DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2016/51

Investigation at Gilleleje Flak and Tragten in preparation for reef restoration

Geophysical, biological and hydrographic investigations performed for SVANA by GEUS, Orbicon and TT Hydraulics

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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Table of contents

Appendices

A Maps of the results of the geophysical and biological investigations

A1 Overview

A2 Map of investigations

A3 Bathymetry

A4 Substrates

A5 Habitat directives nature types

A6 Habitat directives nature types

A7 Sediment/geological map

A8 Side scan sonar mosaic

A9 Design and location of reefs

B Hydrographic model results

C Data sheets for instruments and vessels

D Interpretation of videos

E Description for the MapInfo-files

1 Summary

The aim of this project is to identify areas for restoring stone reefs in the Gilleleje Habitat area 195. Extensive geophysical, biological and hydrographic efforts have been put together by GEUS, Orbicon and TT Hydraulics to achieve this goal.

Results of the geophysical survey show the spatial distribution of the stones on the seabed surface, the bathymetry, and the seismic stratigraphy of the surveyed area. Results indicate that a major part of the area is composed of till (containing stones of different sizes) of glacial origin, with stretches of stratified glaciomarine clays (containing fewer stones) and some areas covered with sandy younger Holocene marine deposits.

Biological work was endeavoured to validate the geophysical interpretation of the seabed substrate, and to gather information of marine biological communities at selected locations and selected depths. Biological interpretation and classification of the dives (paravane and spot dives) show very well developed macro algae communities associated with the widely distributed stones in the area. The macro algae communities dominate at all depth intervals but most species divers on depths above the thermocline (approx. 11-12 m). Different epi fauna species and fish were observed associated with the macro algae communities. The biological communities are typical for the southern part of Kattegat.

The hydrographic model for waves and wave generated currents show that the area is stable and the effect of the proposed reef on wave height is minimal. It also indicates that sediment transport is only affecting sand and small gravel sediments when the wind speed is high (18-25m/s).

Information about the type and size of stones to be used in the reef restoration project were obtained from consulting engineering companies that had previous experience with such endeavour. Other important information was deduced from the Blue Reef project guidelines and reports.

After contacting several offshore building companies and individuals who has long experience with this kind of work a project proposal has been completed. On the basis of this information two optimum positions were chosen for reef restoration, one at shallow waters <10m and the other on deeper water >10m. The location of the proposed reefs will ensure the flourishing, abundance and diversity of the pelagic fish as well as the benthic fauna and flora. The southern reef PR1 location will ensure connectivity between two existing reef areas.

The deep northern proposed reef PR2 is a 600 m long dam of 3m height and a 15 m base. The shallow southern proposed reef PR1 is a series of 18 circularly truncated cones with 4 m height and a 20 m base.

2 Introduction

2.1 Purpose

Many areas with stone reefs, in particular shallow waters (<10m) and coastal areas, have previously been destroyed by the removal of stones and boulders for use in the construction of piers, wave breakers, harbours etc. Removal of stones and boulders from the seabed was ultimately banned through an amendment to the Danish Raw Materials Act in January 2010. So far, there has been no regular and systematic mapping and monitoring of stone reefs in the Danish waters (except in Natura 2000 areas through NOVANA programme), so the extent and occurrence of natural reefs are not known. The removal of boulders from stone reefs causes the remaining stones to be influenced by sanding which renders the stones unsuitable for habitat flourishing or fish spawning. Since stone reefs are important for marine biodiversity, nature restoration projects can be an important tool to conserve marine plants and animals.

Especially the extents of cavernous stone reefs have decreased due to the extraction of stones. These types of stone reefs with high complexity are characterized by high species diversity, high productivity and function as refuge for many fish species especially juveniles. Furthermore, it is a foraging area for many fish species and marine mammals. Species of wrasses (*Labridae*), cod (*Gadidae*) and gobies (*Gobiidae*) are often seen in areas with stone reefs in Danish waters.

The primary objective is to recreate cavernous stone structure that will re-establish the biological structure and function of the stone reef habitats (1170 Reef) in this EU Natura 2000 site of Gilleleje Flak and Tragten. The purpose is to improve the status of the reef towards favourable conservation status by enhancing their natural function and improve biodiversity of the region. This is in coherence with EU Commission Biodiversity strategy that aims at reversing loss in biodiversity and ecosystem services in the European waters by 2020 (http://ec.europa.eu/environment/nature/index_en.htm) . The new cavernous stone reef is an ideal habitat for the pelagic fish as shelter or spawning locality, benthic fauna, as well as the benthic animals.

2.2 Survey methods and results

A desk top study was endeavoured using the existing reports and publications of geological and biological work performed previously in the region. The most recent was in 2012, where few geophysical survey lines were made, supplemented by a biological ground truth at selected points (Jensen et al, 2012). This information were used as a background for planning a new survey, which started in May 2016 and aimed at a full coverage mapping of a selected area in the Gilleleje Flak and Tragten Natura2000 area.

A suite of geophysical systems including side scan, swath bathymetry, and sub-bottom profiler were used in the survey campaign. A robust ground truth survey followed the geophysical investigation to validate the geological results and identify species of epifauna, fish and macro algae and their distribution.

