 8.24 Drainage outlet at pumping station in northern part of Presen. Left: rubble mound inlet jetties. Right: beach north of the outlet, sand and shingle

Figure 8.25 Coast off Klausdorf. Left: transition from dike to cliff. Right: till cliff, shingle beach with boulders, Klingen Wind farm in the hinterland

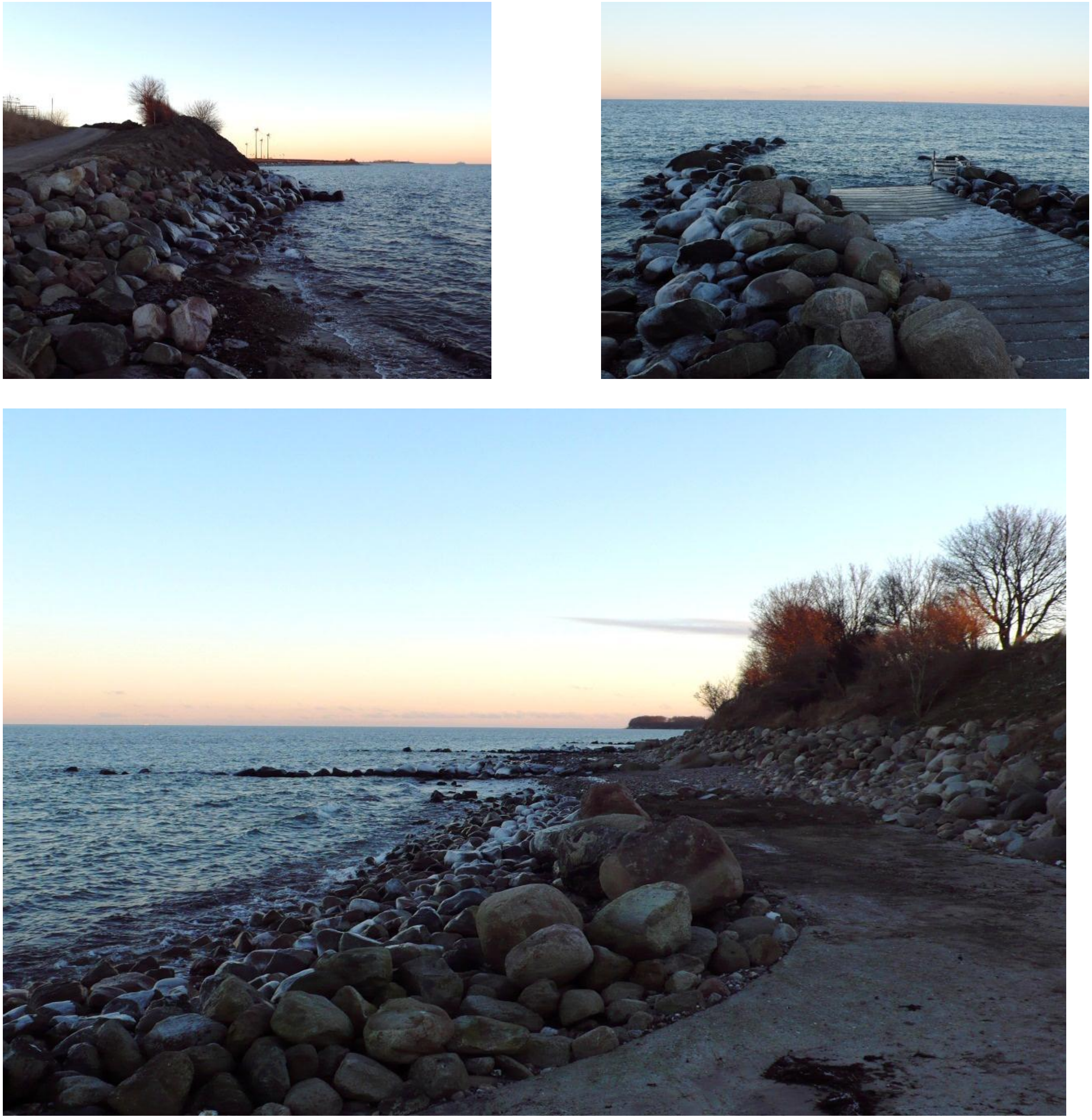


Figure 8.26 *At Klausdorf Strand Camping Site. Upper left: headland protected by revetment. Upper right: boat ramp between two groynes. Lower: revetment and groynes towards SSE, shingle/boulder beach*

8.1.6 Recreational areas

The north coast

The entire stretch between Markelsdorfer Huk and Puttgarden is dominated by the dike, which is equipped with a gravel road open for public walking and biking. This means that the stretches with dike can be considered as recreational areas.

The coastal hinterland along the north coast of Fehmarn is generally low. Some of it is protected by the dike but most of the protected low-lying areas is maintained as coastal wetlands and only minor areas are reclaimed by pumping. Along the remaining sections the dike is built behind the low lying coastal wetlands, such as at Markelsdorfer Huk and at Grüner Brink. These meadow and coastal lake areas are valuable wetlands with a lot of birds. Many of the relatively higher areas are developed with camping sites. The entire north coast of Fehmarn is consequently a very popular recreational area with the following caravan sites:

- Camping Fehmarnbelt at Markelsdorfer Huk
- Camping "Am Belt"
- Camping "Am Deich"
- Camping "Am Niobe"
- Johannisberg (1 km inland from Grüner Brink)
- Campingplatz Puttgarden

There are also some parking areas along the north coast.

The east coast
The low lying area off Presen is protected by a dike and the hinterland is reclaimed by pumping and developed as farmland. The dike is equipped with an asphalt road open for public walking and biking. This stretch is not of the same recreational value as the north coast; it is mainly used by the local population for promenading and the shingle beach is used for angling. The sand accumulation SE of Puttgarden is not characterised as a recreational beach as there is no easy public access.

The stretch off the naval coastal station at Marienleuchte is heavily protected by a seawall and a glacis and this stretch is not easily accessible.

There is a camping site at Klausdorfer Strand, which is located about 4.5 km SSE of Puttgarden.

8.2 Historical shorelines and coastal structures

Information on the historical development of the north coast of Fehmarn has been collected from the literature and historical maps.

8.2.1 Historical shorelines

Fehmarn has low-lying areas originally prone to coastal flooding. Flood-prone lowlands in Schleswig-Holstein including Fehmarn are shown in Figure 8.27. Low-lying areas prone to flooding from the sea are seen to cover large parts of the coastal areas except for the southeastern part of the island.

Dike construction and reclamations
For the coastal areas of Fehmarn, the single most important storm was an extreme event, which hit the Baltic Sea on 12-14 November 1872. The event caused extreme storm surges in the eastern Baltic Sea, including the Fehmarnbelt area. With a level of up to 3.3 m above mean sea level, this event was almost 1 m higher than all previous and following surges and initiated the planning of flood defence at the Prussian Government (Hofstede 2008).

Dikes were constructed along the western, northern and northeastern coastlines of Fehmarn following the storm in 1872 to protect the low-lying hinterland from further flooding. Along the north coast, a continuous dike was built from Markeldorfer Huk to Puttgarden. Along the northeast coast the dike was built from south of Ohlensborg Huk and further towards the southeast, see Figure 8.1.

Large portions of the western Fehmarn were at that time low-lying unprotected meadow, which was flooded during the 1872-storm, see also the coastal flood-prone lowlands on Fehmarn shown in Figure 8.27. Areas such as the Nördliche Binnensee east of Markelsdorfer Huk and Blankenwisch east of Grüner Brink, are presently partly dried out lakes and wetland areas behind the dike, see Figure 8.2. Prior to the construction of the dike, the old maps from 1852 and 1858, see Figure 8.28 and Figure 8.29, indicate they were active morphological elements in the coastal landscape.

The construction of the dikes at Fehmarn resulted therefore in a great loss of coastal lagoons and lowlands. The north- and west coast of Fehmarn were before the construction of the dike after the 1872-storm dominated by sand spits, barrier islands and shallow coastal lagoons, see historical maps of Fehmarn from 1852 and 1858 in Figure 8.28 and Figure 8.29. It is noted that the dike alignment is landwards of the Grüner Brink formation and Markelsdorfer Huk. Presently, these are the only remaining areas of this type of coast along the north coast of Fehmarn. An aerial photo of Fehmarn today is shown in Figure 8.30.

Based on the historical maps from 1852 and 1858, the northeast coast of Fehmarn east of Puttgarden seemed to have changed much less than the landscape west of Puttgarden. The map of flood prone areas (Figure 8.27) indicates a relatively large area of lowland around Presen inshore of the dike. This area was probably a wetland area prior to construction of the dike and has been reclaimed.

8.2.2 Grüner Brink

The historical shoreline evolution of Grüner Brink between 1874 and 1995 is presented in Figure 8.31. During that period, clearly two new spits have formed. One has grown in length and attached to the 'main' shoreline and a new short spit is seen in the 1995 shoreline. Remains of 'old' spits can still be identified from aerial photos of the area of the coastal lagoon/lake, see Figure 8.8.

It is not possible to evaluate the migration rates of the spits from these shorelines, but the total length of the formation – measured from the western location near Gammendorfer Strand where the Grüner Brink starts and to the location where the shoreline again meets the 'main land' – has increased by about 200-300 m between 1874 and 1979. In average, the eastern front of the shoreline moved east by about 2-3 m/year in that period.

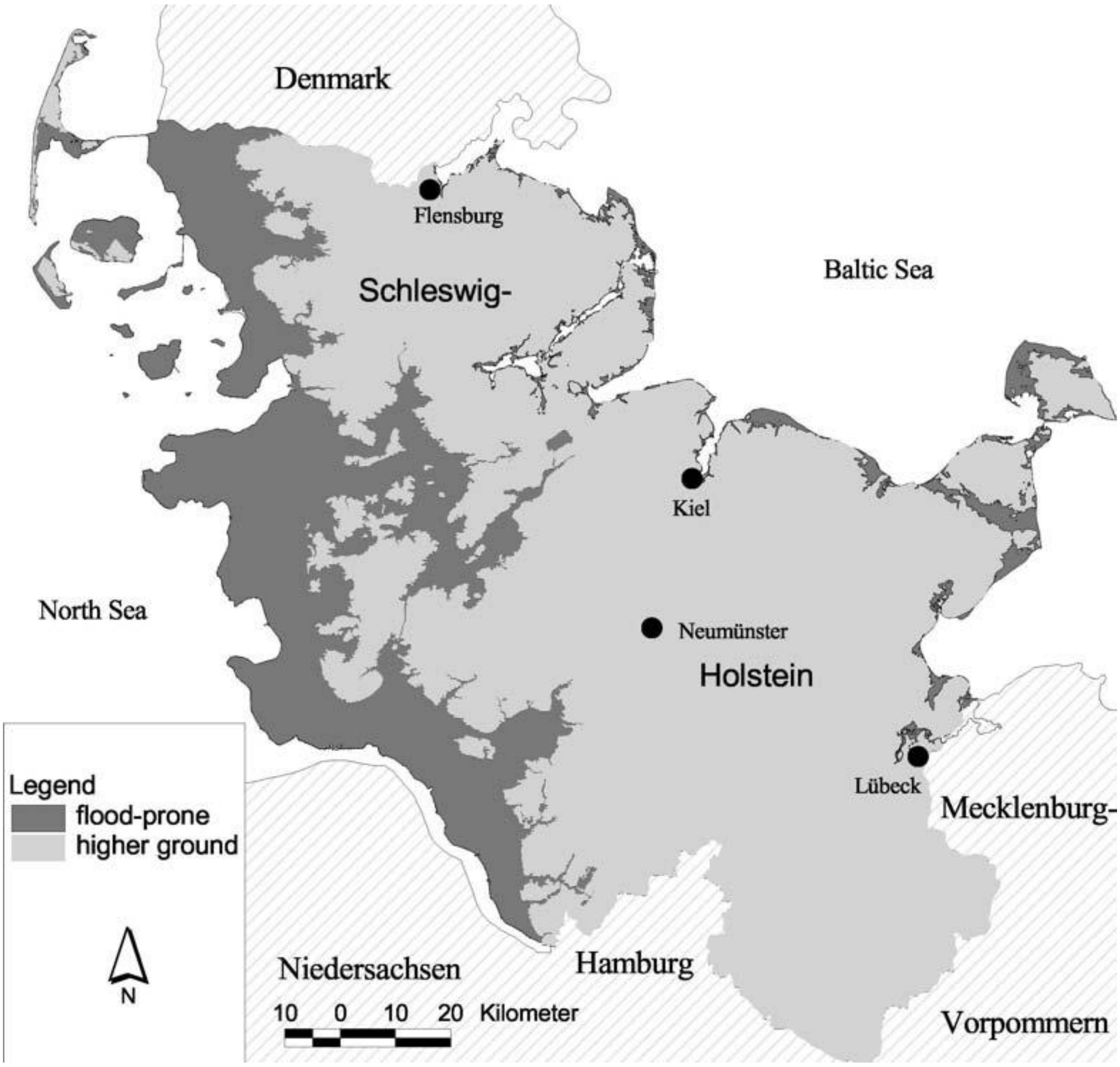


Figure 8.27 Present coastal flood-prone lowlands (dark shading) in Schleswig-Holstein including Fehmarn, from (Hofstede 2004)

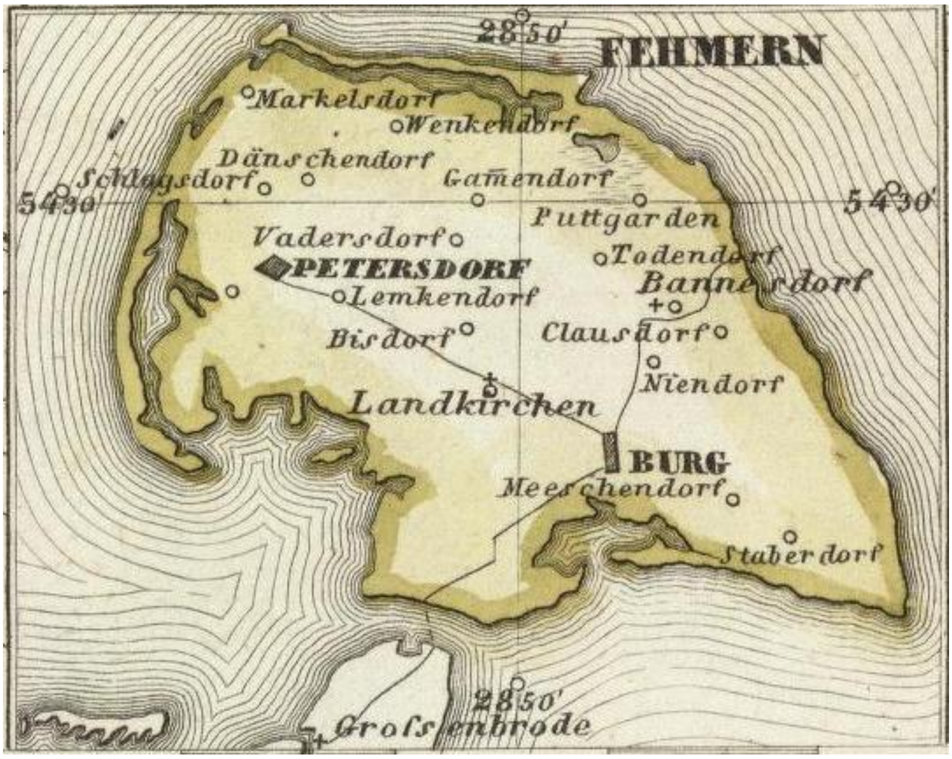


Figure 8.28 Historical Map of Fehmarn. Meyer's Handatlas 1852, No 138, Herzogthum Schleswig. From: http://rumsey.geogarage.com/maps/g4807080.html

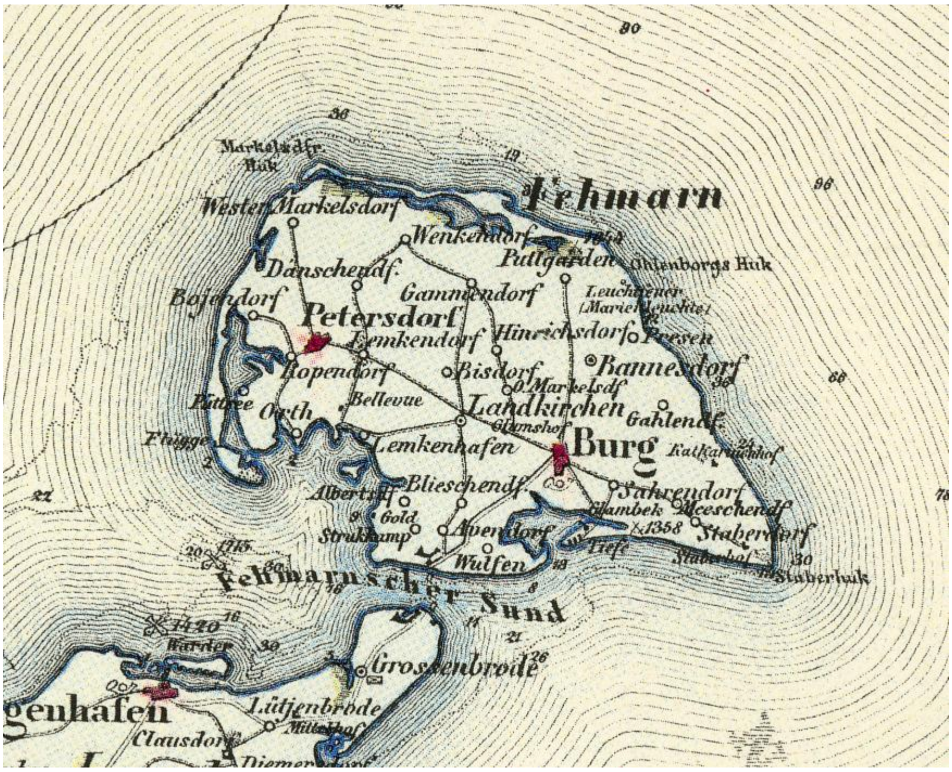


Figure 8.29 Section of historical map showing Fehmarn from 1858. General-Karte von den Hertogthü-mern Schleswig, Holstein und Lauenburg. © GeoBasis-DE/LVermGeo SH (www.LVermGeoSH.schleswig-holstein.de, Landesvermessungsamt Schleswig-Holstein)

Figure 8.30 Aerial photo of Fehmarn today (DDO® 2008, © COWI). Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen.

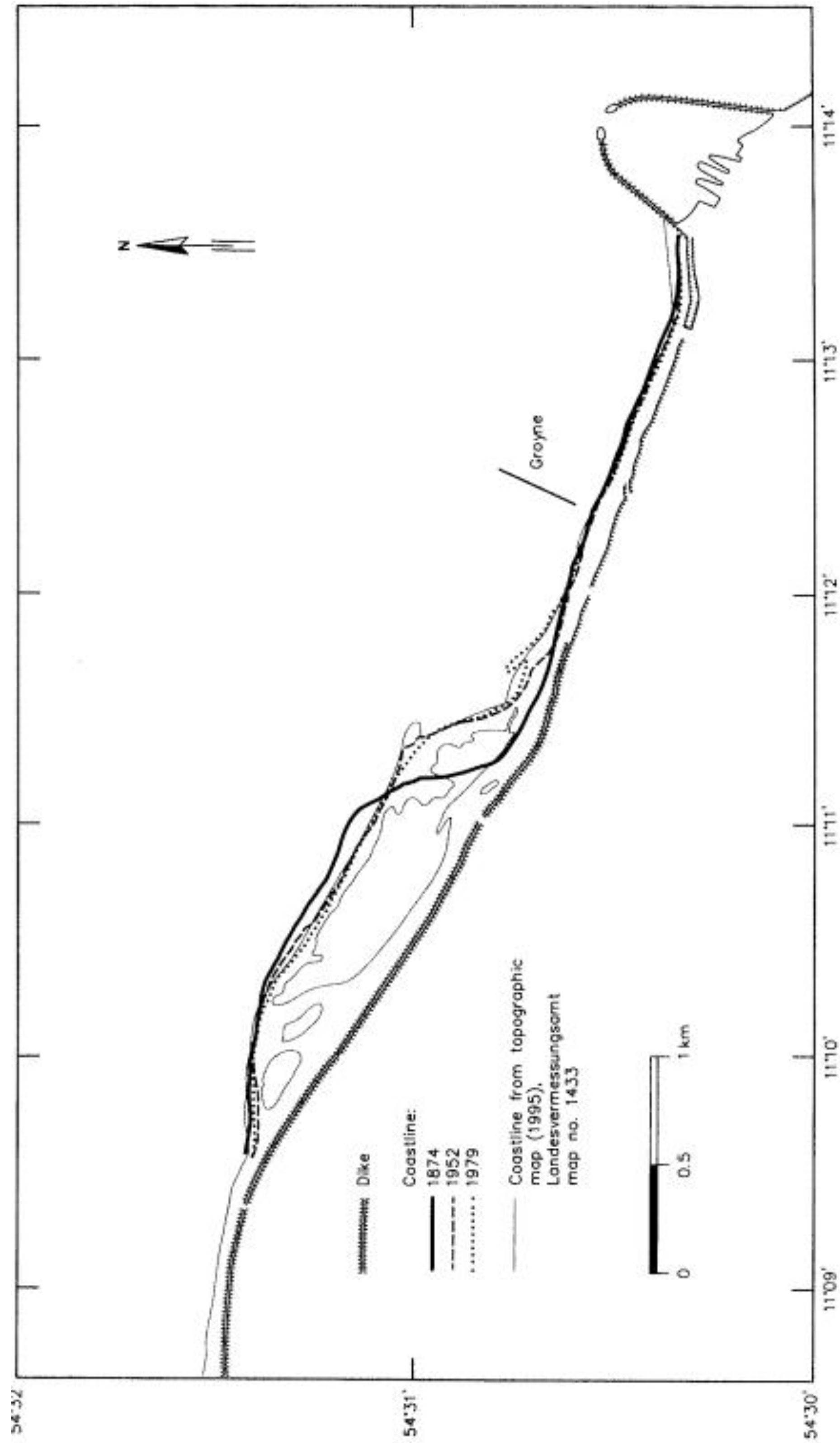


Figure 8.31 Shoreline evolution west of Puttgarden. From (Fehmarnbelt Environmental Consultants 1996)

8.3 Recent shoreline changes

The recent shoreline development between Grüner Brink in the west and Presen in the east is presented below. The shoreline development is primarily analysed based on aerial photos from 1999, 2004 and 2009. Zooms of sections along the entire stretch between Grüner Brink and Presen showing the variation in the shoreline location in the three years in details can be found in Appendix E.