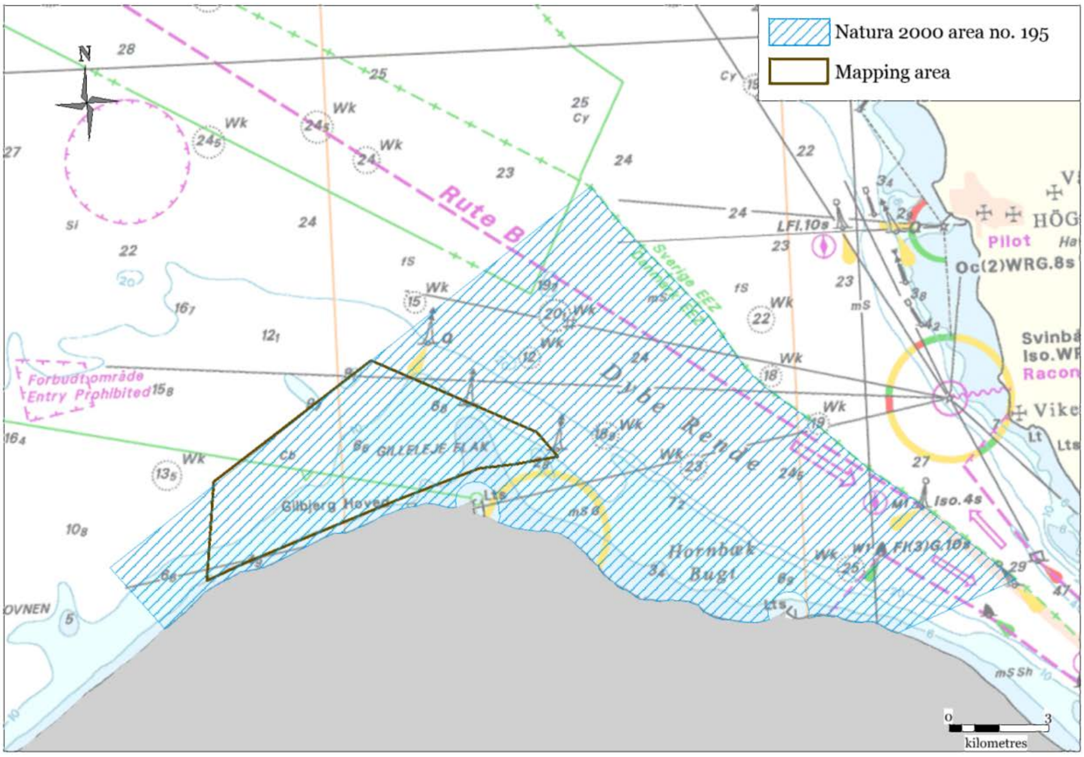


Figure 2-1 Natura 2000 area no. 195 with the sea chart 102 from the Danish Geodata Agency and with the mapping area.

Results show that substrates containing >25% stone is observed in the central part of the area, surrounded by substrates with 10-25% stone contents and few patches of substrates with <10% stone contents. Stones are spread in the area and do not form structures that rise above seabed except at a stone ridge with limited extension.

The thickness of the postglacial layer, including the Holocene deposits, was interpreted from the sub-bottom profiler data. The resulting map of the lateglacial deposits is a good indication of the underlying substrate types, their bearing capacity and structure. Potential areas for establishing cavernous stone reefs are delineated from the above measurements.

The available description of the biological conditions in the investigation area was based on existing data from various studies. Data from the national monitoring of macro algae, which includes coverage and species of macro algae and hard substrate fauna in different depth intervals, as well as coverage of different sizes of stones observed during several years are included.

Several visual verifications with ROV were conducted in relation to the previous mapping of the Natura 2000 area in 2012. The coverage and species of macro algae and epifauna as well as the coverage and sizes of stones were registered in logbooks.

Additional existing data on e.g. fish in the area were obtained from existing literature and database search. Data from the Fish Atlas Database (Fiskeatlasdatabasen), which is administered by the Natural History Museum of Denmark, is included in the baseline description.

In this study transects with video documentation as an overview of the investigation area and as visual verification of the acoustic survey was carried out in selected sites of the studied area.

Furthermore, quantitative studies of macro algae in the investigated area according to the guidelines in NOVANA-programme were conducted.

The biological surveys showed a dense macro algae community dominates the areas with large coverage of stones. Thirty-four species of macro algae were observed dominated by species of red algae especially *Coccotylus truncates*, *Cystoclonium purpureum*, *Furcellaria lumbricalis*, *Phycodrys rubens*, *Polysiphonia fibrillosa* and *Ceramium virgatum*. The epi-fauna were sparser but 30 fauna elements were observed and most frequently observed species were starfish (*Asterias rubens*), moss animals (Bryozoa), Porifera, sinistral spiral tubeworm (*Spirorbis spirorbis*) and goldsinny wrasse (*Ctenolabrus rupestris*). No cavernous stone reefs were registered in the area.

Because the area is dominated by stones, and the focus is stone reefs, no infauna sampling has been conducted. Therefore the biological community descriptions do not include infauna.

3 General area description and background

The stone reef at Gilleleje is located about 2 km west north-west of Gilleleje Harbour in the Kattegat. The site consists of large areas of boulder reefs and sandy patches in between. Leaking methane has been oxidised and carbonate cemented smaller parts of the sand areas. These hard sandstone structures are occasionally preserved as carbonate bobble reefs. The bathymetry in the area is relatively flat with depths reaching 18 m only 5 km north-west of the harbour of Gilleleje. The moraine plateaus with a spatial extension of app. 6.8 km^2 are in water depth between 4.6 m and 10 m. The sediment on the plateau consists mainly of stones in different sizes with patches of larger boulders in between with a few cavernous elements.