8.3.1 Grüner Brink

The development of the Grüner Brink formation between 1999 and 2009 is seen in Figure 8.32 and Figure 8.33. The spit at the eastern part of the formation has increased about 200 m in length over the period 1999 to 2009, i.e. a growth rate of 20 m/year (Figure 8.32). The deposited volume of littoral drift to provide this migration of the spit is estimated to be about 6,000 m^3. The width and height of the spit are estimated to about 60 and 0.5 m, respectively, see Table 8.1.

The shorelines along the north-northwest and north-northeast facing shorelines of Grüner Brink are very stable; however, these shorelines are exposed to some moving sand features, but with no long-term trend (Appendix E, E-1 and E-2).

Aerial photos from 1999, 2004 and 2009 (Figure 8.33) indicate that the submerged front moves forward by about 100 m in 10 years. The deposited volume of sea bed material (sand) at the front is estimated to about 150,000 m^3. The submerged front is estimated to migrate with a width about 750 m and the height of the front is (from bathymetric information) estimated to 2 m (see Table 8.2).

Table 8.1 Accumulation of sand at sand spit of Grüner Brink

Parameter	1999-2009
Migration rate of spit (m/year)	200
Height of spit (m)	0.5
Width of spit (m)	60
Total accumulated volume (m^3/year)	600

Table 8.2 Accumulation of sand at submerged front of Grüner Brink

Parameter	1999-2009
Migration rate of the submerged front (m)	100
Height of submerged front (m)	2
Width of submerged front (m)	750
Total accumulated volume (m^3/year)	15,000

8.3.2 West of Puttgarden

Very little sand accumulation occurs along the beaches between Grüner Brink and Puttgarden between 1999 and 2009(Appendix E, pages E-4 and E-5).

Along the long groyne, there is hardly any sand accumulation and only a slight salient on the shoreline as seen in Figure 8.36, which does not seem to have changed much in the periods 1999-2004 and 2004-2009.

A local sand accumulation east of the structures protecting the water outlet from Blankenwisch is seen (Figure 8.34). The local accumulation is estimated by assuming the following: the shoreline has moved by about 25 m at the outlet decreasing to 0 m 350 m further east. The accumulation is assumed to take place across the active part the coastal profile assumed to be about 2.5 m height. The total accumulated volume is hence estimated to about 11,000 m^3 in ten years between 1999 and 2009, or about 1,100 m^3/year. The annual net westward transport at this location may have been larger, since the accumulation extend to the end of the protection structures and by-pass have most likely taken place around the structures.

Table 8.3 Accumulation of sand at water outlet from Blankenwisch

Parameter	1999-2009
Length of accumulation (m)	350
Height of active coastal profile (m)	2.5
Average shoreline movement (m)	12.5
Total accumulated volume (m^3)	11,000

8.3.3 Puttgarden

There is no sandy beach along the coast immediately west of Puttgarden. There is only a minor accumulation of sand at the seabed in front of the dike in the corner between the coastline and the west breakwater, see the detail of the aerial photo from 2009 in Figure 8.35. The sand accumulation reaches only a short distance along the breakwater, which indicates that there is no transport of sand along the breakwater to the entrance area of the harbour. The lack of sedimentation confirms that there is no or very limited supply of sand to the area between Grüner Brink and Puttgarden, see discussion in Section 8.1.2 and Section 0.

A small sand accumulation has taken place between 1999 and 2004 in the transition between the east breakwater and the adjacent coast towards south, see Figure 8.35. The shoreline along this sand accumulation has been stable since 1999. An active sand transport zone can be seen along this sand accumulation and half way along the breakwater; however, the transport zone does not reach the tip of the breakwater.

The small volume of accumulation indicates a small net transport of loose sediments from the southeast coast.

The observations from aerial photos indicating that only very minor amounts of sand can be seen at the seabed west as well as east of the breakwaters fit well with the information that there is no sedimentation in the entrance to the harbour. It has been informed from Scanlines that there has never been any maintenance dredging in the entrance nor in the basin. It is not known if this only covers recent times (the last 10 years) or the period since 1963 when the harbour was built.

8.3.4 East of Puttgarden

Very small changes in the shoreline position in the two five-year periods 1999-2004 and 2004-2009 can be identified in the section between Marienleuchte and Presen (). The largest shoreline changes are in the order of ~5 m and are hence in the order of the estimated accuracy (within about 2 m) of the positions of the shorelines, see details in Appendix E, pages E-6 to E-9.

Slight accretion is seen between 2004 and 2009 for a section of the coast of about 500-600 m centred around the termination of the dike southeast of Presen. Erosion – also minor – is on the other hand seen in the same period from the coast southeast of Presen towards the campsite southeast of Klausdorf.

Figure 8.32 Development of the spit of Grüner Brink 1999-2009. Aerial photo from 2009 (©COWI Orthophoto April 2009)

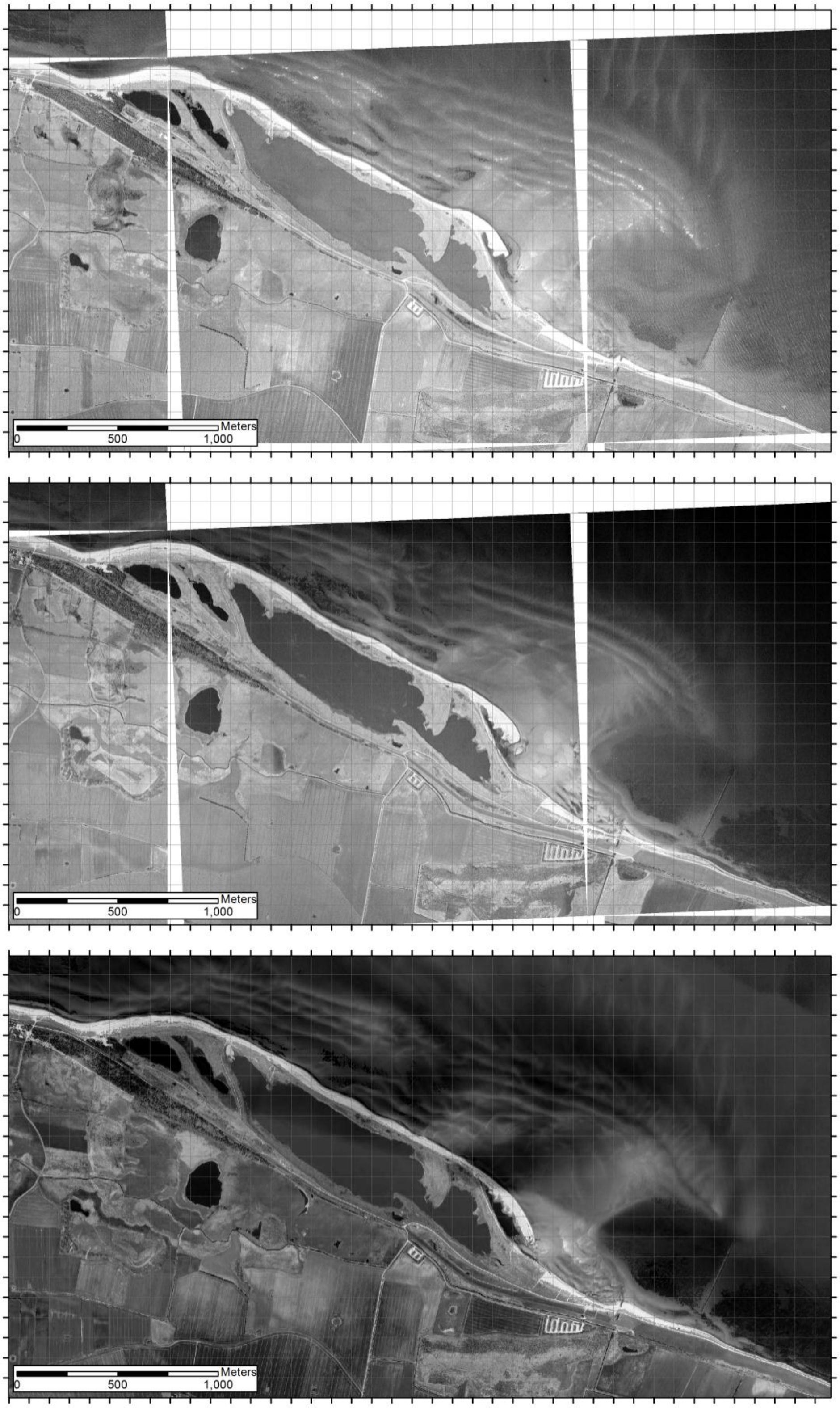


Figure 8.33 *Aerial photos 1999 (upper), 2004 (middle) and 2009 (lower) of the Grüner Brink area. 1999 and 2004: ©GeoBasis-DE/LVermA-SH (www.lverma.schleswig-holstein.de). 2009: ©COWI Orthophoto April 2009*

Figure 8.34 Recent shoreline evolution at the drainage outlet structure between Grüner Brink and the long detached groyne. Shorelines 1999, 2004 and 2009. Based on analysis of aerial photos, see Section 4.3. Aerial photo from 2009 (©COWI Orthophoto April 2009)

Figure 8.35 *Recent shoreline evolution near Puttgarden. Shorelines 1999, 2004 and 2009. Based on analysis of aerial photos, see Section 4.3. Aerial photo from 2009 (©COWI Orthophoto April 2009)*

8.4 Coastal profiles

Analysis of the profiles and changes identified to the profiles between the 1998 and the 2009 surveys are described below.

Near Fehmarn Harbour, where the coastal profiles are measured with only 25 m interval, a bathymetric model has been interpolated from the 2009 profiles, see Figure 8.36, in which also the names of the profiles are shown. Depths from the location of the 1998 profiles have been extracted from this interpolated bathymetry for comparison with the 1998 profiles.

Outside the areas of the densely measured 2009-profiles, measured profiles are compared directly, where 1998 and 2009 coastal profiles are measured at the same location.

Selected profiles are shown below but all profiles can be found in Appendix F.

8.4.1 West of Puttgarden

The coastal profiles west of Puttgarden reflect the variation in the area: the morphological active and complicated area at Grüner Brink represented by profiles

PW08-PW06; and the less morphological active area west of the harbour represented by profiles PW04-PW01.

Coastal profile PW08 is located in the middle of Grüner Brink. The profiles are nearly identical near mean water level (i.e. near the shoreline) for the two surveys from 1998 and 2009. Further offshore, between water depths of 1 to 3 m, the profiles show large variations between the two surveys, and also further offshore (at water depths greater than about 3 m) in the area dominated by sand waves. These variations show that the morphology is active in this area. It is seen that the active shoreface has a width of about 500 m at this location and that it stretches out to a depth of about 2.5 to 3 m. The slope of the shoreface is very gentle; in the order of 1:200. High morphological activity on the shoreface is indicated by moving bars and some accretion between 1998 and 2009, however, no shoreline movements. The type of bed forms changes in nature beyond the width of the shoreface. Off Grüner Brink sand waves can be distinguished. This indicates a change in the transport regime from wave-generated transport on the shoreface to current-dominated transport in the zone of sand waves. Sand waves are discussed in great detail in (FEHY 2013a).

Coastal profile PW06 is located immediately downstream of the Grüner Brink formation. This is also a very morphological active and very complicated area which is confirmed by the variations between the profiles for the two years, which show some variations out to a water depth of about 4.0 m, beyond which depth the profiles are nearly coinciding. No long term trends can be interpreted from this single profile.

Profile PW03 is characteristic for the coastal profiles in the area immediately west of Puttgarden. The profiles drop quickly to a water depth of about 2 m. Between water depths of 2 to 7 m, the profiles are gentle, but offshore the 7 m contour the water depth increases quickly in all four profiles. The two sets of profiles from 1998 and 2009 show no signs of significant morphological activity. The two sets of profiles are nearly identical.

8.4.2 East of Puttgarden

The coastal profiles east of Puttgarden are represented by profiles PE03, PE07 and PE12 shown in Figure 8.38. East of the harbour the profiles have a moderate steepness, but the remaining profiles are all characterised by being very steep for water depths less than about 4 m.

The coastal profiles PE03 represent the stretch between Puttgarden and Marienleuchte. The profiles are relatively steep down to 4-6 m depth. At greater water depths, the slopes become more gentle. There are signs of accretion from 1998 to 2009 along the deeper parts of the profile; however, this is assumed to relate to survey inaccuracy. There are no signs of shoreline accretion which fits well with the shoreline evolution analysis, see Section 8.3.

Profile PE07 characterises the coastal profiles at the east-southeast of the headland Ohlenborg Huk at Marienleuchte. PE07 has a steep shoreface to a water depth of about 5 m, from which depth the profiles have a transition into a nearly horizontal shoal of a width of about 800 m. There are no significant changes from 1998 to 2009 in these profiles.

Profile PE11 is characteristic for the profiles further to the southeast. They have a steep shoreface down to about 4 m. Further offshore, the slope becomes much more gentle. There are no significant changes from 1998 to 2009.

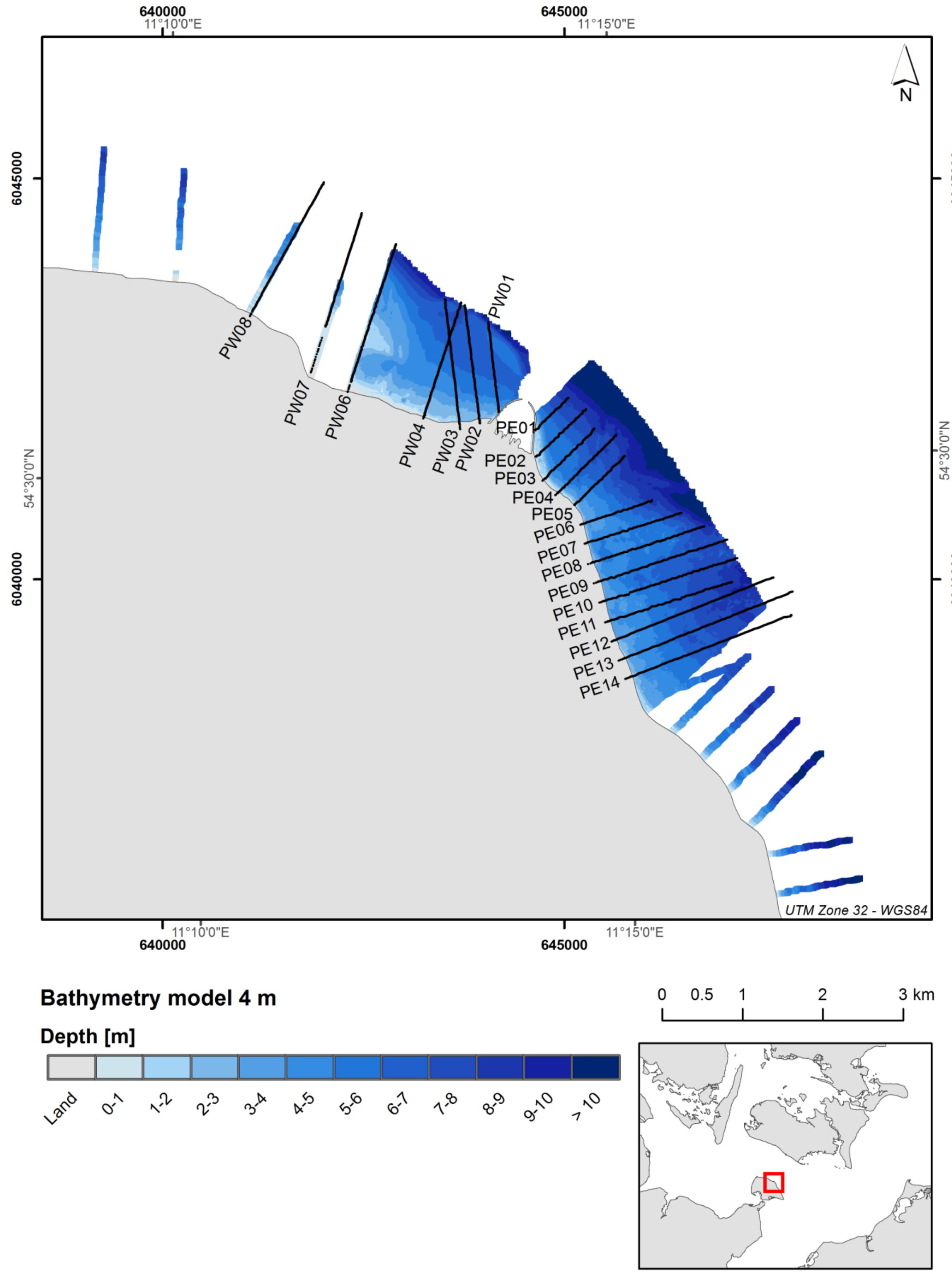


Figure 8.36 Bathymetric map for the Fehmarn coastal area from the 2009 survey with locations of 1998 profiles indicated as black lines

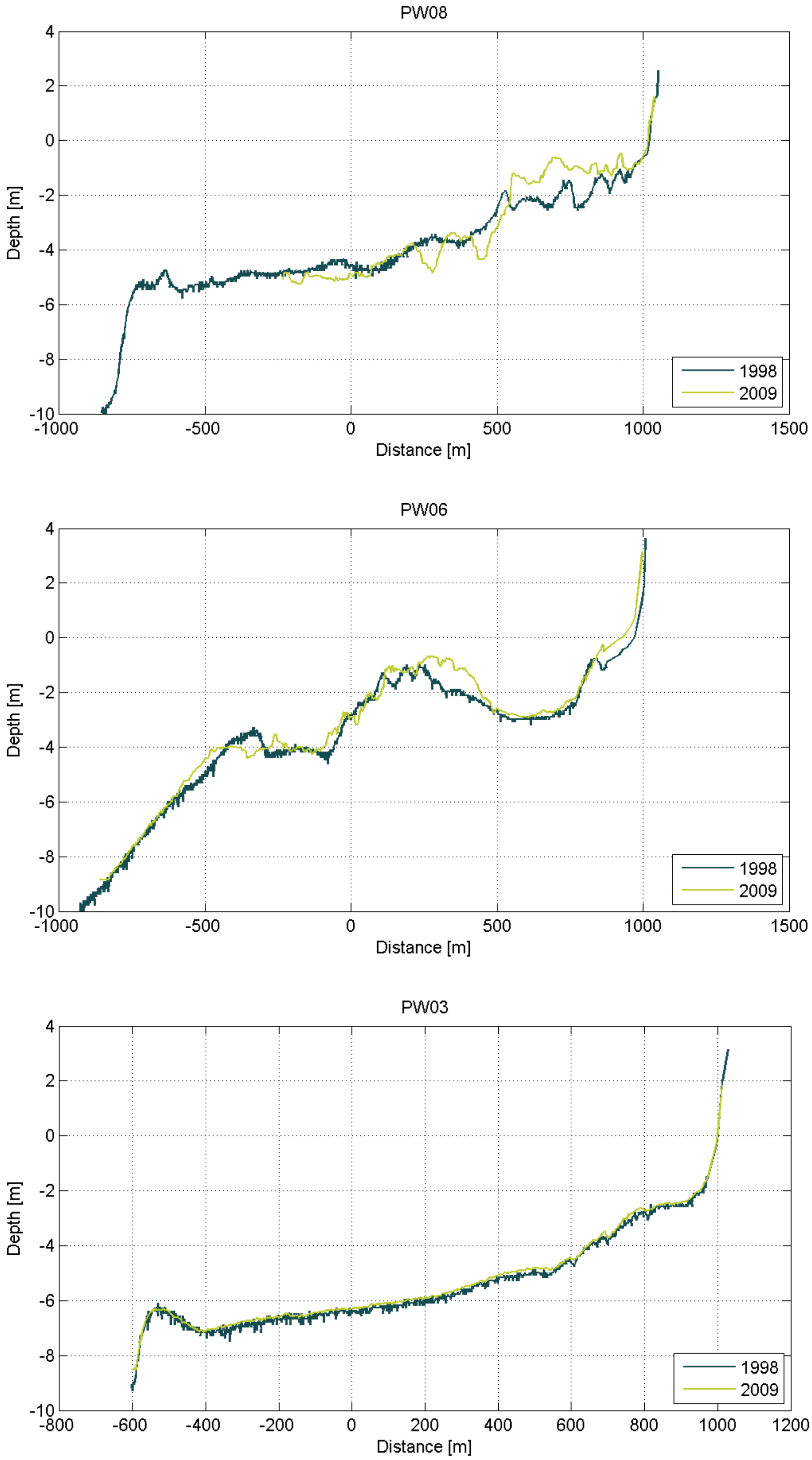


Figure 8.37 Coastal profiles PW08, PW06 and PW03 west of Puttgarden, 1998 and 2009. Depths relative to DVR90