3.1 Geology

The Pre-Quaternary in Kattegat was controlled by a complex fault history as the study area is located at the north-eastern edge of the Sorgenfrei-Tornquist Zone, which is an old crustal weakness zone. The depth to the Pre-Quaternary varies from 25 m to 150 m. The thickness of the Quaternary top-layers is highly controlled by the height of the Pre-Quaternary landscape ranging from few meters in thickness to about 150 m in the deep parts and in the local tectonically valleys in the subsurface landscape.

The oldest Quaternary deposits have only been documented in a few deep corings and seismic lines and these show the existence of Elsterian and Saalian till together with Eemian interglacial deposits. The Weichselian ice age has also formed the landscape with dislocations and moraine deposits and has moulded the landscape in moraine ridges deposited by recessive glacial advances during the final deglaciation. Proximal meltwater sediments were deposited in front of the glaciers, and up to 150 m thick glaciomarine sediments with a high clay-content were deposited as the sea during late glacial time.

After the Weichselian deglaciation at around 17,000 BP the relative sea level was higher than the sea level of today. During the marine Yoldia Sea phase that lasted till 10,700 BP, the relative sea level was characterized by a regression and the relative sea level fall resulted in dry land of great parts of the southern Kattegat, before the final Littorina transgression, where the increasing relative sea level resulted in repeated marine conditions of the Kattegat region.

The late- and postglacial sedimentation history has resulted in large areas with stony till deposits (substrate type 3 and 4) and proximal coastal structures with sandy and gravelly deposits (substrate type 1 and 2). The sea level rise in the period 10,000 to 5,000 BP gradually eroded the till deposits and deposited sand in the lee-side of the till-structures (Jensen, J.B. et al., 2012). Recent mobile sandy units represent the youngest sediments, deposited by strong currents and wave action in the period from mid Holocene until to today.

3.2 Biology

The part of Gilleleje Flak that is in focus is dominated by stones of different sizes in all depth intervals from 0 to app. 15 meters. That means that the stones are in the photic zone, and therefore dominated by macro algae that totally cover the stones in almost all depth intervals. The existing data and the data recovered from this survey show diverse macro algae communities with a typically 3 layered structure. A community which consist of tough algae as brown and red crusts, *Coccothylus truncatus and Ahnfeltia plicata* directly on the stones surface, and larger brown and red algae as *Fucus serratus, Laminaria digitate, Chondrus crispus, Phycodrys rubens* and *Delesseria sanguinea* in the middle layer, and a large variety of different filamentous species at the top layer. These species include both species of red and brown algae, but are dominated by red algae species.

In the deepest part of the area (12 to 15 meters) the species diversity declines and the three layered structure become more or less a two layered structure, still with high coverage – and dominated by different primarily red species. The macro algae species diversity is typical for the southern part of Kattegat both over and under the thermocline that exists at about 11 to 12 meters.

In regard to fish, scattered observations were made during the diving surveys, but the most important base line data came from Fish Atlas Database. It showed some 625 records with 83 species. An expert assessment compiled by associate professor Peter Rask Møller from Natural History Museum in regard to this project, found that app. 39 species will benefit from the recreation of cavernous stone reefs in the area– but only app. 30 of these 39 species are common. The most common species in the area (in regard to stone reefs and macro algae communities) are sea trout, (flounder on the sandy substrates), cod, eelpout, scorpion fish, garfish, pollock, seaweed fool, goldsinny wrasse and other wrasse species, pipefish, black goby and other goby species (data assessment – Natural History Museum 2016).

3.3 Hydrodynamics and coastal morphology

Gilleleje Flak is located just outside the north coast of Zealand, Denmark, which forms the southern boundary of the Kattegat. Accordingly the hydrodynamics of the waters on the location is controlled by the conditions in the Kattegat. The Kattegat is a semi enclosed sea highly influenced by the North Sea, but the Kattegat is also a transition zone between the Baltic Sea and the North Sea. Brackish water from the Baltic Sea passes the Belt Sea and is mixed with saltier water from Kattegat. With respect to the reef and the coastal morphology at Gilleleje Flak, the most important factors are the wind induced waves and currents in the Kattegat, but the wind induced water level variations in the North Sea which penetrates into the Kattegat play also a significant role.

3.3.1 Hydrodynamics – water level, waves and currents

The tide (the M_2 tidal-constituent with a period of 12.45 hours) at Gilleleje is around 0.4–0.5 m, but storm from NW can generate a high water level up to 2.0 m above mean sea level (MSL). Storms from SE can form a low water of down to 1.5 m below MSL. These water level variations mainly originate from the North Sea.

With the exception of the west coast of Jutland the actual north coast of Zealand is the most severe wave exposed coast in Denmark because

- Most severe storm come from NW
- Longest free fetch for the wind occurs in the sector wind coming from NW to N.
- Highest water levels occur under storm from NW.

The worst storms from NW–N have winds speeds of 25–30 m/s and the significant wave height reaches around 3-6 m and corresponding wave peak period is around 6–10 s.

Strong currents occurs simultaneously with strong winds and because of the distribution of water depths in the southern Kattegat and observations near Gilleleje Harbour (Havnelods, 2016) it is estimated that the maximum current is east-going with a speed of 3 knots (approx. 1.5 m/s) during storm from NW.

3.3.2 Coastal morphology

Gilleleje Flak as an abrasion flak was initially formed as the result of coastal wave erosion of the moraine landscape of North Zealand during the post glacial transgressive period 10.000 – 8.000 years BP. The erosion process has taken place in the near-shore wave breaking zone where long-shore sediment transport has removed the fine materials (sand and finer sediments) simultaneously with the transgression of the coastline.

Because of the intense wave impact only the largest particles such as rubble and stones are left on the location and have formed the stone reefs. This significant east-going long-shore sand transport is estimated to be 60 – 70.000 cubic meters yearly (DHI, 1999). A smaller part ends as a coarse-grained accumulation just west of the western breakwater for Gilleleje Harbour. Accordingly the majority of the sand transport passes the harbour on the system of sand banks and continues eastward on the banks approximately 1 kilometer from the coast. Therefore, the coast east of the harbour distinctly suffers from lack of sand.

In the recent decades the erosions process of the coastline has been reduced by extensive establishment of groynes. In the coming years, further initiatives for protection of the coast can be expected.

4 Methods

4.1 Decision on method

Building a stone reef in a region requires an integration of input parameters that describe the substrate type, the seabed depth, the energy (wave and current), the sub-seabed layers and their bearing capacity, the current biological conditions, and the expected impact after reef re-establishment. This study is using geological, geotechnical, hydrographic, and biological parameters to describe the area and to achieve the objectives of this project.

The acoustic mapping area is located in the southwestern part of the Natura 2000-area 195, Figure 2-1. The southwestern area was chosen because the eastern part of the Natura 2000-area consists of sand and sandbanks. The survey area was mapped with swath bathymetry with the newest technology "Multi Phase Echo Sounder (MPES)". The system produces accurate bathymetry with a coverage op to 10 times the water depth, which means large area can be mapped with relatively few survey lines for side scan coverage, and at the same time collect high resolution bathymetry data.

The geophysical survey included 100% side scan sonar coverage for detailed mapping of stone reef spatial extension. This, combined with the full swath bathymetry, gives a precise delineation of the stone reef and other sea bottom features and their precise position and height above the seabed. The collected Innomar seismic data combined with archive boreholes were used to generate the geological model of the area including the glacial till surface and the thickness of the till. The seismic data also gives the opportunity to delineate stony sediments from the late glacial and early Holocene deposits, with less stone percentage. This also gives a qualitative indication about the bearing capacity of the sediment and hence the suitable position for new reef re-establishment.

4.2 Geophysical mapping

A suite of geophysical systems including side scan, swath bathymetry, and sub-bottom profiler were used in the survey endeavour and a total area of 30 km^2 was surveyed with 310 line kilometres of full coverage side scan and swath bathymetry.

4.2.1 Survey vessel

GEUS's vessel Maritina was used for the geophysical survey. A detailed description of the survey vessel is included in Appendix C. The motor vessel is a twin engine 31 feet long with top speed of 20knots and survey duration of up till 12 hours per day. The vessel is very suitable for surveys in the inner Danish waters. It has booms that can handle heavy equipment such as the Innomar sediment echo sounder and the EdgeTech swath bathymetry/side scan. Maritina provides a stable working platform for this type of survey. On board was a technician and most of the time a geologist together with the captain of the vessel. Figure 4-1 shows the location of the equipment on board Maritina.

The survey vessel is 10 m long and 3 m wide. Maritina's displacement is 6 tons and it has a draught of 1.5 m. The vessel has been equipped with dual frequency swath bathymetry/side scan sonar (EdgeTech 6205) together with a parametric sediment echo sounder (Innomar SES-2000). Figure 4-1 shows the location of the instruments on the vessel. The parametric echo sounder is mounted on a pole on the port side of the vessel, with the transducer placed in 1 m water depth, while the motion sensor is mounted right on top of the transducer to achieve the best possible attitude corrections.

The EdgeTech-system is mounded in the front of the vessel where it is fixated on an in-house produced pole. This ensures a minimum of noise from bubbles in the water column and noise from the surface of the water. At the same time it is located as far from the other instruments as possible to reduce the interference as much as possible.

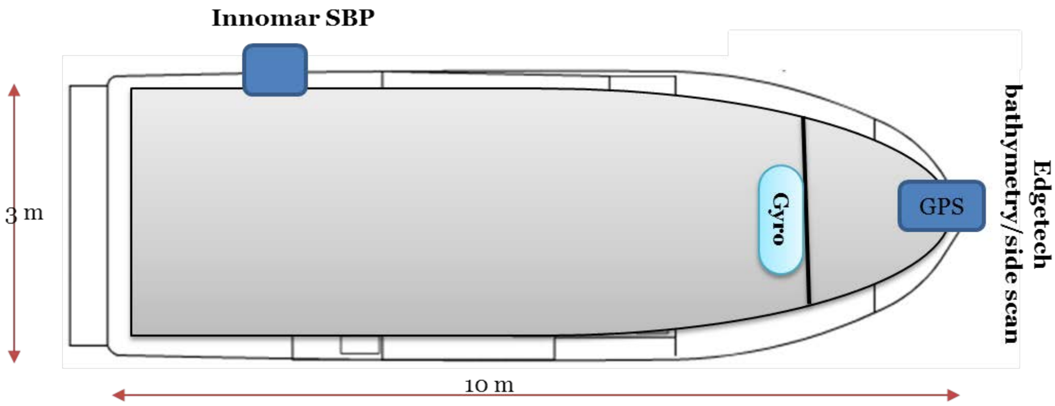


Figure 4-1 A sketch of the systems on board the survey vessel Maritina. The parametric sediment echo sounder is mounted to the port side of the vessel and the EdgeTech-instrument is mounted in the bow of the ship.