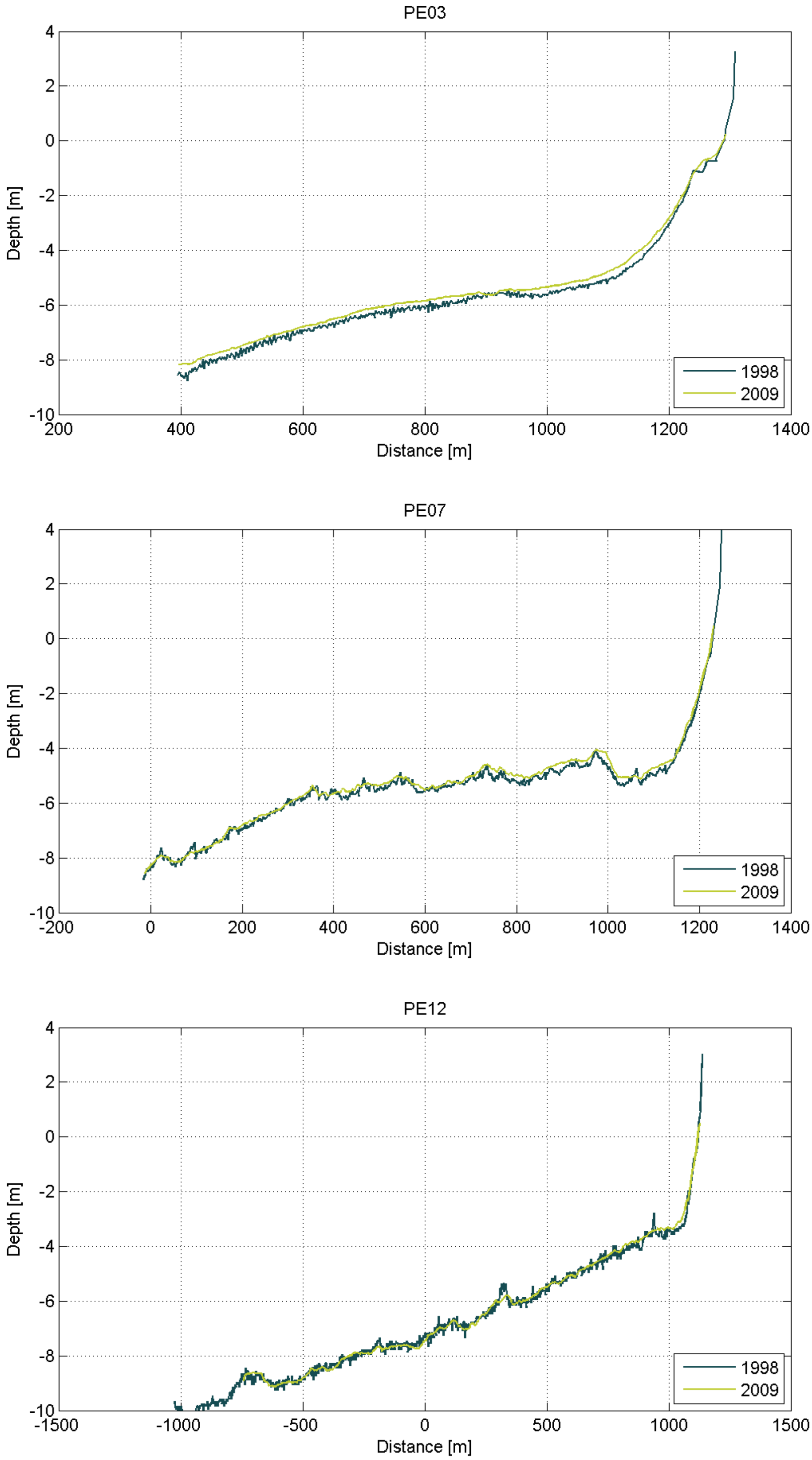


Figure 8.38 Coastal profiles PE03, PE07 and PE12 east of Puttgarden, 1998 and 2009. Depths relative to DVR90

8.5 Sea bed near the coast

The conditions and the grain size distribution of the surface sea bed material in Fehmarnbelt are described by analysed grab samples. A large number of grab samples were collected in 2009 in the entire Fehmarnbelt area and some grab samples were collected in 1998 along some of the measured profiles described above. Diver observations of sand and vegetation-cover, aerial photos and substrate mapping are also included in the interpretation of the sea bed conditions along the coast; see further information on the data material in Section 4.6.

A narrow band of mobile sand is present along the coastline between the long groyne (west of Puttgarden) and Puttgarden, and also along the coast southeast of the harbour. Coarser sea bed material or hard bed is found at water depths larger than about 3-4 m. In the area of Grüner Brink, a larger availability of mobile sand was found. Mobile sediment in the nearshore zone is in general finer than along the Lolland coast.

Appendix G includes detailed figures with information on the sea bed conditions along the section from Grüner Brink to the coastline off Presen.

Figure 8.39 shows the median grain size, d_{50}, in grab samples collected along the north coast of Fehmarn.

The samples collected in the area around Grüner Brink indicate a sea bed of fine to medium sand extending to water depths greater than 5 m. Samples with coarser sand iare collected at the shoreline. Fine sand is found east of the 'offshore front' of Grüner Brink (refer to Section 8.1.2), and also inshore of this front.

Between the long groyne and Puttgarden, the grab samples indicate fine to medium sand near the shoreline. Further away from the shoreline, the samples show a large variation. At some sample locations, sampling was not found possible due to hard bottom indicating scarcity in fine material; these locations are marked with black markers in Figure 8.39. At other locations, fine or medium sand is found. Aerial photos of the area (Figure 8.40) indicate a narrow band of loose sediments below the 1 m depth contour and a sea bed partly covered with vegetation at water depths between approximately 1 and 4 m. Vegetation on the sea bed indicates that hard substrate such as larger stones are present on the sea bed. In areas with a high coverage of vegetation, the sea bed can therefore be assumed to be relatively hard and contain little mobile sediment. A lighter colour in the aerial photo near the shoreline indicates finer sea bed material and little vegetation. Diver observations of the percentage of sea bed covered by vegetation (macroalgaes) are included in the figure.

Immediately east of Puttgarden, grab samples with very fine and medium sand indicates a local accumulation area (Figure 8.39). Further towards southeast, the sediment samples indicate medium to very coarse sand in a narrow band along the coast. Coastal profiles are steep here and below the 2-3 m depth contour (~100 m from the coastline), the samples indicate coarse sea bed material or hard bed. At many test locations, sampling were unsuccessful as shown with the black markers in Figure 8.39.

The substrate map created by FEMA (FEMA 2013a), see also Figure 6.5, shows the same picture, see example in Figure 8.41. A narrow band along the coast has been interpreted as sand, while coarser sediments are seen at greater water depths. Diver observations of the percentage of sand coverage are also presented in the figure.

In general, the sediment along the north coast of Fehmarn is graded with a geometric standard deviation ($\sigma = \sqrt{d_{84}/d_{16}}$) of 1.4 or higher. The sediment in the area of Grüner Brink and in the accumulation zone east of Puttgarden is somewhat more homogeneous. No differences in the grain size distribution can be identified between samples from 1998 and 2009.

Figures similar to Figure 8.40 (aerial photo including grain sizes and diver estimates of vegetation cover) and Figure 8.41 (substrate map including grain sizes and diver estimates of sand coverage) can be found in Appendix G for the north coast of Fehmarn between Grüner Brink to Presen.

The general picture of the sea bed conditions is consistent with the geological conditions (Section 5) at the coast of Fehmarn and the understanding of the transport conditions around Grüner Brink. The sea bed consists of moraine till and areas of marine sand. A thin layer of reworked glacial sediments (lag sediment) on top of the till bed is characteristic along most of the section, a so-called residual seabed. This layer, about 0.10 m thick, consists mainly of gravel and coarser material as seen in the above analysis. The nearshore band of finer material origins from transported material along the coast. Sediment transported along the Grüner Brink deposits at the eastern end of the formation and is not supplying sediment to the shoreline west of Puttgarden.

An overview of the sediment conditions in the nearshore zone along the north coast of Fehmarn coast is presented in Table 8.4.

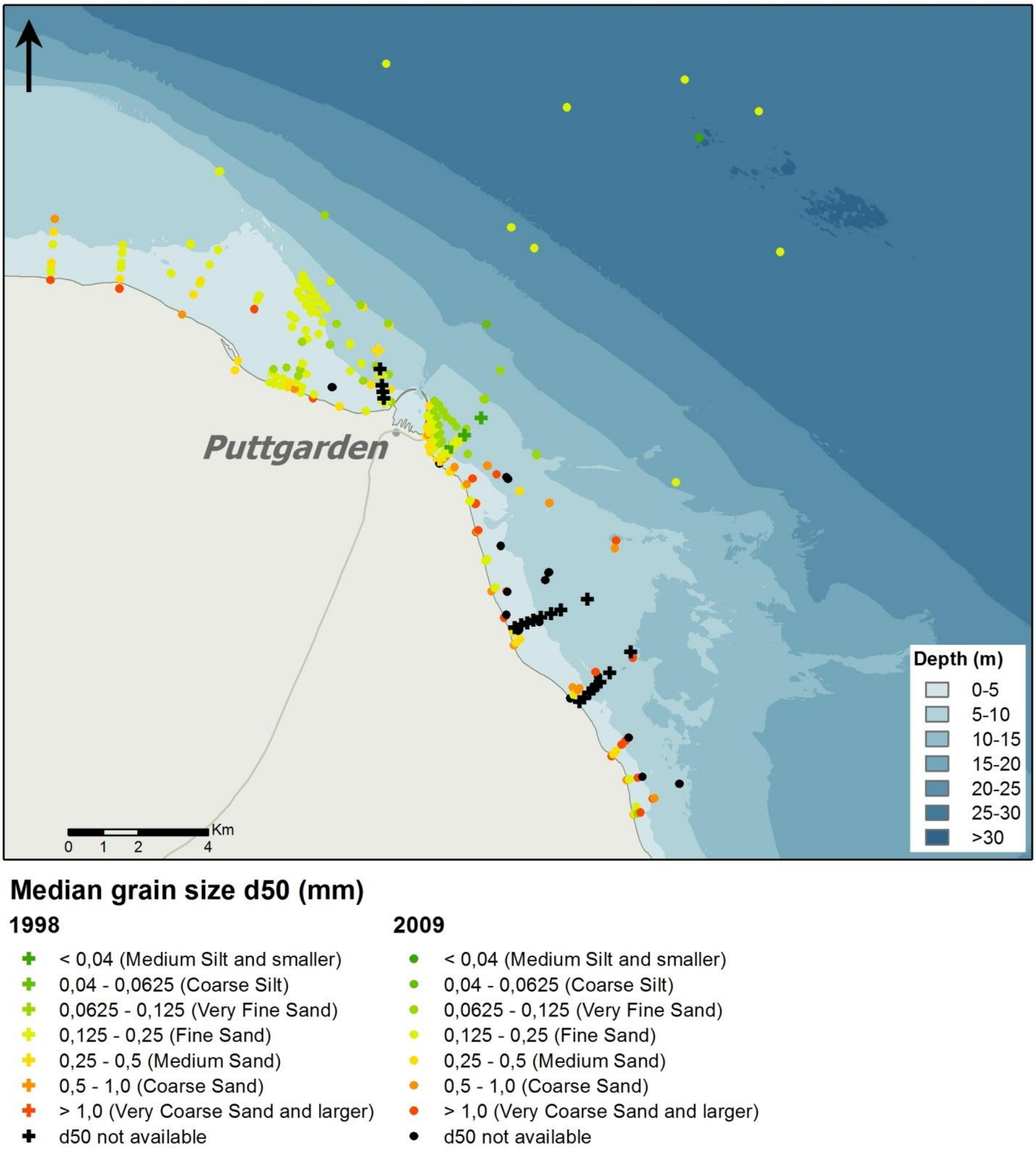


Figure 8.39 Median grain size in grab samples collected along the north coast of Fehmarn

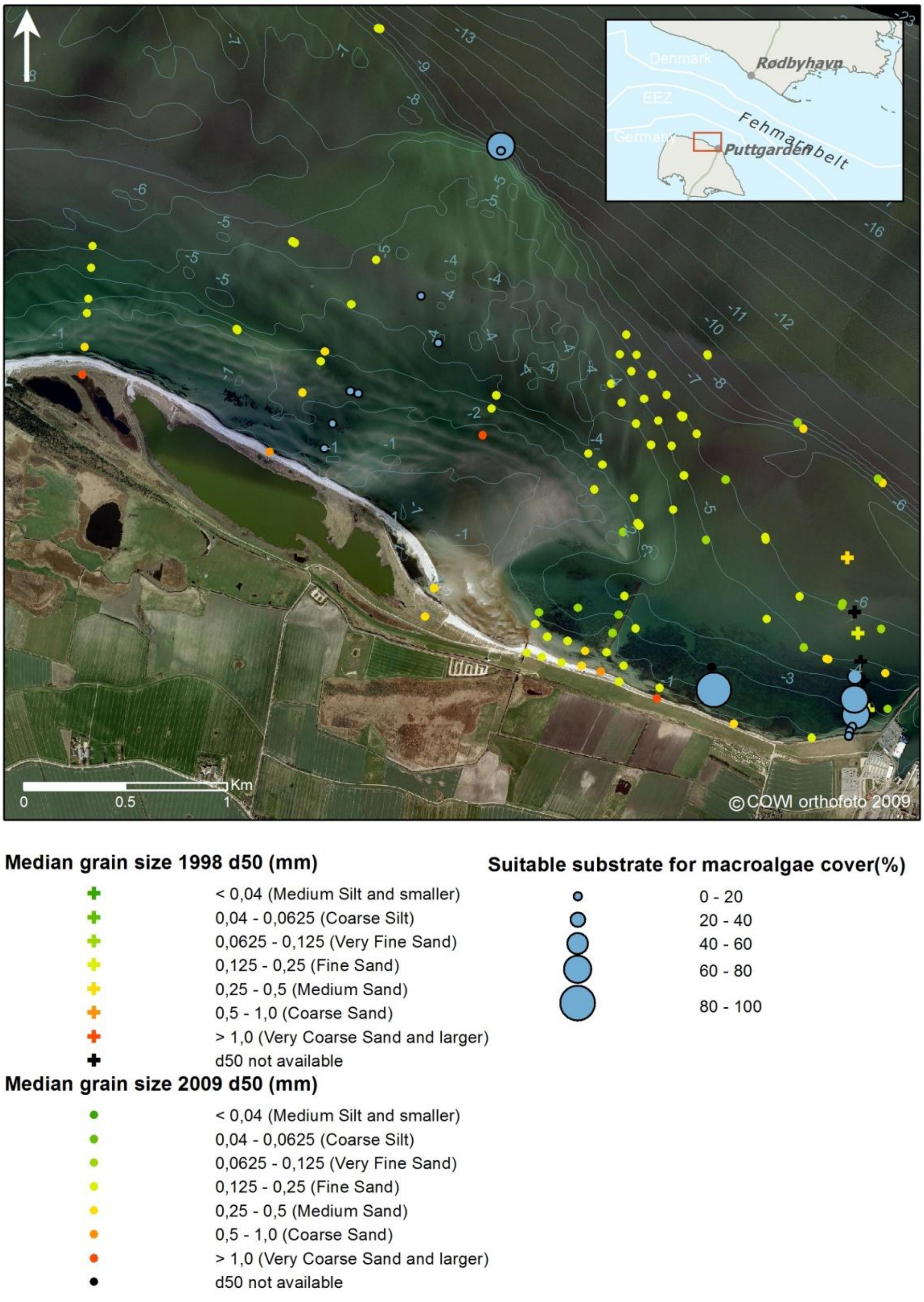


Figure 8.40 *Aerial photo of the nearshore zone near Grüner Brink. Median grain size from grab samples and diver observations of vegetation coverage. Aerial photo from 2009 (©COWI Orthophoto April 2009)*

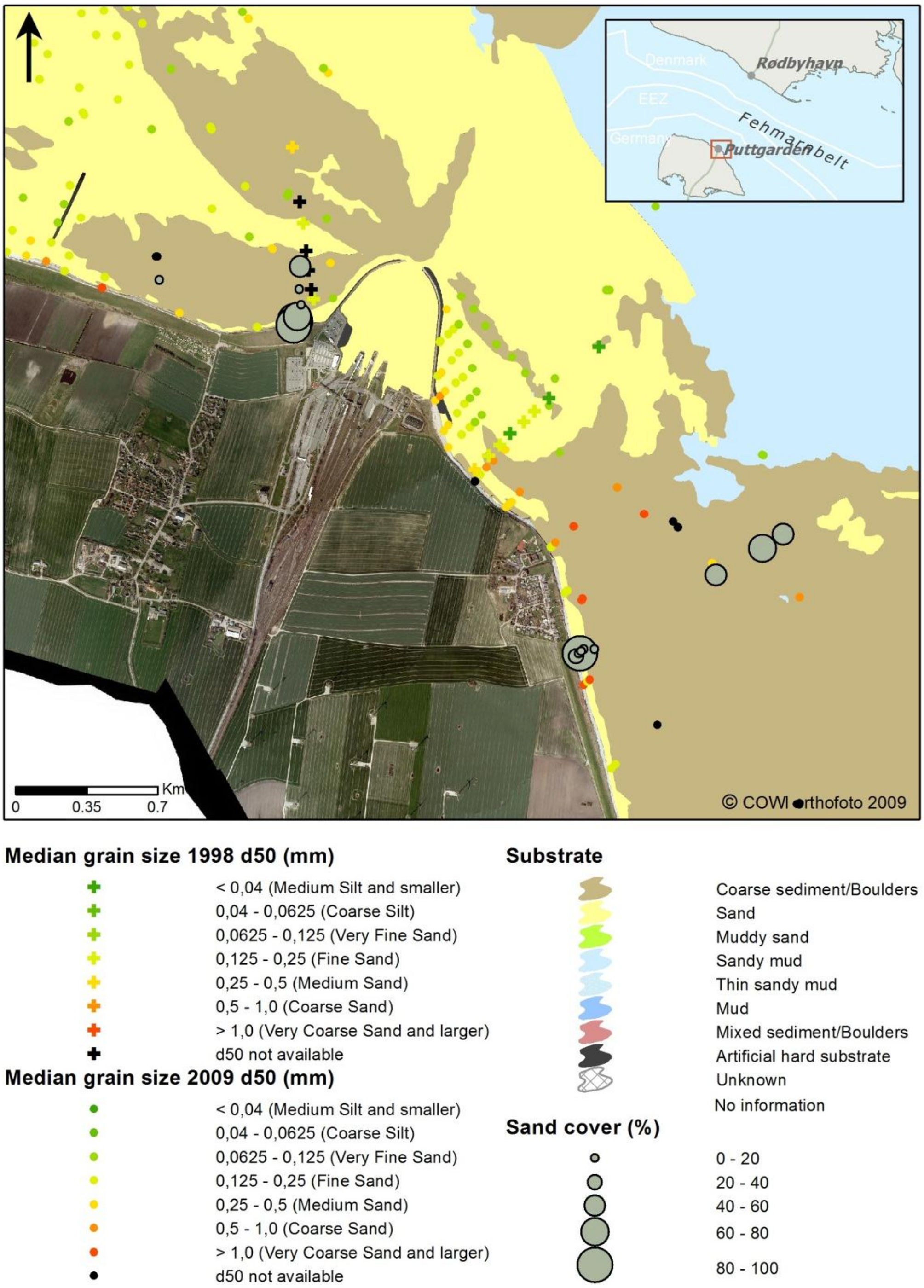


Figure 8.41 Substrate map for the nearshore zone near Puttgarden. Median grain size from grab samples and diver observations of the percentage of sand coverage at test locations. Aerial photo from 2009 (©COWI Orthophoto April 2009)

Table 8.4 *Overview of sediment in the nearshore zone at water depths less than about 3-4 m at the coast of Lolland*

West of Puttgarden		East of Puttgarden
Fine and medium sand around Grüner Brink, coarse sand on the shoreline, but very fine sand west of Grüner Brink. No changes from 1998 to 2009.	Puttgar-den Harbour	Very fine and medium sand immediately east of Puttgarden indicating local accumulation area, medium to very coarse sand further towards SE and seabed without movable sand (dominance of residual sediments). No changes 1998 to 2009

8.6 Nearshore Waves and Currents

The overall hydrodynamic conditions were described in the previous Section 5. The nearshore wave- and current conditions for the north- and east coast of Fehmarn are described below.

8.6.1 Establishment of wave conditions

Calculations of the time-varying wave conditions in the larger Fehmarnbelt area, including the entire Baltic Sea and the Danish Straits, have been carried out by numerical modelling. A refined numerical model has been established for the Fehmarnbelt area and has been used to simulate the 21-year period, 1. Jan. 1989 – 30. April 2010. In each calculation point, wave parameters such as wave height, wave direction and wave period, are calculated with hourly intervals. Distances between calculation points are typically small along the sections of coast (about 50-100 m), and increase further offshore and further away from the area of interest. Details of the wave modelling are given in (FEHY 2013b).

Comparison of modelled and measured wave conditions

The results from the wave calculations have (mainly) been calibrated and validated against measurements of wave conditions at two measuring stations in the central part of the Fehmarnbelt, MS01 and MS02. MS01 is located approximately 7 km south of Rødbyhavn at a water depth of -20 m DVR90. MS02 is located approximately 6 km north-northeast of Puttgarden at a water depth of -29 m DVR90. Both of the measuring stations were deployed in March 2009, see further information in Section 4.7. The period available for comparison of measurements and calculated wave conditions is March 2009 - April 2010.

The comparisons between modelled and observed wave conditions show some deviations between measured and modelled wave directions and heights.

Wave roses for measured waves are shown in Figure 7.41. The upper wave roses represent the measured wave conditions in the period March 2009 – April 2010 at the two measuring stations.