Figure 4-2 Fotos of the survey vessel Maritina and the equipment (GEUS 2016).

4.2.2 Sub Bottom Profiler (Innomar)

A parametric sub bottom profiler Innomar SES-2000 medium was used to map the upper layers of the subsurface. It can penetrate the top 70 m depending on the sediments and frequency used. It operates with frequencies between 2 kHz and 7 kHz with either a chirped signal or a continuous wave signal. Connected to a motion sensor the motion of the transducer is compensated for heave, roll, and pitch which ensures good data in a broad weather window. A detailed description of the instrument is included in Appendix C.

4.2.3 Swath bathymetry and side scan sonar

An EdgeTech 6205 Multi Phase Echosounder (MPES) was used to map the sea bed surface. It is a combined swath bathymetry system with 550 kHz frequency and a side scan sonar with the frequencies 230 and 550 kHz. This combination gives rise to real time high resolution, 3D maps of the seafloor while providing co-registered simultaneous dual frequency side scan imagery. The high number of channels enables superior rejection of multi-path effects, reverberation and acoustic noise commonly encountered in the shallow water survey environment. The two simultaneous channels in the side scan system provide wider coverage with high resolution acoustic images. The swath bathymetry part of the system has a swath of up to 10 times the water depth giving a large coverage of highly accurate bathymetry. Detailed description of the instrument is included in Appendix C.

The seabed acoustic image was obtained for the entire survey area (Gilleleje) with 150% overlap. This was done by surveying with wide swath side scan sonar system and line spacing (distance between survey lines) that ensures the required overlap. The acoustic imagery was acquired in two different frequencies of 230 and 550 kHz, the low frequency yields the general seabed structures while the high frequency part enables the detection of small objects such as stones or man made features.

4.2.4 Positionen

C-Nav 3050 was used to correct the GPS heights to DVR90 using DKGEOID02. This gives an input to a depth measurement which subsequently is corrected for tidal model data from DHI. All positions are recorded, saved and presented in ETRS89/EUREF89 UTM Zone 32.

Applanix POS MV (Positioning and Orientation System for Marine Vessels) provides accurate navigation and attitude data for use by the on board systems such as the multibeam to compensate for vessel motion during the survey.

The software navigation programme NaviPac was used for logging the GPS positions. These positions was stored on the main navigations computer, which simultaneously collect the antenna position and distributes off sets and corrected navigation data to the instruments' recording software. Detailed description of the software is included in Appendix C.

4.3 Biological/environmental investigations

There are several sources of existing knowledge on the biological conditions in the Natura 2000 area N195. In relation to the national monitoring of macro algae the area has been monitored a number of years along transects in accordance with the guidelines of NOVANA program (Figure 4-3). The data includes coverage and species of macro algae and hard substrate fauna in different depth intervals, which illustrates the development/changes in the macro algae communities over the years. Furthermore, the coverage of different sizes of stones and information on epifauna were registered in during/as part of these surveys.

Twenty-two visual verifications with ROV were conducted in relation to the previous mapping of the Natura 2000 area in 2012. The coverage and species of macro algae and epifauna as well as the coverage and sizes of stones were registered in logbooks. Data from this project is combined with the existing mapping with side scan sonar carried out in relation to the project in 2012.

Additional existing data on e.g. fish in the area were obtained from literatures and database search. Data from the Fish atlas database (Fiskeatlasdatabasen), which is administered by the Natural History Museum of Denmark, is included in the baseline description.

The biological surveys were carried out as a supplement to the geophysical study, the biological conditions, and to identify sizes of stones in the investigation area:

1. Transects with video documentation as an overview of the investigation area and as visual verification of the acoustic survey were conducted.
2. Quantitative study of macro algae in the investigation area according to the guidelines in NOVANA-programme (diving with 25 m^2 frames).

The aim of the desktop study of the biological conditions combined with the biological mapping (incl. mapping with the side scan sonar) is to describe the baseline conditions:

- The species composition and coverage of vegetation in different depth intervals
- The biodiversity in relation to vegetation, epifauna and fish with focus on stone reefs habitats including cavernous stone reefs
- Comparison with previous vegetation studies and thus the development throughout the years
- The coverage and size of stones in different depth intervals

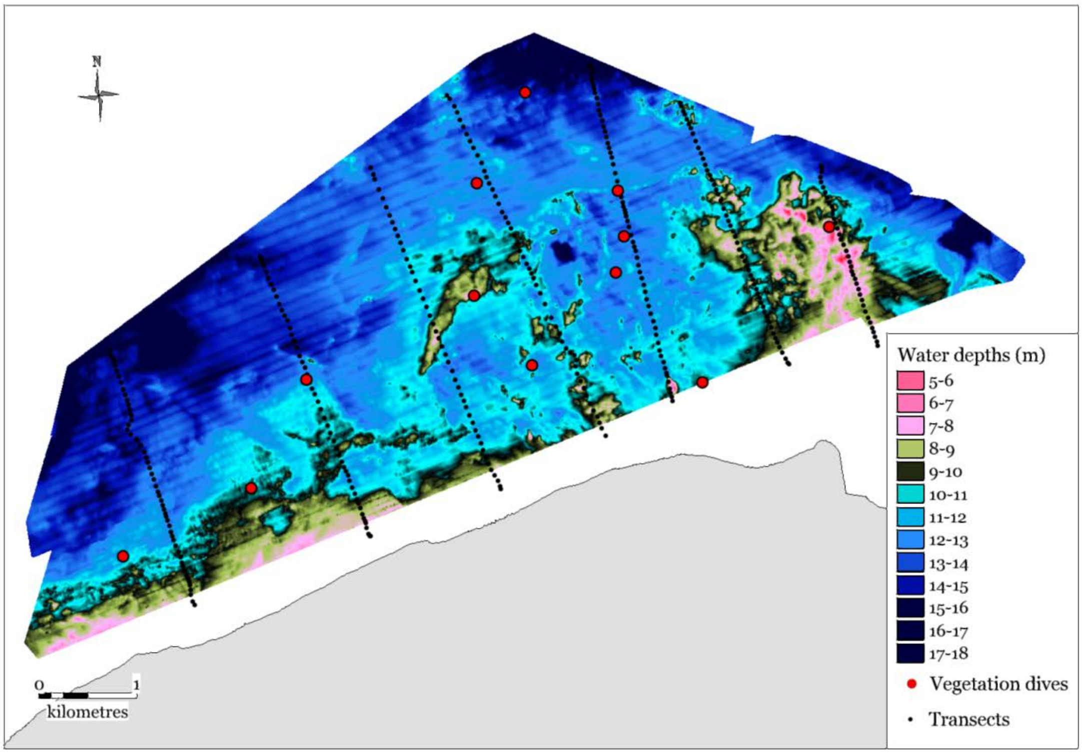


Figure 4-3 Overview of the biological surveys and existing locations for registrations of macro algae in relation to NOVANA.

4.3.1 Survey vessel

The biological survey was conducted from Orbicon's vessel "Warrior 175" (115 hk). A detailed description of the survey vessel is included in Appendix C. The vessel is very suitable for surveys in the inner Danish waters. The survey vessel is 5.35 m long and 2.3 m wide and it has a draught of 35 cm.

Figure 4-4 Orbicon's survey vessel "Warrior 175".

4.3.2 Transect dives

Transect dives were completed in order to verify and document the substrate and biological conditions for each of the substrate types in the study area.

The coverage of different species of macro algae, blue mussels, stones and the occurrence of epi-fauna and fish were registered along approx. 20 km transects (Figure 4-3). One observation was registered every 50 m, resulting in a total of 349 observations.

Two experienced commercial divers conducted the survey. Two-way communication between the diver and the surface crew was used during the diving. The diver was towed after the vessel at a speed of 2-4 km/h. The diver's height was adjusted continuously to achieve the best possible view of the seabed contents and variations. The observed data were reported regularly by the diver and recorded by the surface crew by entering data on a laptop into the program "Paravane 02". This program links observations with a simultaneous calculation of the diver's positions. The GPS of the vessel was used for positioning. The transect observations were verified with video as documentation.

The 7 transects were placed across the investigation area and covered all depth intervals as well as substrate- and nature types. The final location of transects was appointed based on the acoustic surveys and in dialogue with the Agency for Water and Nature Management (SVANA).

4.3.3 Vegetation surveys

Vegetation surveys were carried out by divers using video recording to document the finding. The dives were carried out at different depth intervals using frames of 25 m^2 in accordance with the NOVANA (National Danish Monitoring program) guidelines. In total 36 frames were distributed at different depth intervals (5-14 m) in the investigation area based on the acoustic survey and in dialogue with the Nature Agency (SVANA). The technical instruction for macro algae on coastal hard substrates were followed (DCE 2014). The vegetation dives were carried out by an experienced marine biologist.

At each location, the flora, fauna and substrate conditions in three frames of 25 m^2 each were described. For each frame the diver described the coverage of stones (stone size: large stones > 60 cm, medium sized stones 10-60 cm and pebbles 2-10 cm in diameter), the macro algae species and each species coverage on the stones, coverage of blue mussels, as well as the occurrence of epifauna and fish. The frames are documented by underwater video.

Two-way communication between the diver and the surface crew was used during the diving. The surface crew entered the vegetation data into a data sheet on a laptop. The positions were read from the GPS (Lowrance HDS 12) on the vessel.

4.4 Hydrological modelling

The studies included numerical modelling of different wave and current conditions. The numerical modelling of the hydrodynamics and the wave conditions provided input to the assessment of the sediment transport of the existing situation as well as the situation with the new reefs.

The wave model has been calibrated and validated against existing data for the weather conditions of the region with three different wind directions (WNW, NW and N) and with three different wind speeds (12 m/s, 18 m/s and 25 m/s). The model was applied for the existing situation and with the new reef which adds up to 18 simulations.

In order to model the setup of wind generated waves, the model area covers the whole Kattegat from Skagen in the north to north coast of Zealand in the south. Bathymetric data covering the model area have been provided by GEUS, including newly conducted high density measurements in the area of interest.

The modelling results are shown in Figure 4-5 and Figure 4-6. The mesh density is increasing towards Gilleleje Flak. The same mesh has been used for simulation of the actual conditions and for reef conditions; hence result differences due to mesh differences are eliminated.