The magnitudes of the deviations were found to vary with the directions from which the waves approach the Fehmarnbelt area. The deviations in the modelled wave directions at the measuring stations, MS01 and MS02, are shown in Figure 7.42. The mean deviations for some directional sectors (of 10 degrees each) reach about 25 degrees, but for the main wave directions (W-WNW and SE at MS01, see Figure 7.41) the deviations are below 10-15 degrees. A similar picture is seen at MS02 closer to the German coast. The tendencies for the deviations to vary with the wave direction are the same, but slightly shifted in the directions. Figure 8.44 shows that although a clear variation with the wave directions is seen, a large scatter appears in the comparison between measured and modelled wave direction. The wave heights deviate also for some directions, Figure 8.45.

The deviations have their origin in the wind field applied as forcing for the wave generation mechanism in the wave modelling. The deviations seem to be related to the presence of 'upstream' land areas. A comparison of measured conditions against the applied wind forcing in the wave model shows similar tendencies at a wind measuring station just 25 km east of MS01 (Nysted). According to DMI (the provider of the wind data) the observed differences between modelled and measured wind directions may origin from uncertainties in the applied 'air-land' resistance parameters over land areas in the applied meteorological model. The resolution of the (many) land areas surrounding the Fehmarnbelt in the meteorological model or the modelled static stability over land areas as well as the coarse resolution of the wind fields of 10 km are also possible explanations.

The wave directions as well as the wave heights in the 21-year timeseries of wave conditions applied in the littoral drift calculations have been adjusted using the findings described above. The adjusted wave roses at the measuring points are seen in Figure 8.42.

It should be mentioned that the adjustments of the nearshore wave directions are smaller than at the offshore locations. The reason is the fact that waves turn when propagating towards shallower water if they approach the coast with an angle to the normal of the bed contours. Waves propagate fastest on deeper water and the wave direction will therefore tend to approach the normal to the beach orientation (defined as the normal to the depth contours at the beach). 'Errors' in the offshore wave directions will due to this mechanism reduce to somewhat smaller errors in the nearshore wave directions.

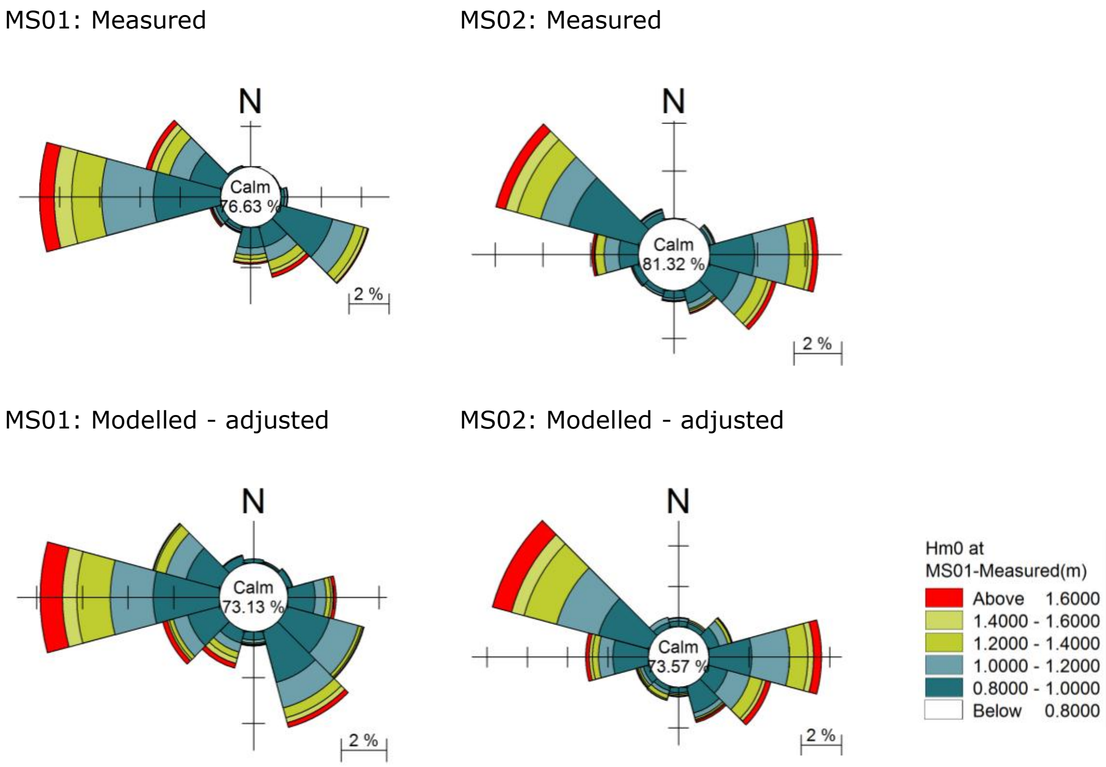


Figure 8.42 *Wave roses for wave heights>0.8m for the measured wave conditions (upper figure) and adjusted modelled wave conditions at measuring station MS01 (left, 7 March 2009 - 30 April 2010) and MS02 (right, 30 March 2009 - 30 April 2010). The locations of the measuring stations are shown in Figure 4.9*

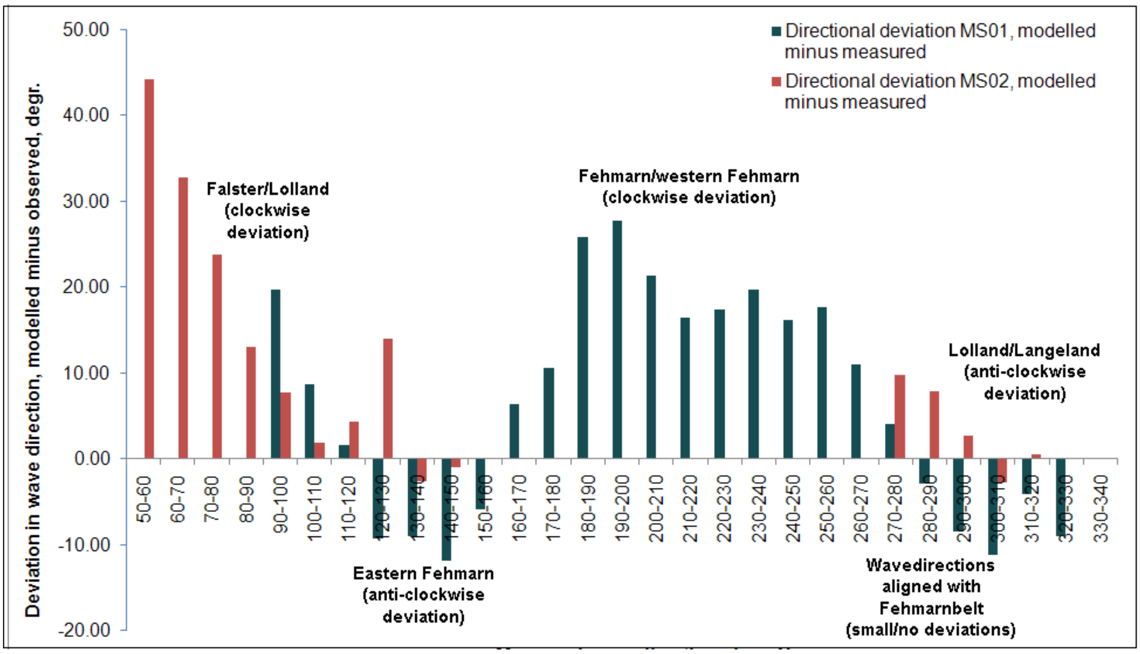


Figure 8.43 *Deviations between modelled and measured wave directions at measuring station MS01 and MS02. The analysis is made for measured wave heights >0.8 m at MS01 and >1 m at MS02*

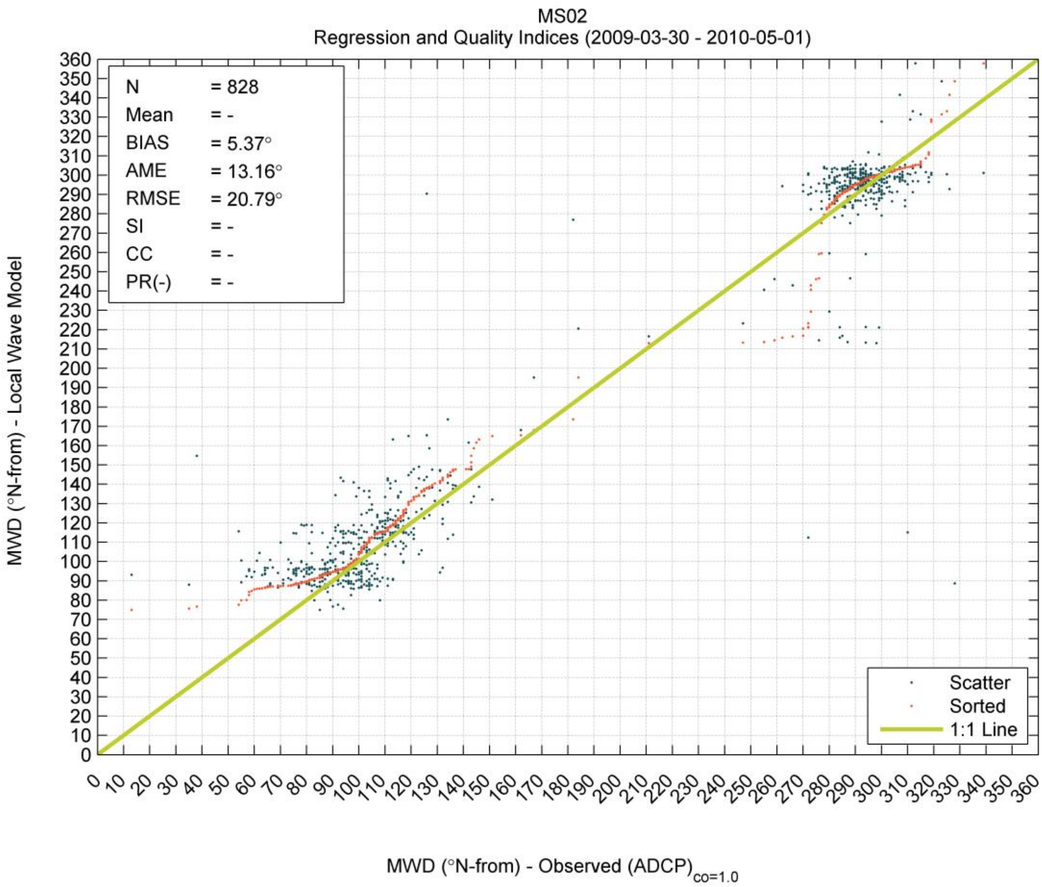
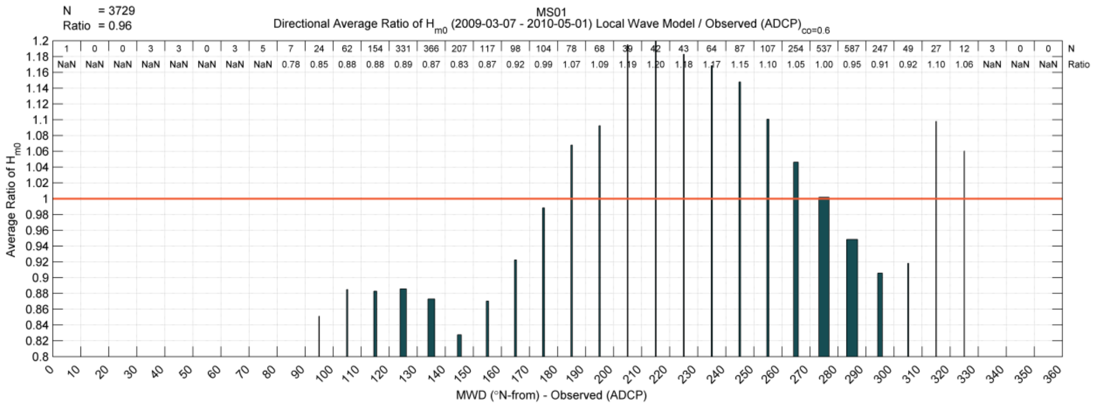


Figure 8.44 *Correlation between measured and modelled wave directions at MS02 nearest the Fehmarn coast (‘Scatter*; Simultaneous directions. ‘Sorted’: lowest direction modelled versus lowest direction measured, second lowest direction modelled versus second lowest direction measured etc.)*



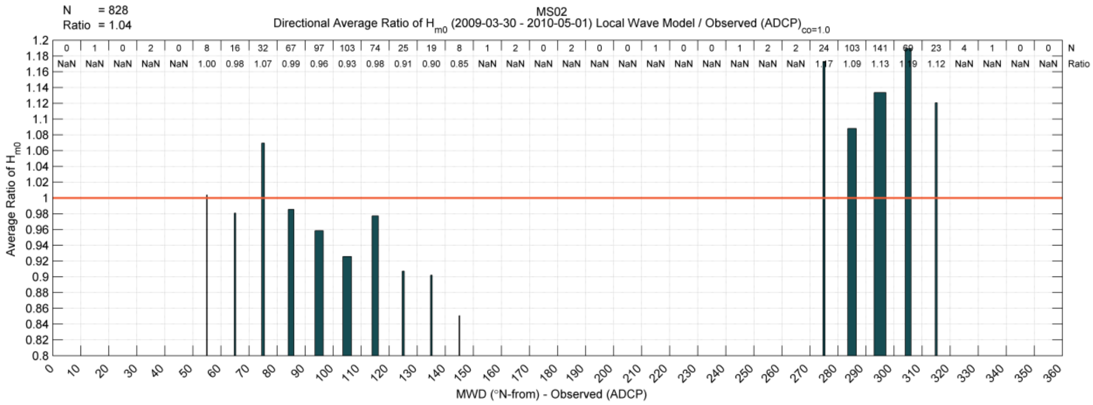


Figure 8.45 Deviations between modelled and measured wave heights at measuring station MS01 and MS02. The analysis is made for measured waves >0.8 m at MS01 and >1m at MS02

8.6.2 Nearshore wave conditions

Nearshore wave conditions have been established for about every 1 km along the north and east coasts of Fehmarn, in most cases at a water depth of 4 m. This extraction depth for the waves is selected to be just offshore of the active littoral zone to benefit from the modelled two-dimensional wave field in the one-dimensional calculations of the littoral drift (in LITDRIFT). At certain special locations, such as along the stretch located between Grüner Brink and Puttgardens, the wave roses have been extracted closer to the shoreline. This has been done in order to include the sheltering effect of the feature/structure in the local wave conditions. The locations of the extracted wave roses (yellow dots) as well as the wave roses are presented in Figure 8.46 and Figure 8.50.

It is seen that the waves east of and along Grüner Brink are divided in two distinct directional climates. The main waves are from NW, i.e. at a large angle with the orientation of the shoreline (the orientation is defined as the normal to the shoreline) and the secondary waves are from ENE. This very oblique wave approach of the predominant waves is responsible for the development of Grüner Brink. Typical wave patterns for the area west of Puttgarden are presented in Figure 8.47 and Figure 8.48 for waves from NW and SE, respectively. The corresponding bathymetry is presented in Figure 8.49.

Grüner Brink refracts the NW-erly waves and partly shelters for the waves along the shoreline immediately east of Grüner Brink. Refraction is the process by which the waves turn when the wave propagate with an oblique angle to the depth contours. The waves will turn towards the normal to the depth contours, when they propagate towards shallower depths. The waves from westerly directions turn so much due to the Grüner Brink formation, that the waves from these directions run more or less parallel to the groyne. This means that the groyne has no or little impact on the waves for this offshore wave direction.

The westerly waves near the west breakwater at Puttgarden are also influenced by the Grüner Brink formation due to incoming wave angles of these waves. The waves west of Puttgarden for offshore waves from southeast are sheltered for by Puttgarden and the resulting waves along the coast west of the harbour are therefore very small. This means that there are almost no waves to drive the littoral transport along the breakwater, which fits well with the fact, that there is no sand accumulation west of the harbour and there is no sedimentation in the entrance.

The wave roses southeast of Puttgarden are presented in Figure 8.50. The dominant offshore wave direction (westerly) is sheltered for by the coast. It is seen that the harbour nearly shelter completely for the NW-erly waves along the stretch from the harbour to southeast of the headlandat Marienleuchte, see also Figure 8.51. Only small waves from a northern direction refract into this coast. The predominant waves along this stretch are from east-southeast; a typical wave pattern from this direction is presented in Figure 8.52. The bathymetry for this section is presented in Figure 8.53. The east-southeasterly waves cause a northwestward littoral drift, which fits well with the observations of small depositions of sand at the southeastern side of the small groynes in the area.

The waves some distance southeast of Marienleuchte have a predominant wave direction from east-southeast and secondary relatively small waves from northerly directions, which are the diffracted/refracted westerly waves from the Fehmarnbelt. This wave climate results in a small northwestern net littoral drift.

Table 8.5 Locations along the north and east coast of Fehmarn where nearshore wave and current conditions were established

Location	**Position (UTM-32 WGS 84)**		**Bathymetry (m DVR90)**
	Easting	**Northing**	
G1	639188	6044333	-4.24
G2	640206	6044236	-4.51
G3	641487	6044058	-4.19
G4	642060	6043698	-3.95
G5	642621	6042549	-2.92
G6	642895	6042446	-3.24
G7	643298	6042260	-2.88
G8	643922	6042101	-3.22
G9	644828	6041487	-4.73
G10	645089	6041235	-5.25
G11	645414	6040556	-4.35
G12	645614	6039930	-4.41
G13	646012	6038977	-4.21
G14	646899	6037986	-5.03

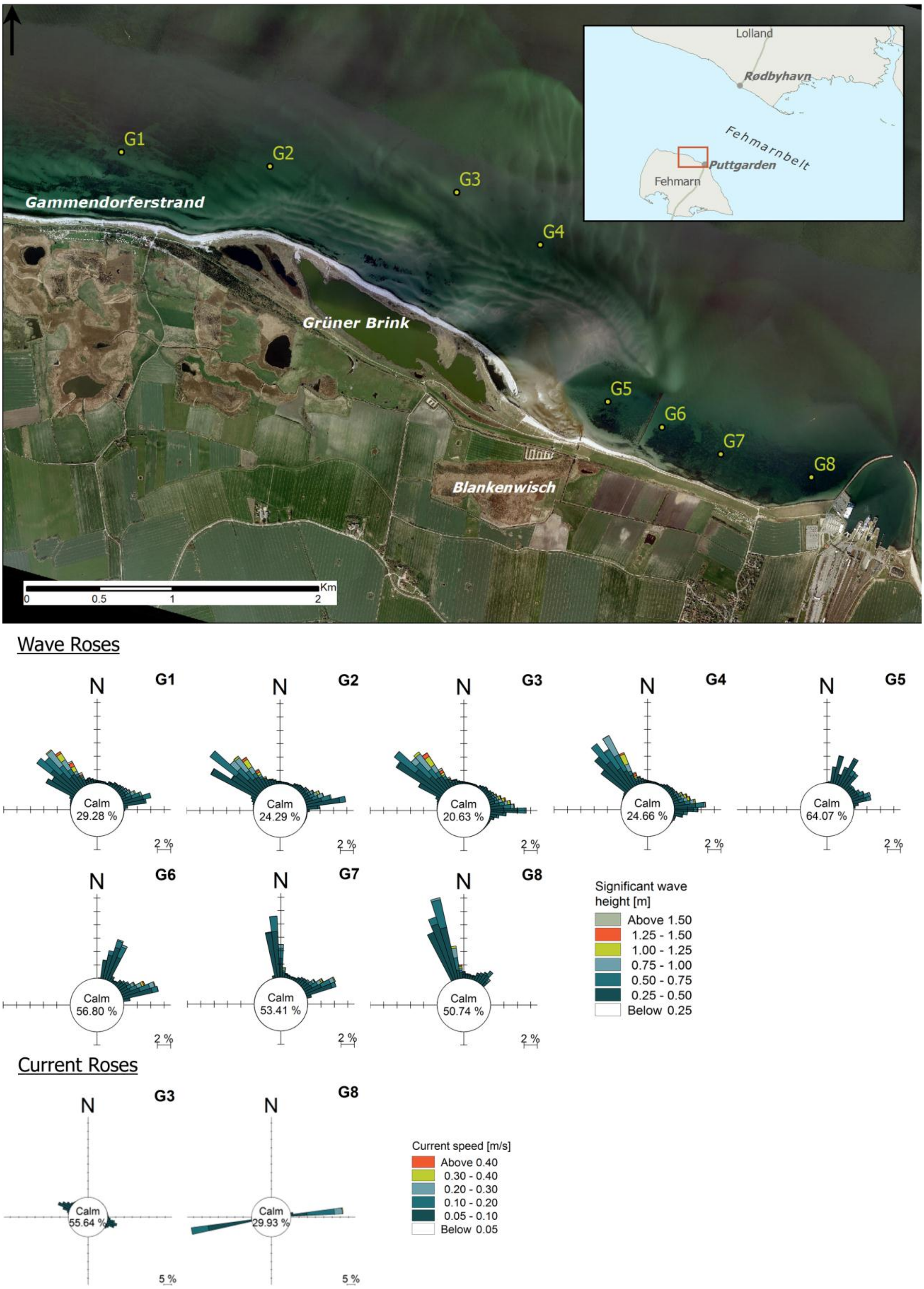


Figure 8.46 *Nearshore wave roses west of Puttgarden. Time of calm wave conditions (Hs below 0.25m) given for each wave rose in % of time. Aerial photo from 2009 (©COWI Orthophoto April 2009)*