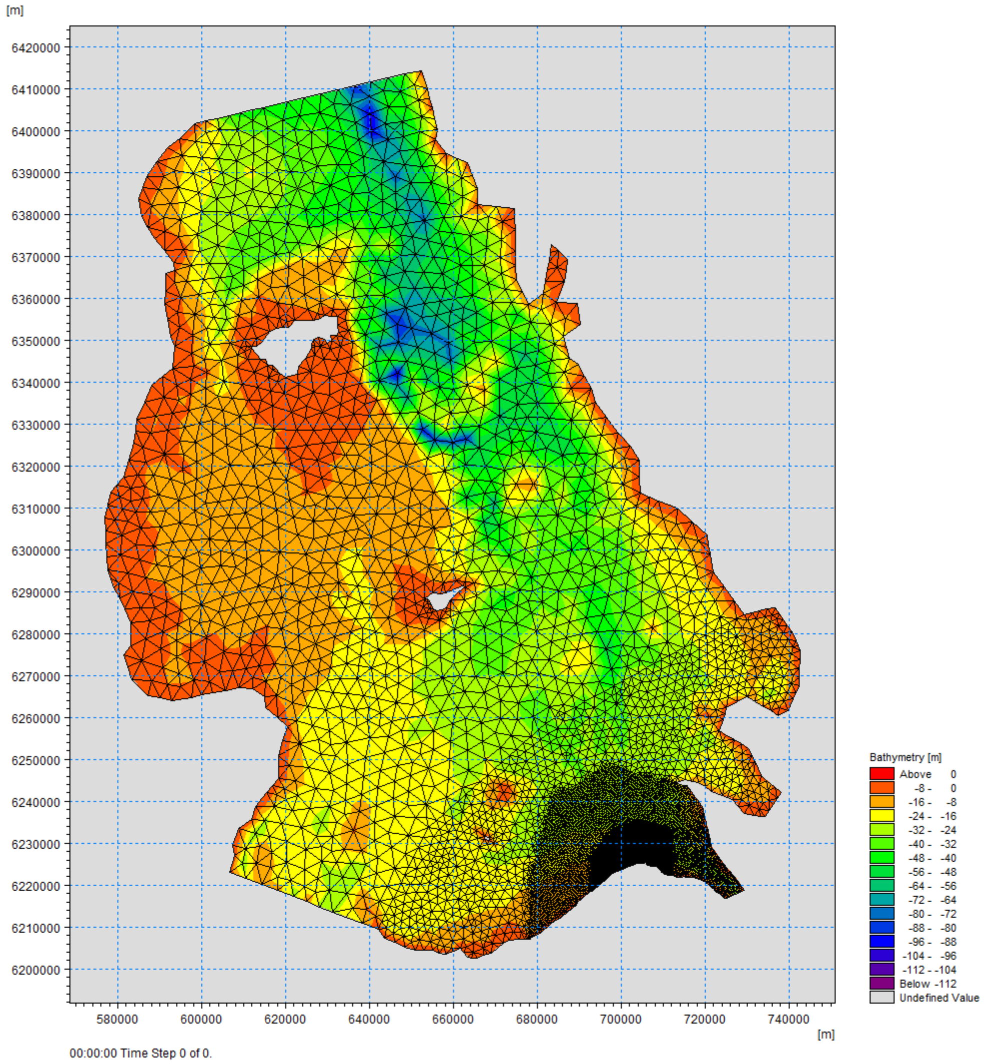


Figure 4-5 Model area and mesh density.

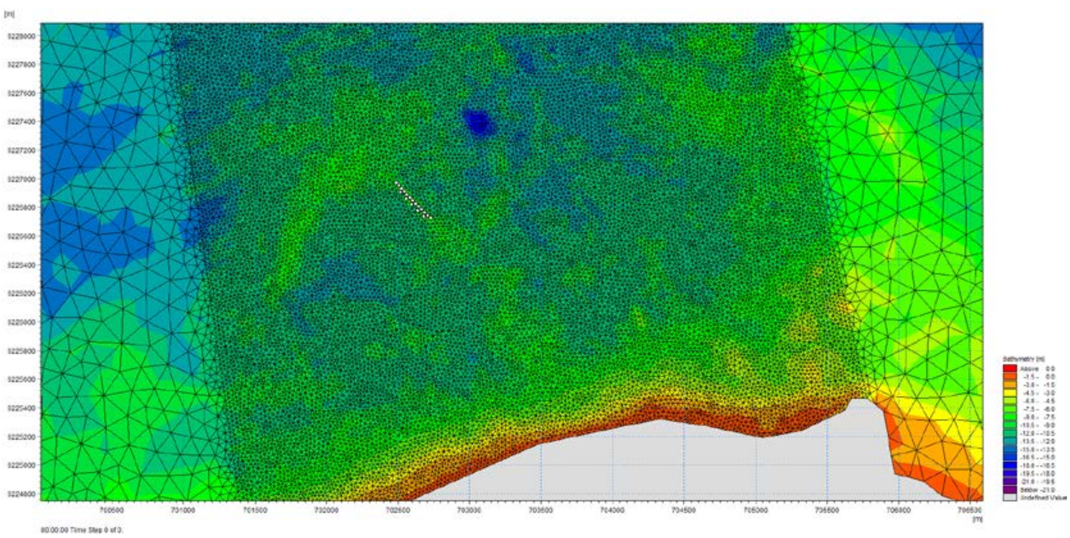


Figure 4-6 Zoom in mesh density in the Gilleleje Flak area.