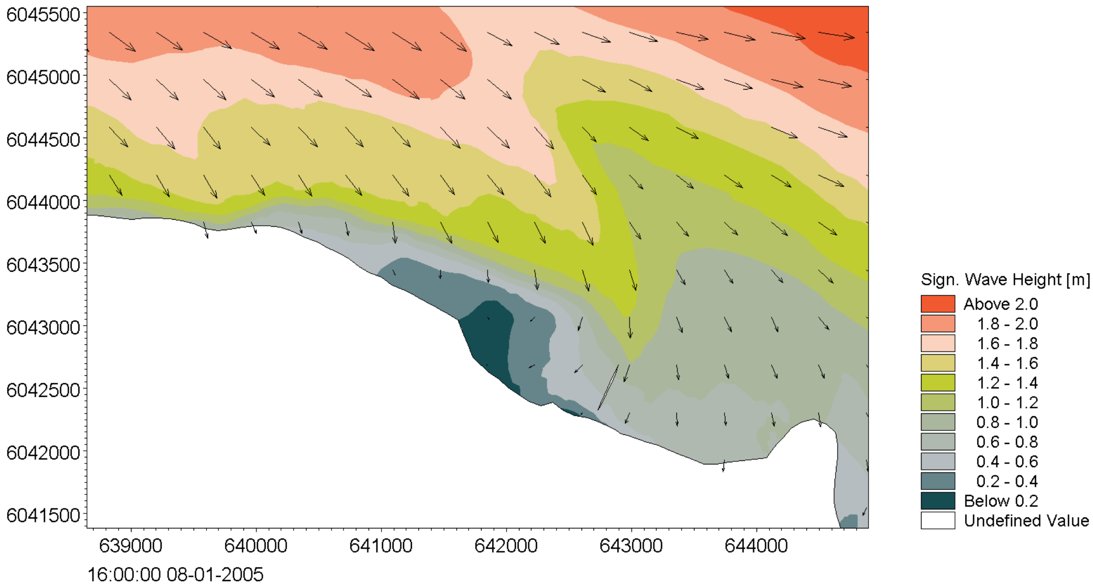


Figure 8.47 Typical wave pattern west of Puttgarden for NW-erly waves. Date of situation: 8.01.2005

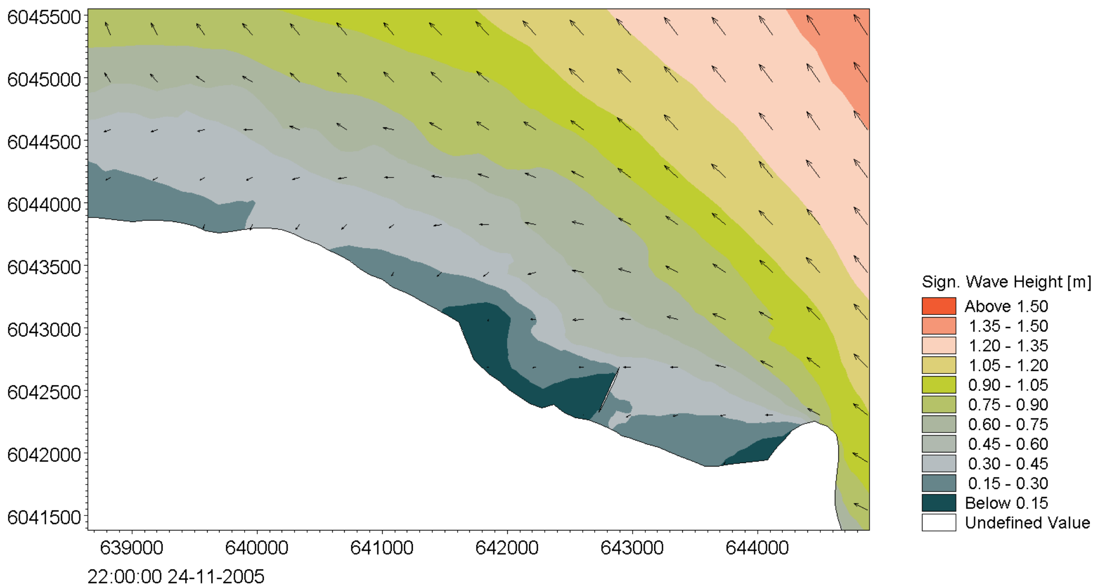


Figure 8.48 Typical wave pattern west of Puttgarden for SE-erly waves. Date of situation: 24.11.2005

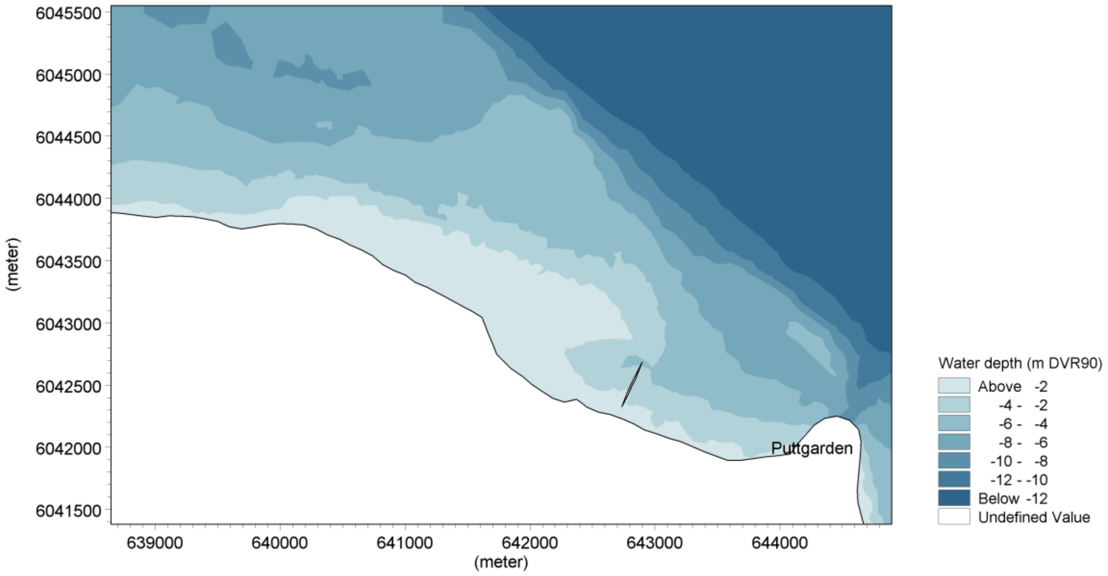


Figure 8.49 Bathymetry west of Puttgarden

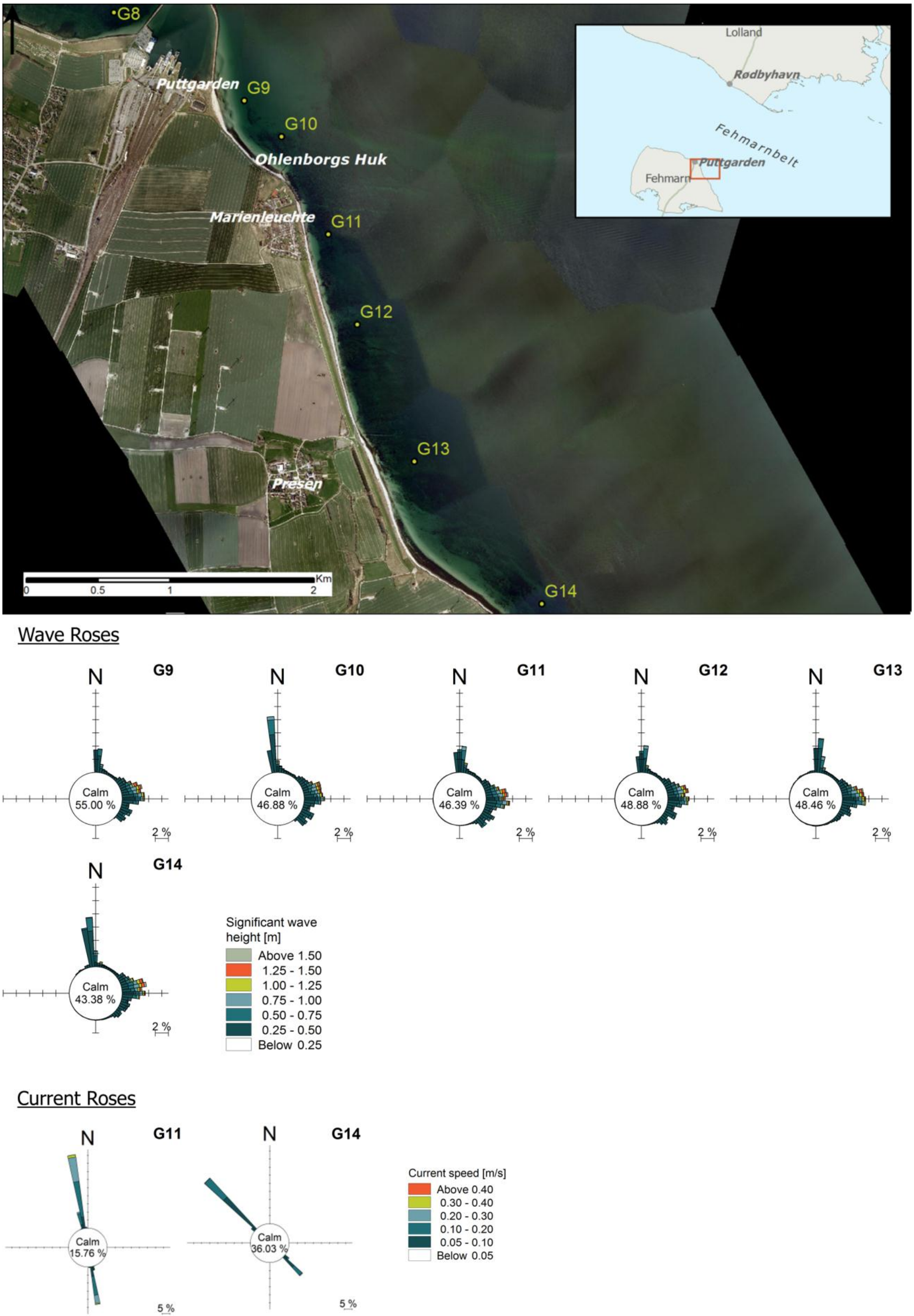


Figure 8.50 Nearshore wave roses southeast of Puttgarden. Time of calm wave conditions (Hs below 0.25 m) given for each wave rose in % of time. Aerial photo from 2009 (©COWI Orthophoto April 2009)

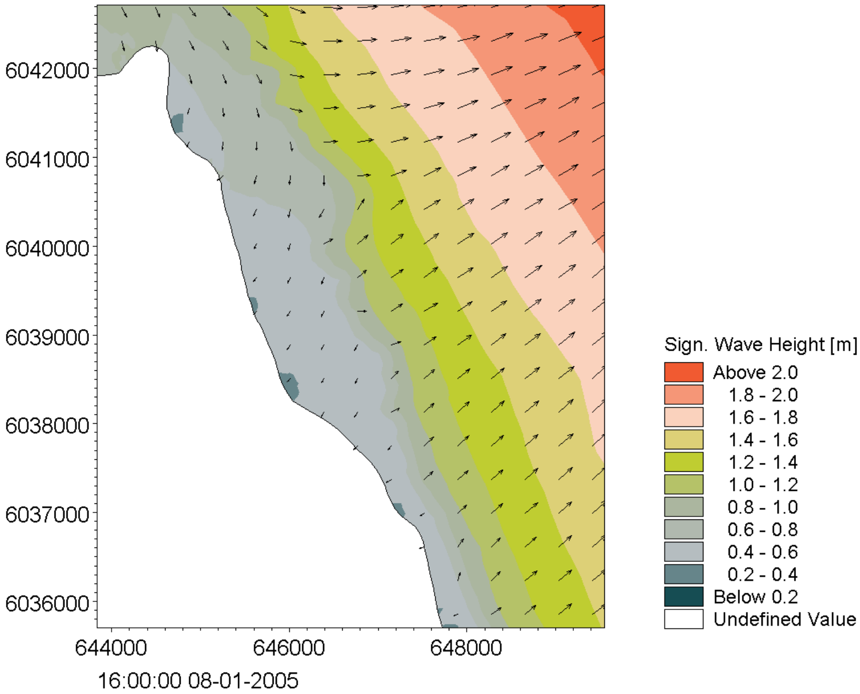


Figure 8.51 Typical wave pattern SE of Puttgarden for NW-erly waves. Date of situation: 8.01.2005

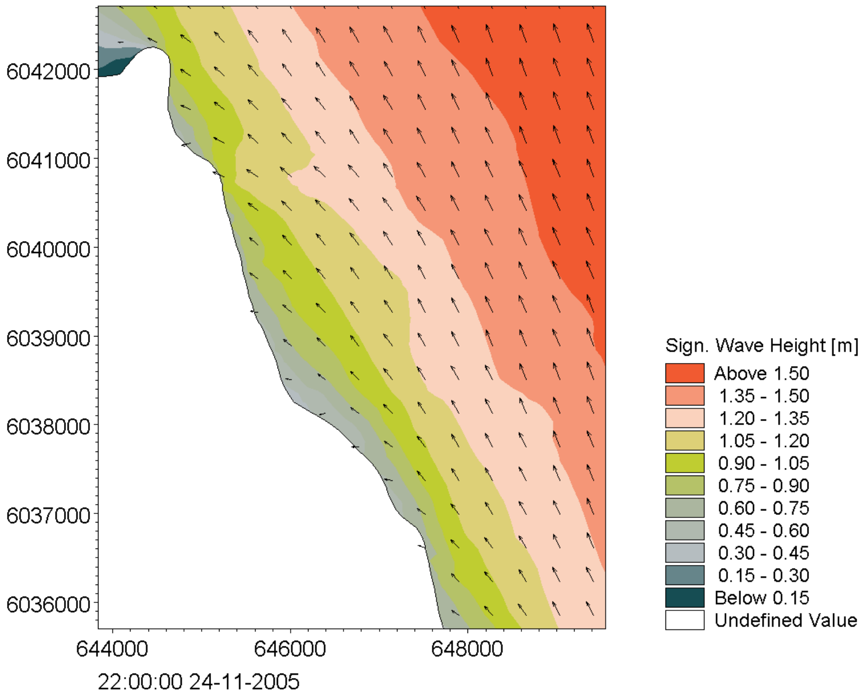


Figure 8.52 Typical wave pattern SE of Puttgarden for SE-erly waves. Date of situation: 24.11.2005

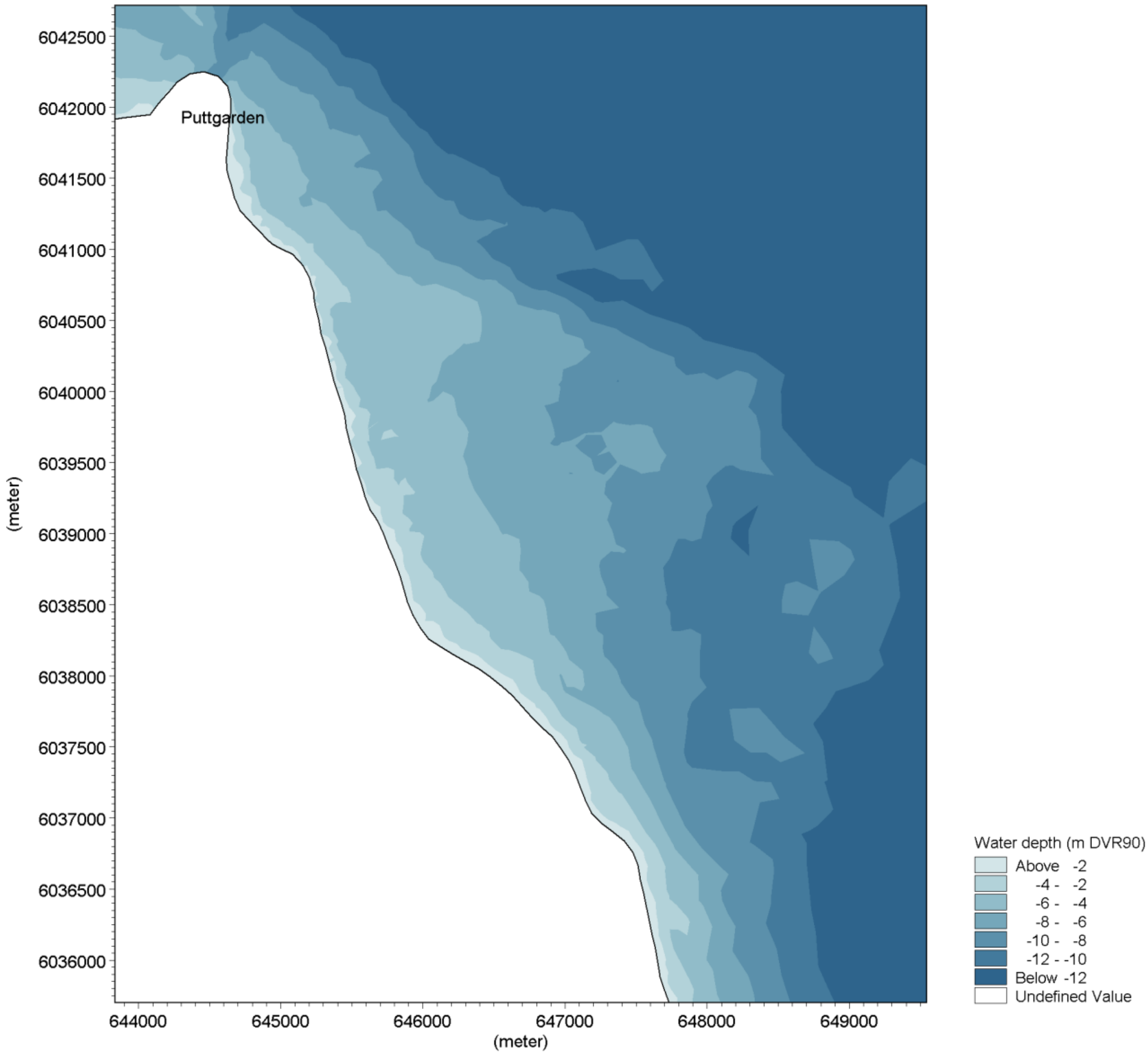


Figure 8.53 Bathymetry east of Puttgarden

8.7 Sediment Budget and Shoreline Evolution

The littoral drift budget has been established along the north and east coasts of Fehmarn for coastal stretches of about 5-6 km length at each side of Puttgardens, i.e. extending from the coastal section west of Grüner Brink to Klausdorf.

The littoral drift budget is described below. The variability of the littoral drift rates along the coast causes erosion or accumulation at the beach, i.e. an increasing or decreasing transport rate along the coast, causes the shoreline to retreat or advance with time.

A model to predict the littoral transport rates and the associated accumulation and erosion has been set up. The model is capable of reproducing the observed tendencies for deposition and erosion along the north coast of Fehmarn.

The results described in this chapter are:

- **Littoral drift rates**: net transport, gross transport and east- and westgoing transport components of the sediment transport along the coast in the littoral zone. These rates are compared to the accumulated volumes of sediment at specific locations such as Grüner Brink, the accumulation at the drainage outlet, the deposition at the East breakwater of Puttgarden

- **Shoreline evolution. Shoreline advance and retreat**: The observed tendencies are compared with results from the model

- **Equilibrium beach orientations**: the equilibrium beach orientation is the beach orientation that gives a net annual littoral drift of zero. Along a shoreline with a dominant incident wave direction, the equilibrium orientation is reached when the coastline is facing this direction. If a new beach is designed such that it faces the equilibrium orientation, the average net transport is expected to be zero leading to a stable shoreline. The difference between the equilibrium orientation and the present orientation is a measure for the transport capacity at a given location

The methodology in the littoral transport calculations are described in Section 8.7.1 and the results are described in Section 8.7.4 and 8.7.5.

8.7.1 Performance of littoral drift calculations

Littoral drift computations have been performed along coastal stretches of about 5-6 km length at each side of Puttgarden extending from west of Grüner Brink to Klausdorf.

A two-step approach has been applied in calculating the variability of the littoral drift rates along the coast:

- **Step 1:** Establishment of the overall sediment budget

- **Step 2:** Refined calculation of the variability along the coast

Step 1: Establishment of the overall sediment budget

Sediment transport computations have been performed at selected profiles with about 1 km distance along coastal stretches of 5 km length at each side of Puttgarden. The locations of the profiles, for which the littoral drift rates are calculated along the Fehmarn coast, are locations G1, G3 – G5, G8 - G14 in Figure 8.46 and Figure 8.50. Nearshore wave and current conditions for the selected profiles are presented in the previous Section.

The littoral transports in the profiles have been computed by the LITDRIFT module of LITPACK. The LITDRIFT module is used to determine the annual littoral drift at a given section of the coast. It simulates the cross-shore distribution of wave height, set-up and set-down, longshore current and sediment transport for an arbitrary coastal profile. The model is based on a quasi-3D approach, where the vertical velocity profile used in the sediment transport is calculated based on input from the 2D flow and wave fields on an intra-wave period time scale. The orientations of the profiles are perpendicular to the depth contours in the main transport zone, which is typically in the depth interval 0.0 to 2.0 m.

In general the littoral drift modelling is based on the physical parameters described in the previous sections of this report (Sections 8.4-8.6). Their representation in the model is provided in Table 8.6. Model parameters are also summarised in the same table.

The seabed conditions along the German coast west of Puttgarden are dominated by a sandy seabed, however with grain sizes varying from fine to coarse sand in the western profiles over very fine and fine sand immediately east of Grüner Brink to a combination of hard seabed and fine sand immediately west of Puttgarden as documented in Section 8.5. The numerous samples with very fine sand are especially located in the lee area east of Grüner Brink, which is not part of the littoral transport zone as the littoral transport in this area is located very close to the shoreline. Consequently, these fine sediments are not considered representative for the littoral transport zone in this area. The littoral transport along the coast west of Puttgarden is actually concentrated in a limited band along the shoreline, where "normal" beach sand is dominating. This is typically fine to medium sand with an average d_{50} in the range 0.2 to 0.3 mm.

The seabed southeast of Puttgarden is dominated by a very narrow band of sand which is generally characterised as coarse. The grain size distribution in the littoral zones shows large variations, typically between 0.10 mm and up to several millimetres. However, the very coarse sediments in the littoral zone, as well as the many sampling attempts without any sample retrieved, indicate a large occurrence of residual seabed in the area. These coarse sediments do not contribute significantly to the littoral transport. At each location a median grain size and spreading factor (describing the homogeneity of the sediment) is chosen to represent the sediment characteristics of the movable sediments in the coastal profile. These conditions are summarised in Table 8.7.

It is evident from the above discussion of the bathymetric conditions and of the sediment characteristics in the coastal areas that most of the stretches are fairly complicated, which constitutes a challenge for performing reliable littoral transport computations. The littoral transport rates have therefore been assessed as described in the following:

1. Calculation of the littoral transport capacity: it is assumed that movable sediment is available in the entire profile. This method provides an *upper* estimate of the actual transport and the potential distribution of the transport in the coastal profile

2. Adjustment of transport capacity: the zone of movable beach sand is restricted due to the occurrence of hard seabed/seabed with coarse sediments as described in Table 8.7

The occurrence of hard seabed/seabed with coarse sediments is estimated based on the analysis of the sea bed conditions in Section 8.5 and Appendix G.

The littoral drift rates calculated in this step are supplying an overall sediment budget for the coastal stretches analysed. Results from this will supply information on the shoreline stability on a larger scale and identify the overall tendency for the coastline to retreat or advance between the calculation locations.

Step 2: Refined calculation
The small-scale variabilities within these locations are not captured in Step 1. The littoral drift is very sensitive to the incident angle formed between the beach orientation and the incoming waves. In some configurations, changing the coastline orientation of a few degrees can have a significant impact on the sediment transport rates. Consequently, if - between two locations where the sediment transport has

been calculated - the shoreline orientation varies this variation should be taken into account to capture the right variation of the littoral transport. This is taken into account in step 2 which is therefore a refinement of the sediment budget obtained in Step 1.

In Step 2, it is considered that for a point, P, located between two points, where the littoral drift transport has been calculated in Step 1, the littoral drift rate can be estimated by interpolation in the transport rates for the adjacent locations, both of which computed with the actual beach orientation at point P. The transport rates to be interpolated to give the transport at P are obtained from the so-called 'q-alpha'-relations for the two adjacent points with the beach orientation at point P. The 'q-alpha'-curves define at a given location (with specified wave conditions, coastal profile and sea bed conditions as described for Step 1) the relationship between the net littoral drift and the beach orientation at the location. For the actual beach orientation, this curve gives the net littoral transport rate at this location.

The resulting shoreline evolution, the shoreline advance or retreat, is calculated from the gradient of the transport rates.

The calculation methodology, Step 1 and Step 2, described above has as a precondition that the transport conditions are in equilibrium with the wave conditions. This implies that the alongshore variations in the coastal profile, wave and sea bed conditions should be limited and slowly varying for the method to supply reliable results. The method is considered applicable along the coast east of Puttgarden. It is not applicable along the stretch west of Puttgarden mainly due to the presence of Grüner Brink, the long groyne and Puttgarden itself. These formations and structures are all so large and within a short stretch of the coast that they result in a large variability of the nearshore bathymetry as well as the wave climates. Littoral transport rates between the eastern part of Grüner Brink and Puttgarden are therefore not considered to be in equilibrium with the wave conditions. The transport rates from Step 1 are in this case considered as correct within an 'order of magnitude', but the shoreline evolution (erosion and deposition) cannot be obtained from these rates with sufficient accuracy to estimate the very small variations along this section.

Table 8.6 Physical and model parameters entering the littoral drift model

Model parameter	Parameter setting	Comments
Nearshore wave and water level conditions	Statistical representation of 1989-2010 wave conditions for each location G1, G3–G14	See Section 8.6 for description of nearshore wave conditions
Nearshore current conditions	Statistical representation of 2005 current conditions for each location G1, G3-G14	See Section 8.6 for description of nearshore current conditions
Coastal profiles	Varies along the coast. In general, measured profiles from 2009 are used	Measured profiles (described in Section 8.4) at the location, where transport is calculated, are used in the model
Sediment conditions	One representative median grain size (d_{50}) and spreading factor (σ) selected for each location. The applied sediment characteristics are summarised in Table 8.7. Graded sediment with 10 fractions	The sediment conditions are applied based on findings in Section 8.5
Width of littoral zone	A nearshore and offshore limit is applied according to sea bed conditions at each location. A summary of the conditions are supplied in Table 8.7	The width of the littoral zone is estimated based on findings in Section 8.5
Beach orientation	Varies along the coastal section, see result section	Estimated based on shoreline orientation and the orientation of depth contours in the active littoral zone (typically with the 1-2 m depth contour)
Active beach profile	West of Puttgarden: G1, G3, G4: 4-4.5 m G5-G8: 2.5 m East of Puttgarden: G9 – G14: 3-4 m	Active part of the beach profile is estimated from the measured coastal profiles, see Section 8.4.
Bed roughness	Apparent bed roughness (for wave-driven current): $20d_{50}$ Bed roughness for skin friction (for littoral drift transport): $2.5d_{50}$. Porosity of deposited/eroded sediment: 0.4	
Critical Shields parameter	$\theta_c = 0.045$	
Water temperature	10°C	
Grid spacing	0.1 m	
Statistical representation of wave and current conditions	ΔH_{rms}=0.1 m ΔT_{02}=0.5 m ΔMWD=5 degr ΔWL=0.1 m ΔV=0.1 m/s	

Table 8.7 *Sea bed characteristics applied in the littoral transport model. The cut-off levels indicate the limits for the littoral zone*

Loca-tion	**Grain size, d_{50} (mm)**	**Geometrical standard deviation**	**Loose sed-iment on the sea bed**	**Offshore cut-off lev-el for transport**
			Upper level (m DVR90)	**Lower level (m DVR90)**
G1	0.25	1.35	-	-3.5
G2	-	-	-	-
G3	0.2	1.35	-	-
G4	0.25	1.3	-	-
G5	0.2	1.3	-	-3.2
G6	0.2	1.3	-	-0.6
G7	0.25	1.4	-	-1.5
G8	0.2	1.4	-1	-2.5
G9	0.2	1.5	-	-
G10	0.25	1.5	-1.5	-2.5
G11	0.2	1.55	-	-0.6
G12	0.25	1.65	-	-1
G13	0.25	1.5	-1	-2
G14	0.25	1.5	-1.5	-1.8

8.7.2 *Summary of significant changes to the shoreline and nearshore bathymetry*

The littoral transport rates along the German coast are calibrated based on the following information:

- At Grüner Brink, the submerged front (west of G4) has migrated about 100 m corresponding to an estimated volume of deposition sea bed material of 150,000m^3 in 10 years or about 15,000 m^3/year. The length of the spit at the eastern part of the formation has increased with a growth rate of 20 m/year between 1999 and 2009 leading to a deposited volume of sediment of about 600 m^3/year (location G3)

- East of the water outlet from Blankenwisch at G5 a small sand accumulation of about 1700 m^3/year has taken place between 1999 and 2009

- Between Grüner Brink and Puttgarden i.e. between location G6 and G8, hardly any sand accumulation occurred along the beaches between 1999 and 2009

- No significant sand accumulation immediately west of Puttgarden and no transport of sand along the breakwater to the entrance area of the harbour can be observed

- A slight accretion is seen between 1999-2009 for the stretch between Marienleuchte and Presen. Small accretion has also been observed for a section of the coast of about 500-600 m centred around the termination of the dike southeast of Presen. Minor erosion has been identified in the same period along the coast southeast of Presen towards the campsite southeast of Klausdorf

The above accumulated volumes and shoreline changes are derived from shoreline changes between the years 1999 to 2004 and 2004 to 2009 and aerial photos of Grüner Brink, see further information in Section 8.3.

Along the Fehmarn coastline, the shoreline changes are relatively small. The shoreline retreat/advance is in the order of maximum 5-10 m during the full 10 years. For these areas the calibration has aimed at reproducing the overall tendency for erosion/deposition during 10 years. The average wave statistics for the period 1989-2010 has been used to quantify the littoral drift and shoreline movement.

Observed changes of the shoreline east of Puttgarden are presented in Figure 8.54for the two five-year periods 1999-2004 and 2004-2009 and the total period 1999-2009. These are used to validate the littoral drift results from this coast. West of the harbour the estimated volumes of accumulation mentioned above are used for validation.

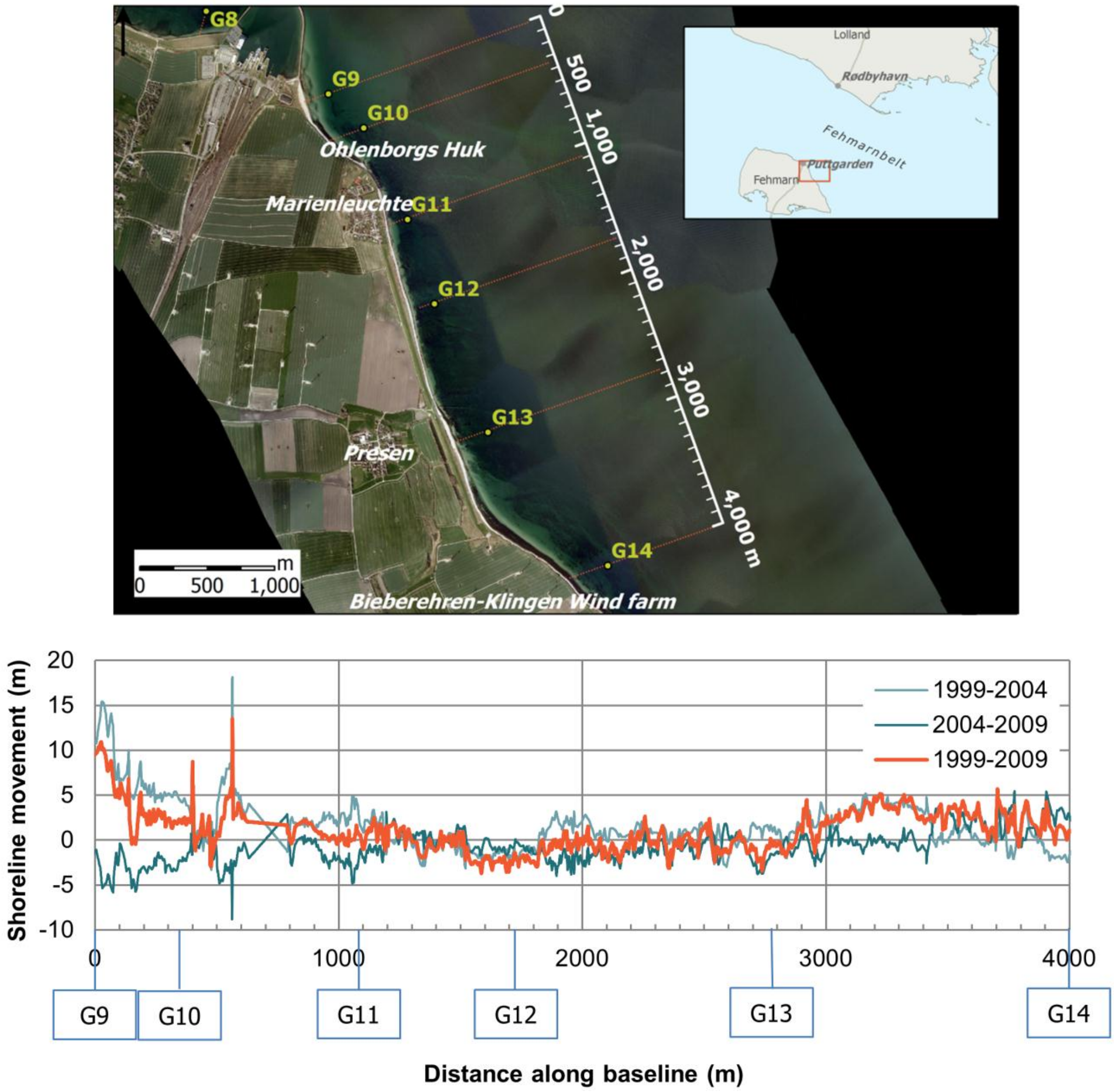


Figure 8.54 Shoreline retreat (negative) or advance (positive) east of Puttgarden between the harbour and the coast approximately 2 km south of Presen. 1999-2004 (light blue curve), 2004-2009 (dark blue curve) and 1999-2009 (red curve). Aerial photo from 2009 (©COWI Orthophoto April 2009). Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen.

8.7.3 Calibration of littoral drift model

The only place where significant changes take place along the north- and east coast of Fehmarn is at Grüner Brink and the changes here take primarily place at the submerged part of the formation. The other consistent and characteristic shoreline changes mentioned in the previous section are all good indicators for the budget, but very small. Calibration of the littoral drift model for the coast of Fehmarn is therefore a more difficult task than for the corresponding littoral drift model at the Lolland side, where the accumulation west of Rødbyhavn is suitable for calibration.

Calibration of the littoral drift rates (Step 1) for the coast of Fehmarn is therefore based on the observed changes at Grüner Brink. The refined calculations (Step 2) of the littoral drift and shoreline evolution along the coast southeast of Puttgarden-have been compared with the observed shoreline orientation. The wave statistics for the period 1989-2009 have been used in the calculation of the littoral drift rates. Experience from calculations of the littoral drift rates along the Lolland coast, where more significant shoreline changes take place, shows that the 1989-2009 wave statistics were able to represent the littoral drift conditions for the 1999-2009 period well. The main calibration parameters are the bed roughness and the exact information about the various physical parameters such as sediment properties and width of the band in the profile which are covered by movable sand, exact orientation of the beach.

The calibrated littoral drift budget at the Grüner Brink formation is seen in Figure 8.55. The estimated deposited volumes at the submerged front and at the spit of the formation in the period 1999-2009 are compared to the net annual littoral transport rates from the calibrated model.

The littoral drift balance for the front of the Grüner Brink is as follows:

- Sand being transported along Grüner Brink (modelled at G4): about 11,000-15,000 m^3/year
- Sand accumulated on the submerged front of the formation: approximately 15,000 m^3/year
- Sand deposited at the spit: approximately 600 m^3/year

The modelled net littoral drift rate at Grüner Brink fits well with the estimated deposited volume at the submerged front. The estimation of the deposited volume is somewhat uncertain since it is based on comparison of aerial photos from 1999, 2004 and 2009. Detailed area-covering bathymetric surveys of the area do not exist.

It is not possible to make a precise separation of the fraction of the transport that passes on to the submerged part of the formation and the fraction of the transport that passes along the shoreline and deposits at the spit. However, from the calculated distribution of the transport in the profile at G4 shown in Figure 8.56 it is seen that only a very small part of the transport takes place near the shoreline. Within a distance of about 300 m from the shoreline, the net transport rate is only about 600 m^3/year. The vast majority of the annual transport hence takes place further away from the shoreline.

This fits quite well with the fact that the majority of the modelled net transport along Grüner Brink is found to deposit at the submerged front and that only a very small part of the transport is expected to deposit at the spit.

The shoreline evolution calculated with the Refined approach (Step 2) for the coast between Marienleuchte and the coast south of Presen southeast of Puttgarden is compared to the observed shoreline changes 1999-2009. The long-term average conditions 1989-2009 have been used in the model. The model describes the main tendencies for small accumulation areas near Marienleuchte and between Presen and the Wind farm. Between Marienleuchte and Presen only very small shoreline changes of less than 0.5 m/year have taken place and this is also reproduced satisfactorily in the model.

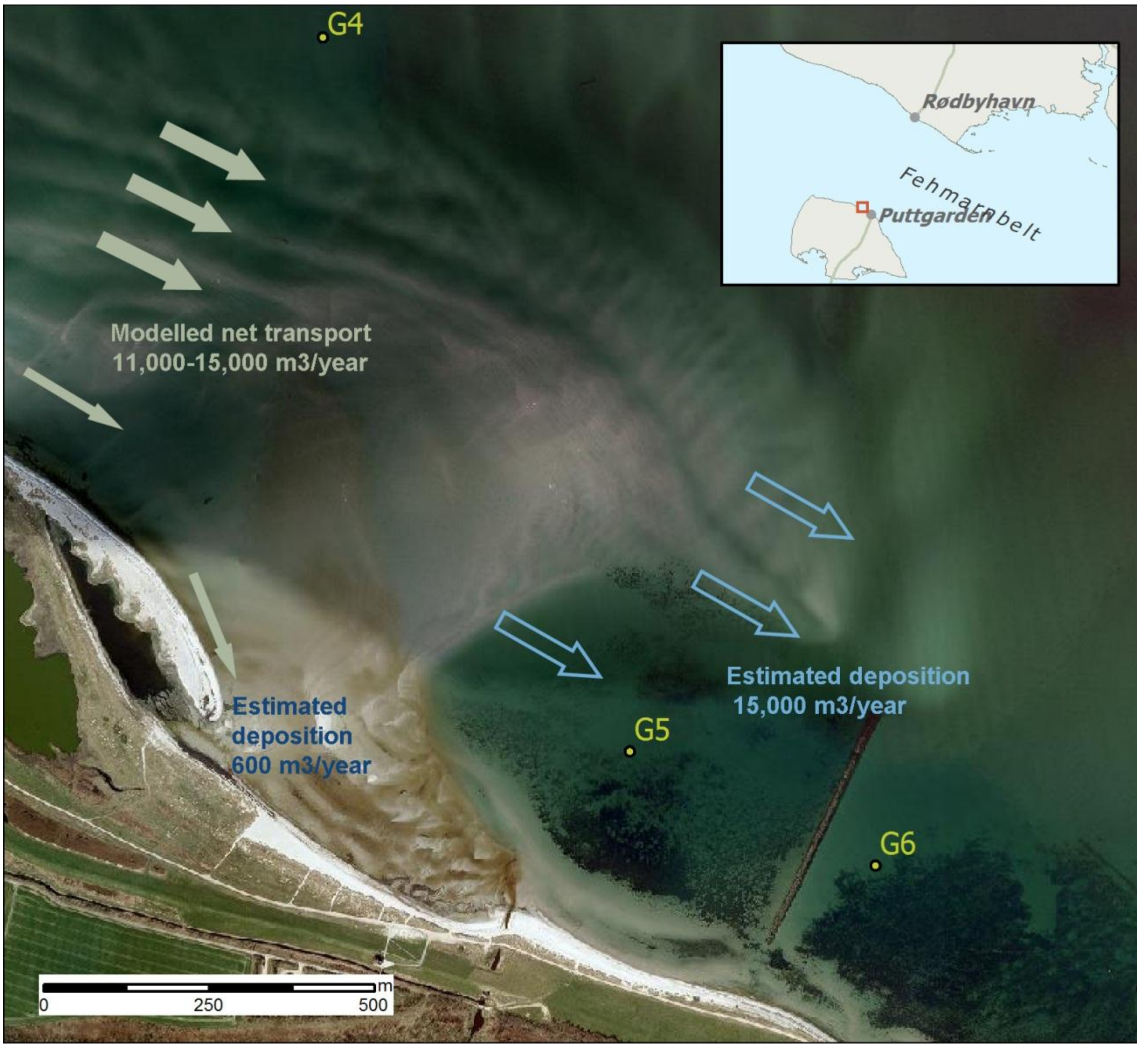


Figure 8.55 Calibrated littoral drift budget for the Grüner Brink formation. Aerial photo from 2009 (©COWI Orthophoto April 2009)

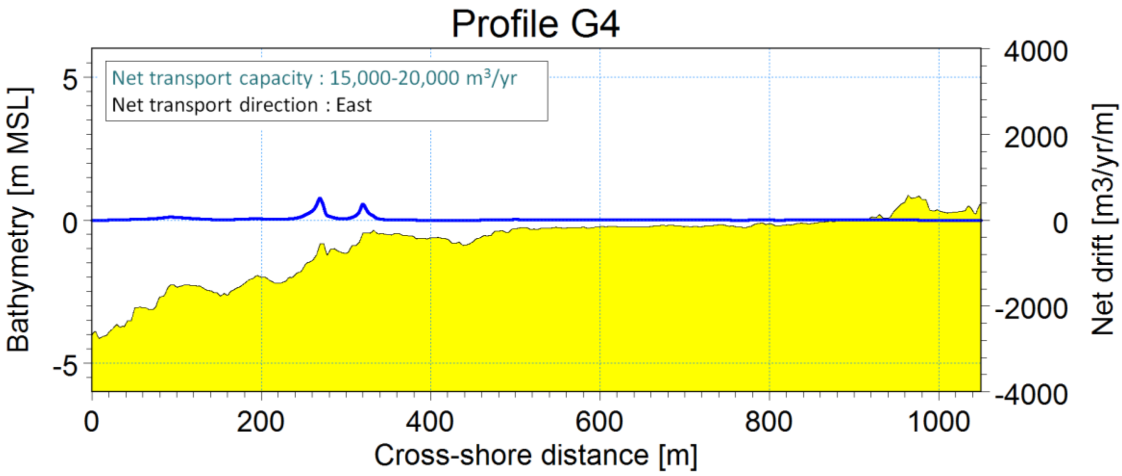


Figure 8.56 Distribution of the calculated net transport in the coastal profile at G4

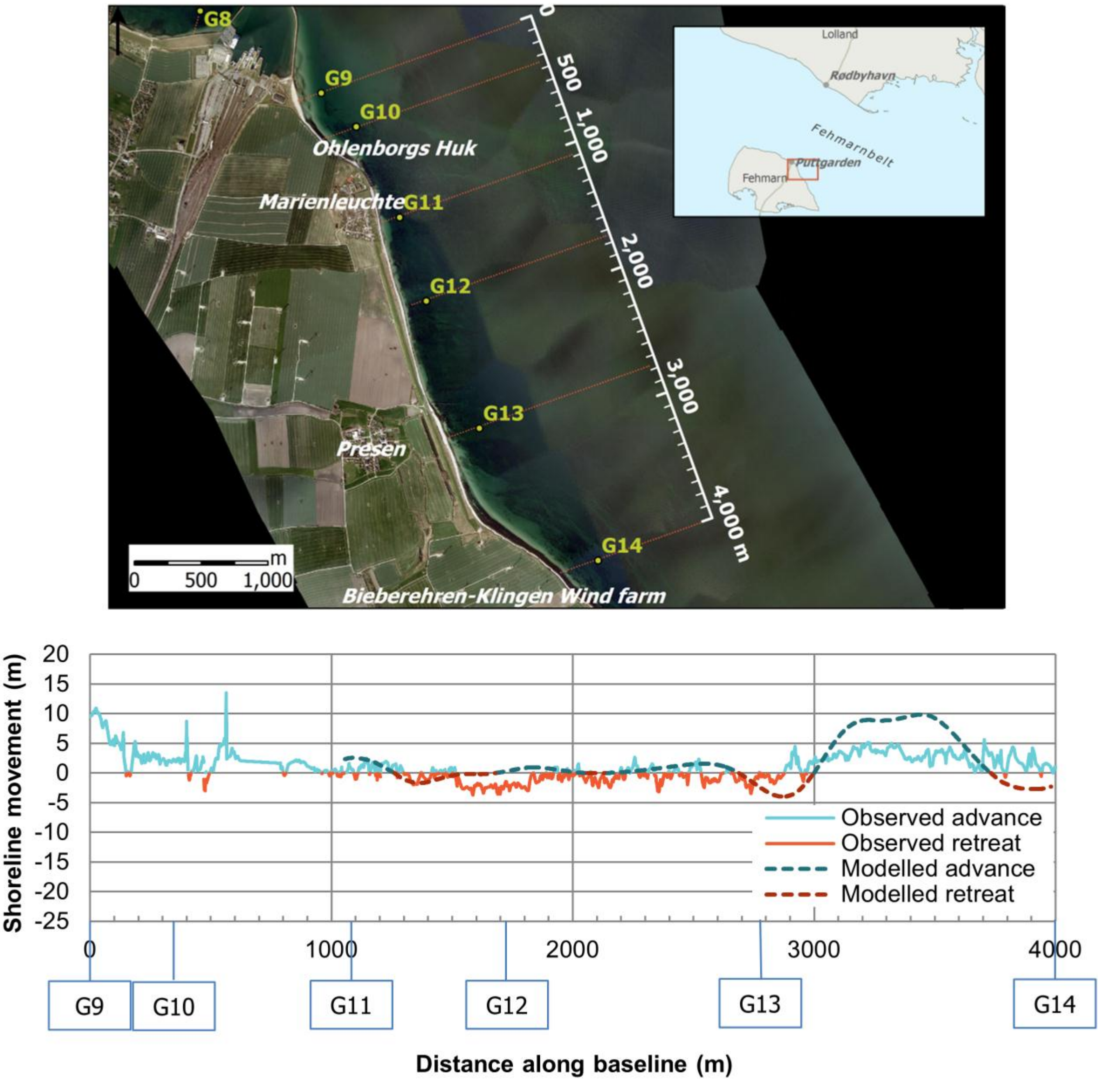


Figure 8.57 Comparison of observed shoreline changes 1999-2009, and predicted shoreline changes for 10 years by the model (average conditions 1989-2010) east of Puttgarden. Aerial photo from 2009 (©COWI Orthophoto April 2009). Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen.

8.7.4 Littoral drift budget west of Puttgarden

The annual littoral drift rates have been calculated along the coast west of Puttgarden between Gammensdorferstrand and Puttgarden, see Figure 8.58, for the long term average wave statistics for 1989-2009. The annual drift rates have been calculated by Step 1 for calculation points G1-G8. The refined method, Step 2, is not appropriate along this section, refer to discussion in Section 8.7.1. The net and gross rates as well as the west- and eastwards components are presented in Table 8.8.

A net eastward transport rate of about 40,000 m^3/year off Gammensdorferstrand is calculated. At Puttgarden the net transport rate of zero is estimated and the calculations therefore indicate a net input of 40,000 m^3/year to this section of the coast. Deposition of this volume of sediment takes place mainly at the Grüner Brink formation and some is transported offshore and feeds sediment to the area of sand waves off Grüner Brink seen in Figure 8.58.

Gammensdorferstrand to Grüner Brink

The equilibrium beach orientations are tabulated in Table 8.9 together with the actual beach orientations along the coastal section. The orientations are shown in Figure 8.59.

Just west of Grüner Brink, at location G1, the orientation of the coast is about 15° anti-clockwise relative to the orientations off the main part of the Grüner Brink formation represented by profiles G3 and G4. This change in the orientation of the shoreline is the reason for the abrupt drop in the net annual littoral drift from about 41,000 m^3/year at G1 to 11-15,000 m^3/year at G4. The change in the orientation of the shoreline combined with the very oblique angle of the dominant waves with the coast orientation at this location is the reasons for the formation of Grüner Brink.

About half of the 41,000 m^3/year transported towards the east at Gammensdorferstrand is predicted to be transported offshore as described above. The vast majority of the remaining transport is deposited at the submerged front of the Grüner Brink formation and a smaller part is depositing at the spit. The littoral drift budget at the front was described above (Section 8.7.3).

Between Grüner Brink and the long groyne

West of the long groyne the net transport direction is westwards (G5). This is due to the turning of and sheltering against the westerly waves as they propagate across the submerged front of Grüner Brink which leads to northeasterly and easterly being the more dominant wave directions. This corresponds well to the small build-up of sand against the water outlet structures seen between 1999-2009 (estimated to 1000 m^3/year for the long-term average wave statistics.

Between the long groyne and Puttgarden

The net annual transport rates along the stretch between Grüner Brink and Puttgarden, represented by the locations G6, G7 and G8, are small. Small net transport rates (less than 5,000 m^3/year) are predicted by the model at G6 and G7 and they are probably even smaller (close to zero). No shoreline changes have been observed in this area. Just west of Puttgarden (G8), the net transport rate is about 0, corresponding well to the fact that there is no sign of sand accumulation west of Puttgarden.

Table 8.8 Littoral transport rates west of Puttgarden. Positive net transport rates towards the east

Location	Net littoral transport rate (m3/yr)	Gross littoral transport rate (m3/yr)	Westward transport rate (m3/yr)	Eastward transport rate (m3/yr)
G1	~41,000	65,000	12,000	53,000
G3	20,000	70,000	25,000	45,000
G4	11,000-15,000	40,000-45,000	15,000	26,000-30,000
G5	-1,000	7,000	4,000	3,000
G6	<-5,000	~10,000	5,000-10,000	0-5,000
G7	<-5,000	~25,000	10,000-15,000 (~0)	10,000-15,000
G8	~0	~10,000	~5,000	~5,000

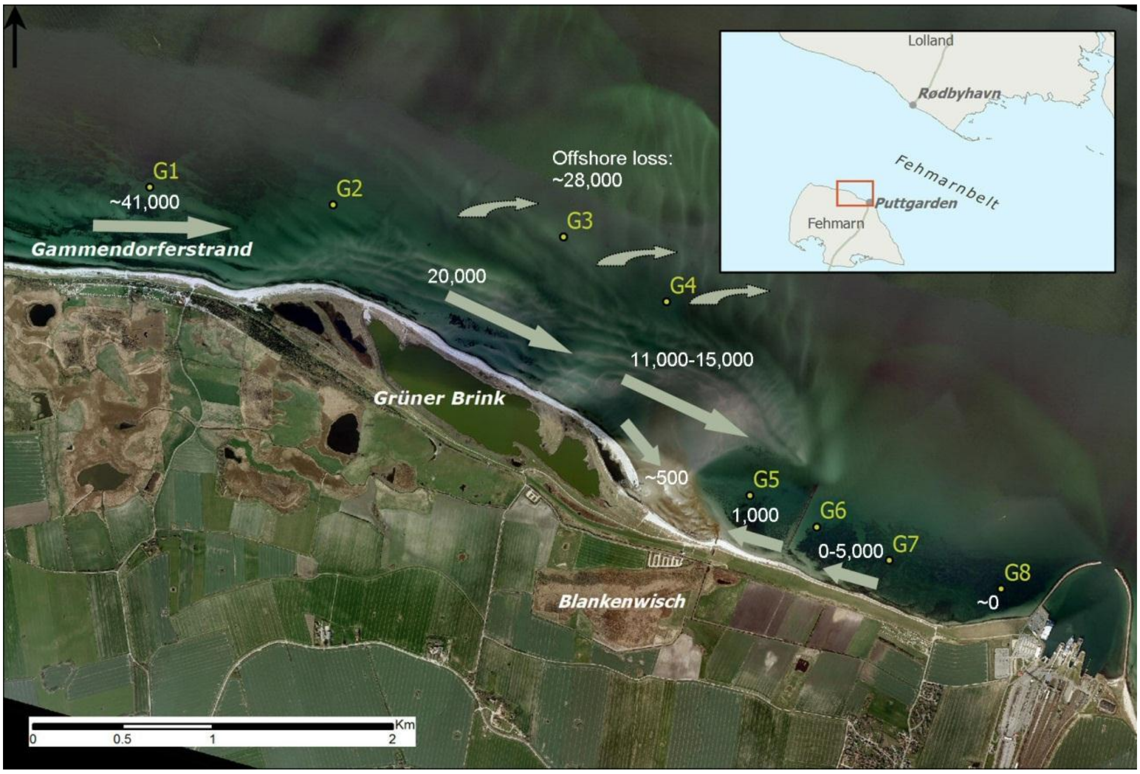


Figure 8.58 Littoral drift budget along the coast west of Puttgarden. Aerial photo from 2009 (©COWI Orthophoto April 2009)

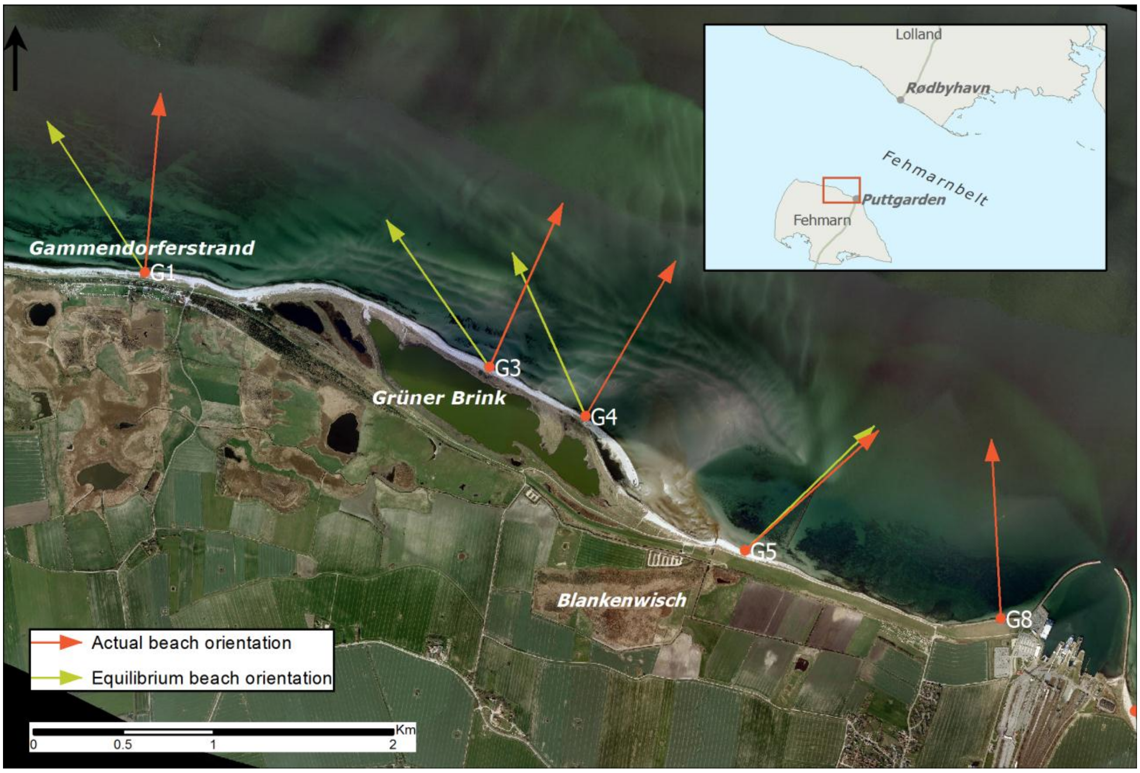


Figure 8.59 Equilibrium and actual beach orientations west of Puttgarden. Aerial photo from 2009 (©COWI Orthophoto April 2009)

Table 8.9 Equilibrium and actual beach orientations west of Puttgarden

Location	**Beach orientation (degr. N)**	**Equilibrium beach orientation (degr. N)**
G1	6	327
G3	19-30[1]	325
G4	21-31[1]	336
G5	48	46
G6	27	48
G7	24	31
G8	357	357

[1]Off the main part of Grüner Brink (G3-G4), the depth contours at -4 m have an orientation of about 19-20°. At shallower water depths the orientation of the depth contours turns further clockwise

8.7.5 Littoral drift budget east of Puttgarden

The littoral drift budget for the coast east of Puttgarden is shown in Figure 8.60 for the average wave statistics 1989-2009. The transport rates have been calculated by the Step 2, Refined method, except for the section just east of the harbour. The net and gross transport rates as well as the northwesterly and southeasterly components of the transport at each of the location G9-G14 are tabulated in Table 8.10. The equilibrium and beach orientations are shown in Figure 8.61 and tabulated in Table 8.11.

The littoral budget along this section shows a small net transport of about 500-2500 m^3/year towards the north along the entire stretch. The transport rates drop slightly between the coast approximately 2 km south of Presen in the south to Presen and are then nearly constant between Presen and Puttgarden with only minor variability indicating a very stable coast with only small shoreline changes.

East of Puttgarden

The net transport rate just southeast of the eastern breakwater is about 1,000 m^3/year. This fits well with the very small shoreline changes observed in this area and the small built up of sand in the profiles. At G10 a high net *potential* transport rate towards the north is calculated (see Table 8.10) indicating a high transport capacity at this point. This is due to the change in the beach orientation, which has turned anti-clockwise. The transport at G10 is not effectuated due to small groynes and the seawall protecting the Ohlenborgs Huk from erosion and lack of loose sea bed material.

Marienleuchte to Presen

Between Marienleuchte and Presen the net transport rates are very small. The sediment transport magnitudes are less than 2,000 m^3/year mainly because the beach orientations are close to the equilibrium orientation along this stretch (G11 to G13). The transport components towards the northwest and the southeast, respectively, reach about 15,000 m^3/year and decrease towards G13. The mobile sediment becomes more limited and coarser in the littoral zone towards the south.

Presen and further south

Along this stretch of the coast (from G13 to G14), the beach orientation turns clockwise by about 20°. This induces an increase in the net sediment input of sand from south to this section. This leads to a deposition along this section, which is well captured by the model.

8.7.6 Remarks on littoral drift budget along the coast of Fehmarn

The littoral drift budget along the south coast of Fehmarn has been calculated from Gammensdorferstrand west of Puttgarden to the coast approximately 2 km south of Presen southeast of the harbour.

Net transport rates in the order of 0-40,000 m^3/year and gross transport rates in the order of 25,000-90,000 m^3/year have been obtained for the average wave conditions.

The wave conditions are one of the primary parameters for estimating littoral drift conditions. The modelled wave conditions were found to deviate from the measured wave conditions. The main source of uncertainty is identified to be inaccuracies in the applied wind fields. The modelled nearshore wave conditions have been adjusted to account for the discrepancies between modelled and measured waves. The uncertainty in the waves will be reflected as an uncertainty in the predicted transport rates. The uncertainty of the littoral drift calculations is estimated at +/-50%. However, with the adjusted nearshore waves a satisfactory calibration against observed shoreline evolution has been obtained.

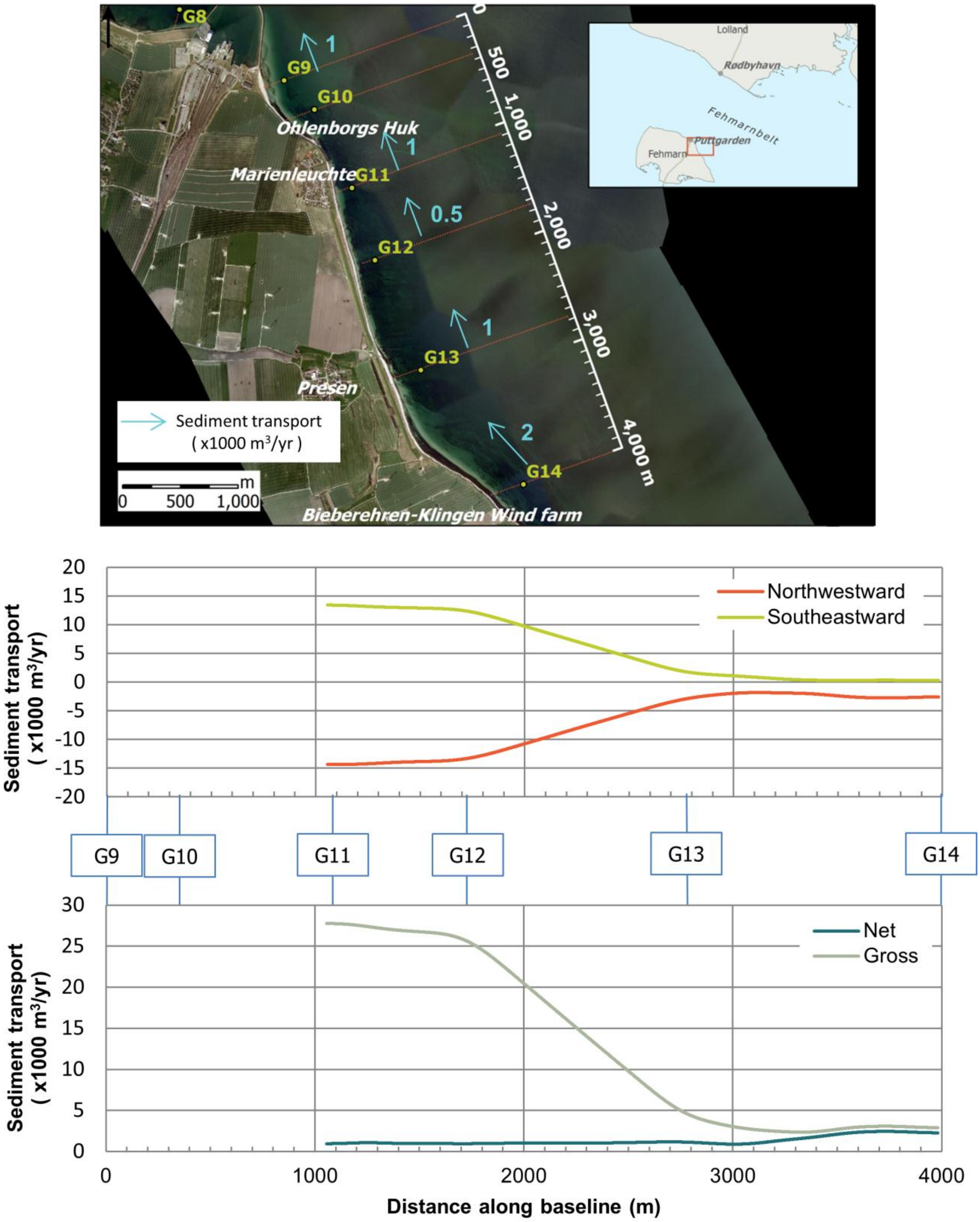


Figure 8.60 *Littoral drift transport rates east of Puttgarden. Average year 1989-2010. Central figure:northwest- and southeast going transport conditions. Lower figure: net and gross transport rates. Aerial photo from 2009 (©COWI Orthophoto April 2009). Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen.*

Table 8.10 *Littoral transport rates east of Puttgarden. Positive net transport is directed toward the southeast. .(-) indicates that these transport rates are not effectuated*

Location	Net littoral transport rate (m^3/yr)	Gross littoral transport rate (m^3/yr)	Northwestward transport rate (m^3/yr)	Southeastward transport rate (m^3/yr)
G9	-1,000	27,500	14,000	13,500
G10	~20-25,000[1]	45,000[1]	34,000[1]	11,000[1]
G11	-1,000	28,000	14,500	13,500
G12	-500	26,000	13,000	12,500
G13	-1,000	4,500	3,000	1,500
G14	-2,000	2,500	2,500	<500

[1]Potential transport capacity not effectuated

Table 8.11 *Equilibrium and actual beach orientations east of Puttgarden*

Location	Beach orientation (degr. N)	Equilibrium beach orientation (degr. N)
G9	75	76
G10	39-45	-
G11	82	83
G12	78	79
G13	78	82
G14	56	80

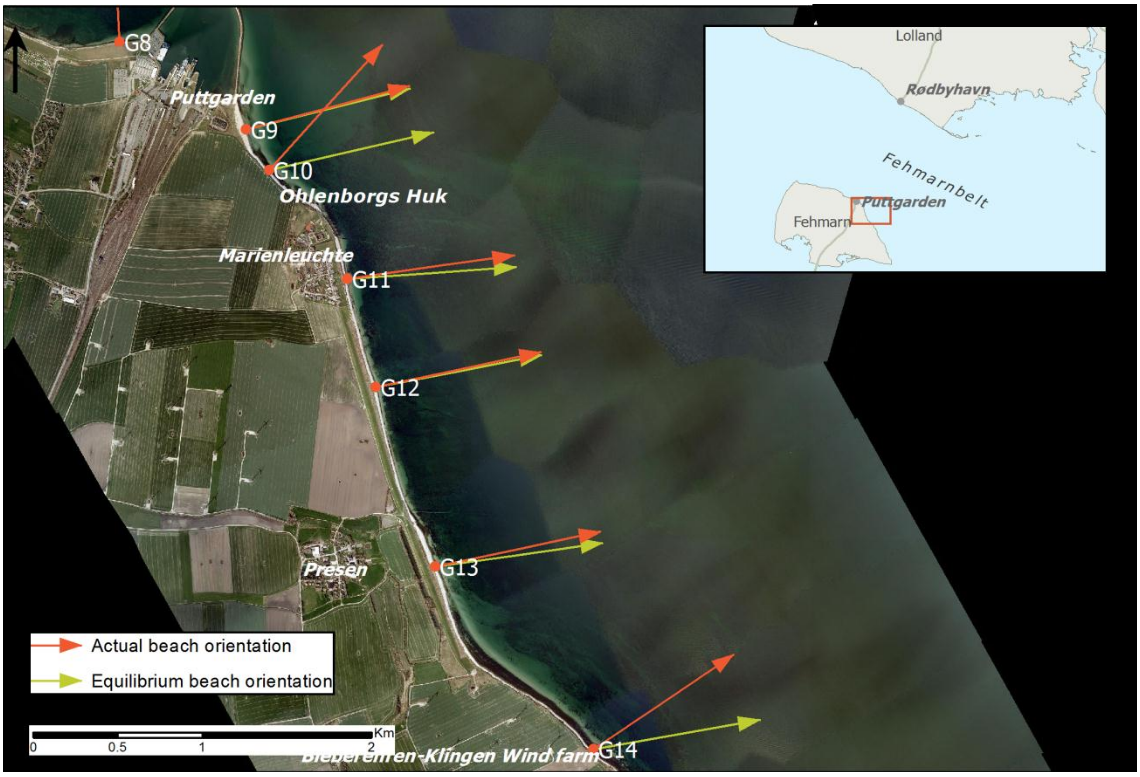


Figure 8.61 *Equilibrium and actual beach orientations east of Puttgarden. Aerial photo from 2009 (©COWI Orthophoto April 2009). Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen.*

9 PRESENT PRESSURES

9.1 Lolland coast

It is evident from the descriptions in Section 7 that the majority of the south coast of Lolland and the coastal hinterland are exposed to pressure from various man-made interventions.

The dike was constructed in response to the very extreme storm surge event in 1872, where the entire southern Lolland was flooded. Before the construction of the dike the south coast of Lolland was characterised by a series of islands aligned with today's shoreline. These islands constituted a barrier between Fehmarn Belt and sheltered coastal lagoons behind the barrier. Rødby Fiord and Rødsand Lagoon were the most prominent coastal lagoons. Historical maps show they were connected by a strait sheltered by the row of islands. The barrier islands had a similar nature as the present Hyllekrog spit, see Figure 9.1.

Figure 9.1 Historical map for the south coast of Lolland for the period 1763-1805 by the Scientific Society (Videnskabernes Selskab (Geographical Institute at Copenhagen University)). The alignment of the dike is also indicated

A 'cut-through' type of dike was selected, which cuts off the previous Rødby Fiord and the western part of Rødsand Lagoon. The coastal area was changed as follows:

- The Rødby Fiord and the western part of Rødsand Lagoon were reclaimed
- The natural morphology of the coastline, characterised by sandy beaches and cliffs along the islands and tidal inlets between the islands, was converted into one long section of partly artificial shoreline

The coastal landscape resulting from the dike construction and reclamation project is in the present context considered as today's basis of reference, which means that the dike dominated coastline is the coastline on which existing pressures are acting.

The shoreline is partially natural, as there are sections where the dike is constructed behind the original coastline. The pressures on this coastline are listed in the following for the section between Kramnitze and Hyllekrog:

- **Kramnitze Harbour** constitutes a blockage for the littoral transport; the net eastward transport is trapped on the upstream side (west side) of the breakwater, where sand accumulation has built up, and some sand is also trapped in the sheltered area immediately east of the harbour. This means that the coast east of the harbour does not receive any sand, which has resulted in erosion of this coastal section

- **Rødby Ferry Harbour** traps the net eastward littoral transport in the sand accumulation west of the harbour and in the reservoir, which has been constructed with the purpose of keeping the entrance channel free of sedimentation. The coast east of the harbour does not receive any sand, which has resulted in erosion of this coastal section

- The erosion caused by the two harbours as described above has necessitated protection of the dike east of the harbours with **revetments**. The revetments stop the erosion of the protected sections. This means that the revetments just shift the erosion further downstream. However, erosion takes place seaward and downdrift off the protected stretches

- A coast protection scheme consisting of **10 detached coastal breakwaters** has been constructed **at Hyldtofte Østersøbad**. This scheme stabilised the section

- The **Rødsand 1 and 2 wind mill farms** are located from mid of Hyllekrog and towards east, see Figure 9.2. The impacts have been investigated in (DHI Water and Environment 2004) and (DHI 2007b). Rødsand 1 has negligible influence on the transport conditions at Hyllekrog. Rødsand 2 increases the net littoral transport along the stretch from Rødbyhavn to Hyllekrog from 0.1% to 1.8%, which is also considered as insignificant compared to the natural variations; however, the tendency is increased erosion along this stretch

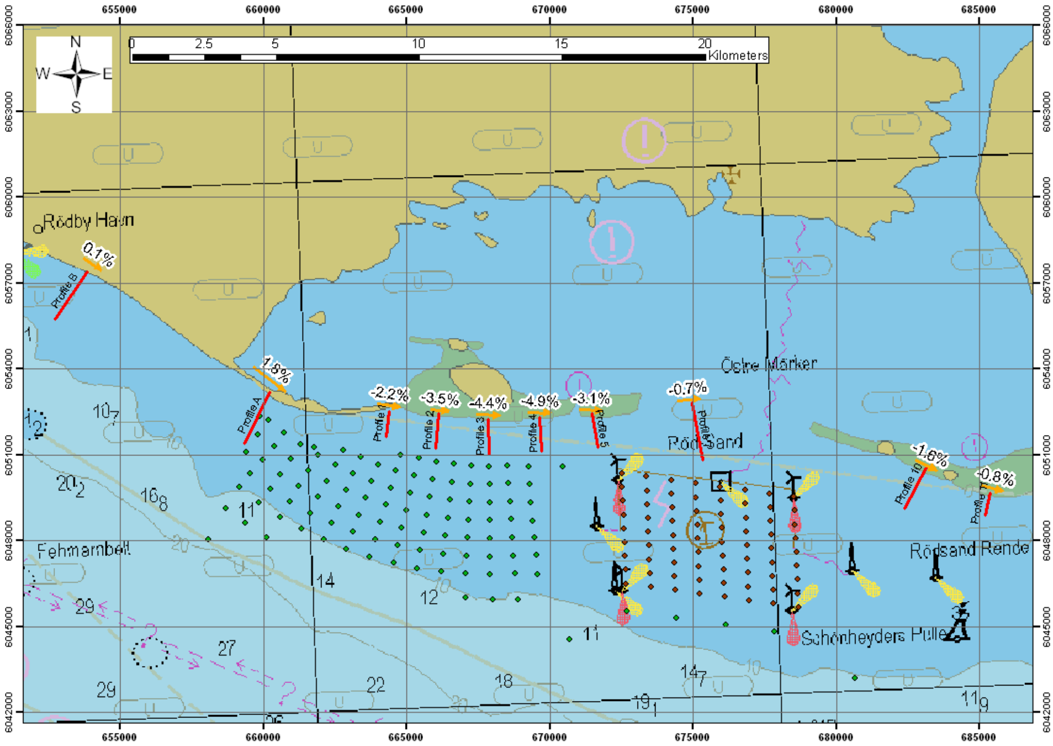


Figure 9.2 The Rødsand 2 (left) and Rødsand 1 (right) wind mill farms (from DHI 2007b)

9.2 Fehmarn coast

It is evident from the descriptions in Section 8 that the north coast of Fehmarn coast and the coastal hinterland are exposed to pressure from various man-made interventions.

Similar to the Lolland coastal area, there was extensive flooding of the low coastal areas along the north and east coast of Fehmarn during the extreme storm surge event in 1872, which resulted in the construction of a dike along the west and north coasts of Fehmarn and off Presen at the east coast, as described in Section 8. However, contrary to what was done at the Lolland coast, the long sections of the dike along the north coast of Fehmarn was constructed behind the important coastal morphological formations of Markelsdorfer Huk and Grüner Brink, whereas other sections were cut off by the dike, e.g. the eastern part of Binnensee. Apart from immediately west of Puttgarden, the dike was constructed a little distance inland, which means that there is actually a nearly natural beach along the north coast of Fehmarn. The dike of Presen at the east coast, however, is constructed on top of the original coastline. The low lying wetlands of Binnensee, Westerwiese and Blankenvisch along the north coast and that of Presen along the east coast are reclaimed via pumping stations, which can be considered as an existing pressure.

However, as for Lolland, the coastal landscape resulting from the dike construction and reclamation project is in the present context considered as today's basis of reference, which means that the dike dominated coastline is the coastline on which existing pressures are acting.

The pressures on this coastline are listed in the following for the section between Markelsdorfer Huk and Klausdorf:

- The **outlet jetties at the pumping station from the Blankenwisch lowland** constitutes a minor blockage of the littoral transport, and has resulted in trapping of a minor amount of sand on the east side of the structure, which has caused lack of sand on the west side. This is the reason for the very narrow beach immediately west of the groyne

- **The detached long groyne between Grüner Brink and Puttgarden** (400 m east of the outlet) has only minor impact on the coastal morphology as most sand is trapped at the east side of Gruner Brink; however, a small salient in the shoreline can be seen landwards of this structure

- **The dike from immediately east of the long groyne up to Puttgarden, is protected by a revetment.** There is no beach along this 1.3 km long section, there is no release of sediments and there is no accumulation of sand west of Puttgarden. However, the lack of sand in this area is mainly due to the special conditions around the eastern termination of Grüner Brink

- **Puttgarden** is a major coastal structure, but the impact on the coastal morphology is small as explained in the following. There is by nature hardly any littoral transport towards this site from west which means that the harbour is not blocking any transport on this side. There is by nature a small littoral transport from SE towards the harbour site along the coast SE of the harbour; this transport is blocked by the harbour, but this has only insignificant impact on the conditions along the adjacent stretches to the harbour

- **The groynes north of Marineleuchte** are very short but have a stabilising impact on the adjacent coastal sections towards SE. This means that the natural coastal development at this stretch is stopped by the presence of these groynes, which contributes to the lack of beach sand in this area

- **The seawall and the revetment at Ohlensborgs Huk off Marienleuchte** protect the coast along this section, which means that no sediments are released from this stretch, which contributes to the general lack of sandy beaches adjacent to this headland

- **The drainage outlet jetties at the pumping station off Presen** have trapped a small amount of sand on the southern side, which causes erosion immediately north of the outlet. The eroding area is protected by an **asphalt revetment**. These two interventions prevent a natural development of this area and contribute to the lack of sand along the dike

- **The revetment and short groynes at the camping site at Klausdorf** have only negligible influence on the state of the adjacent coastal sections

It is seen that the coastal section between Markelsdorfer Huk and Puttgarden is under a relatively mild pressure from artificial interventions. First of all because the dike is mainly constructed inland form coastal morphological active landscape elements and secondly because other coastal structures are located in the area near Puttgarden, which by nature has only small morphological activity. The coastal morphology along the stretch SE of Puttgarden is under pressure from groynes, a seawall, revetments and the dike.

10 ASSESSMENT OF IMPORTANCE

The importance of the coastal sections within the investigation area has been assessed based on the conservation objectives of the Natura 2000 areas occurring within the area of investigation and the key functional importance of these areas.

The following Table 10.1 provides the importance criteria for the coastal morphology component of the sub-factor Marine Soil.

Table 10.1 Importance levels for the Marine Soil component: Coastal Morphology

Importance level	**Description**
Very high	Coastal areas (incl. coastal protection structures along these) within Natura 2000 areas, where coastal morphological elements are part of the conservation objectives. Coastal sections, which are protected under German legislation as NGS areas. Individial marine structures (not coastal protection)
High	Coastal stretches (incl. coastal protection structures along these) with sandy beaches and cusp areas (cuspate foreland) including coastal lagoons, not included under the 'Very high' category
Medium	All other coastal stretches (incl. coastal protection structures along these), which are not heavily influenced by anthropogenic activities as mentioned under the "Minor" category
Minor	Coastal stretches under heavy influence of anthropogenic activities

The justification for Table 10.1 is as follows:

- *Very high importance level*

  A high importance level is assigned to areas with protected coastal morphological elements within Natura 2000 (Danish and German territories) and Naturschutzgebiete (NSG, German territory only)

  The Natura 2000 area SCI DK 006X238 Smålandsfarvandet north of Lolland, Guldborgsund, Bøtø Nor and Hyllekrog-Rødsand has the following conservation objectives:

    - Preservation of the natural coastal dynamics
    - Free landscape formation and coastal dynamics are safeguarded

  Protected physical habitat types related to coastal morphology are part of the conservation objectives along sections assigned with a 'very high importance level'.

  Similarly, the Natura 2000 area SCI DE 1532-391 Küstenstreifen West- und North Fehmarn has the following conservation objectives:

    - Preservation of the storm beach and lagoon landscape, which has been shaped by the natural coastal dynamics because it lies outside the dyke

Protected physical habitat types related to coastal morphology are part of the conservation objectives along sections of the coast assigned with 'very high importance level'.

The coastal landscape between Markelsdorfer Huk and Grunër Brink is composed of these types of coastal elements. Furthermore, the coastal landscape within the NSG area "Grüner Brink" is protected in full to preserve a typical type of coastal landscape on Fehmarn with beach berms, meadows, shallow coastal lagoons etc.

For these reasons, the coastal sections within the Natura 2000 area and the NSG area have been assigned a very high importance level for the sub-factor Marine Soil component Coastal Morphology.

Coastal protection structures along the above mentioned coastal stretches - such as for instance groynes/revetments/sea walls - protect these coastal sections and are similarly assigned a very high importance level

Individual marine structures (such as sluices and water outlets) have a functionality of very high importance for the hinterland. These are therefore assigned a very high importance level.

- *High importance level*
  Sand beaches (and coastal protection structures along these, such as groynes/revetments/sea walls) are considered an important natural and recreational resource. Beaches which are not part of areas classified with 'very high importance level' are therefore considered having a high importance level in Germany as well as in Denmark.

  The preservation of the active coastal morphological processes and the morphological features resulting from these, such as cusps and coastal lagoons, are also considered of natural and environmental value and are therefore classified to be of high importance.

- *Medium importance level*
  All other coasts (including coastal protection structures along these such as groynes/revetments/sea walls), which are not heavily influenced by anthropogenic activities and which have no specific conservation status have been given the classification of medium importance level.

- *Minor importance level*
  All coastal areas under heavy influence of anthropogenic activities, such as harbours and harbour areas, heavily protected coastal stretches without any beaches, excavated areas and dredged navigation channels.

The importance levels assigned to coastal sections within the investigation area on Lolland are seen in Figure 10.1 and similarly in Figure 10.2 for Fehmarn.

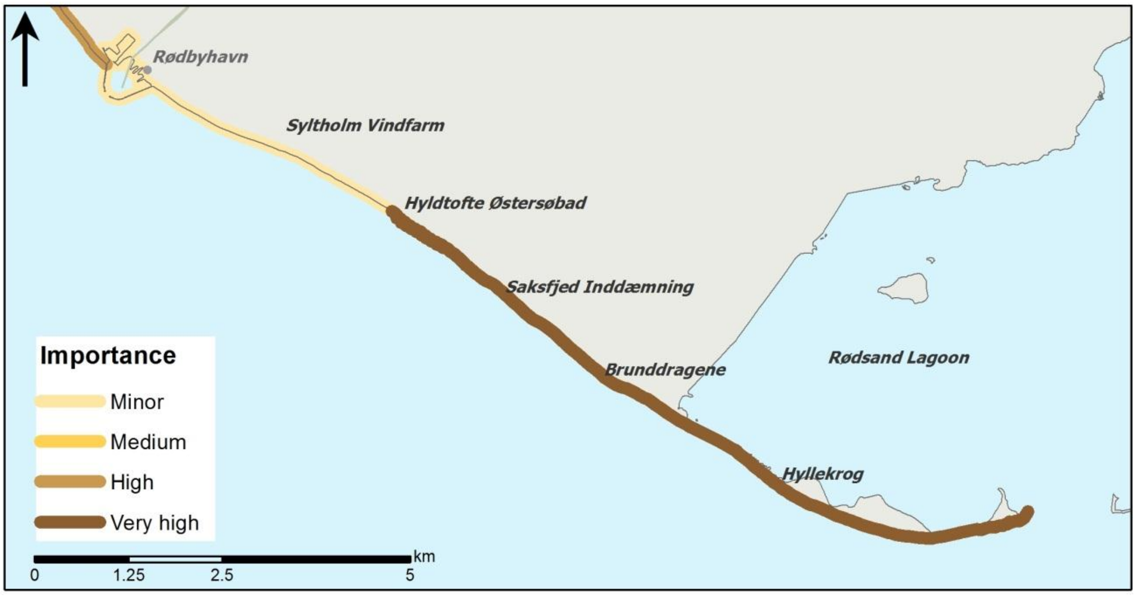
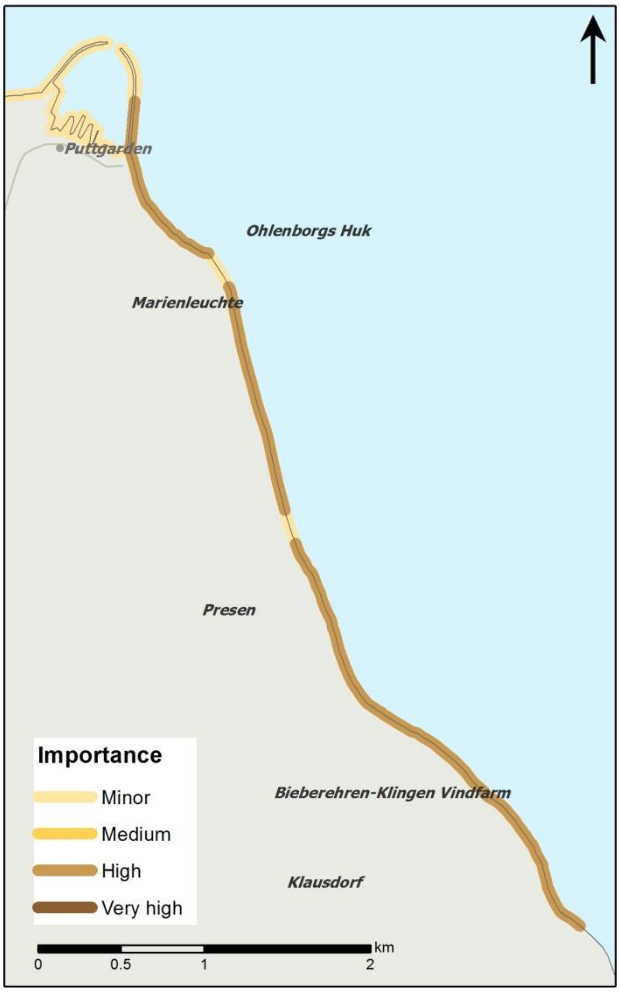


Figure 10.1 Importance criteria for sub-factor Marine Soil component Coastal Morphology along the Lolland coast



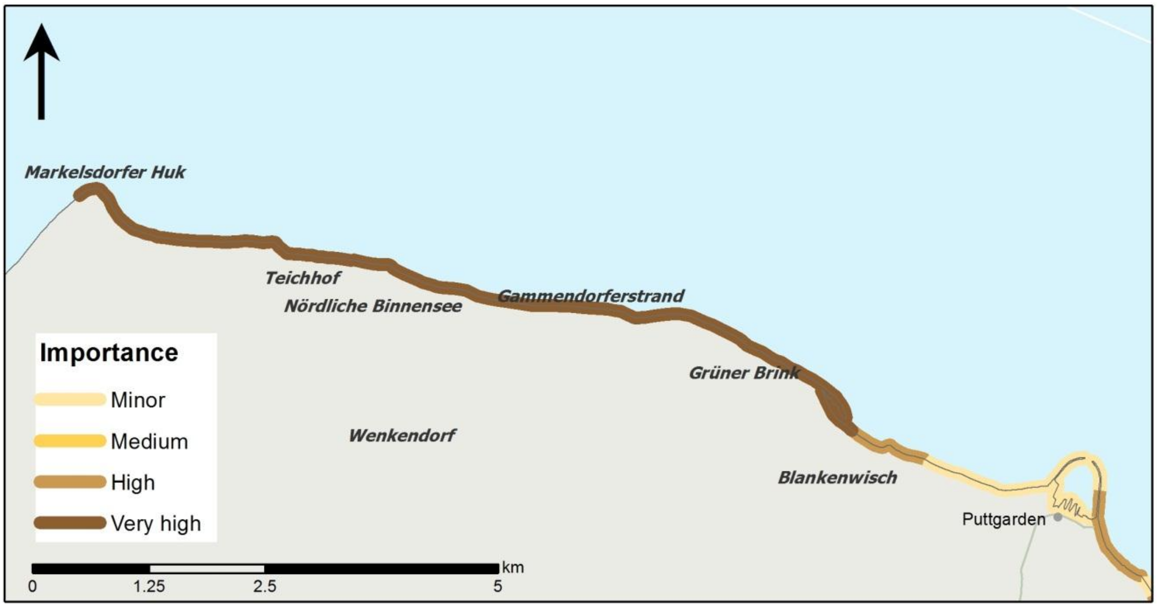


Figure 10.2 Importance criteria for the Marine Soil component Coastal Morphology along the Fehmarn coast. Note: Bieberehren-Klingen wind farm is not the correct name of the wind farm south of Presen.

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