18 scenarios are modelled as fully spectral quasi-steady simulations covering following wind and corresponding water level conditions:

Scenario	Wind direction and speed	Water Level (above 0 m)	Remarks
1	12 m/s - North	0.4 m	With and without reefs
2	18 m/s - North	0.8 m	With and without reefs
3	25 m/s - North	1.5 m	With and without reefs
4	12 m/s - North-West	0.4 m	With and without reefs
5	18 m/s - North-West	0.8 m	With and without reefs
6	25 m/s - North-West	1.5 m	With and without reefs
7	12 m/s - West- North-West	0.4 m	With and without reefs
8	18 m/s - West- North-West	0.8 m	With and without reefs
9	25 m/s - West- North-West	1.5 m	With and without reefs

Tabel 4-1 Model scenarios

The total wave energy loss related to the reef includes both local wave breaking and flow friction. The bottom friction (roughness height) in the area is set to k=0.02 m for simulations without reefs. To insure the right total energy loss in the simulations with reefs the roughness is still k=0.02 m around the reefs, but has been increased on the two reef locations to compensate for the grid resolution in the model.

The reefs can be considered as a submerged breakwaters and reflection of waves can occur, reducing the incoming waves to the coast. To account for this two line structures are incorporated two calculate the reflection and transition coefficients only for the reef simulations. All boundaries, whether these are land or water, are considered closed – meaning that they are all fully absorptive and no waves are generated or enter the domain from beyond the boundaries.

5 Interpretation and classification

5.1 Substrate types

The full coverage side scan mosaic of the surveyed area was classified into 4 substrate types, these are namely: 1a, 1b, 1c, 2, 3, and 4. The classification follows the SVANA Notate in 2012. The description of these classes is listed below:

1a. Soft seabed: These are homogeneous silty sand seabed or mud where there is no observed dynamic activity at the seabed and the sediment is composed mainly of silt, silty sand or mud.

1b. Sand: A homogeneous sandy seabed (sand is defined after the grain size of 0.06-2.0mm) with dynamic formations such as sand waves, ripple marks etc. In this class one can also find some shells or gravel.

1c. Patterned sandy seabed with clay: The seabed in this class is composed of clay or large relict clay blocks on silty or sandy surrounding where the clay high acoustic reflectivity gives a unique pattern of the seabed. This pattern can very possibly be caused by the high current at the seabed.

2. Sand, gravel, small stones with scattered (<10%) stones of >10cm: Highly variable substrate type dominated by sand and coarse sand with variable amount of gravel and small stones as well as few scattered large stones. The substrate is composed of a mixture of sand, coarse sand and gravel of ~0.06 – 20mm grain size, small stones of ~2-10cm grain size. The substrate may also contain larger stones of >10cm but only up to 10% of the coverage.

3. Sand, gravel, small stones with scattered (10-25%) stones of >10cm: The region classified as substrate 3 is a mixture of sand, gravel, small stones and scattered large stones of >10cm size. This substrate is similar to substrate 2, but it differs from substrate 2 in the percentage of the large stones content being 10-25% in substrate 3. The stones are often scattered in the area.

4. Stones >10cm with >25% coverage: The area classified as substrate 4 is dominated by large stones of >10cm in size, but sand, gravel, and small stones can also be observed in the area. Similar to substrate 3 the large stones can be found as a scattered layer, but substrate 4 may contain actual stone reef. Special type of substrate 4 is the pre-quaternary hard deposits such as granite and limestone. Substrate 4 includes also the bobbling reef and the biogenic reef.

5.2 Habitat nature types

Two habitat types mentioned in Annex 1 of the Habitat Directive are of relevance to the area under investigation:

- Sandbanks which are slightly covered by sea water all the time (1110)
- Reefs (1170)

These two habitat nature types are described in more detail in the following paragraphs.

5.2.1 Sandbanks which are slightly covered by sea water all the time (1110)

1) Sandbanks are elevated, elongated, rounded or irregular topographic features, permanently submerged and predominantly surrounded by deeper water. They consist mainly of sandy sed-

iments, but larger grain sizes, including boulders and cobbles, or smaller grain sizes including mud may also be present on a sandbank. Banks where sandy sediments occur in a layer over hard substrata are classed as sandbanks if the associated biota are dependent on the sand rather than on the underlying hard substrata. "Slightly covered by sea water all the time" means that above a sandbank the water depth is seldom more than 20 m below chart datum. Sandbanks can, however, extend beneath 20 m below chart datum. It can, therefore, be appropriate to include in designations such areas where they are part of the feature and host its biological assemblages.

2) Plants:
North Atlantic including North Sea - Zostera sp.- free living species of the Corallinaceae family. On many sandbanks macrophytes do not occur. Central Atlantic Islands (Macaronesian Islands) - Cymodocea nodosa and Zostera noltii. On many sandbanks free living species of Corallinaceae are conspicuous elements of biotic assemblages, with relevant role as feeding and nursery grounds for invertebrates and fish. On many sandbanks macrophytes do not occur. Baltic Sea - Zostera sp., Potamogeton spp., Ruppia spp., Tolypella nidifica, Zannichellia spp., carophytes. On many sandbanks macrophytes do not occur. Mediterranean - The marine Angiosperm Cymodocea nodosa, together with photophilic species of algae living on the leaves (more than 15 species, mainly small red algae of the Ceramiaceae family), associated with Posidonia beds. On many sandbanks macrophytes do not occur. Animals: North Atlantic including North Sea - Invertebrate and demersal fish communities of sandy sublittoral (e.g. polychaete worms, crustacea, anthozoans, burrowing bivalves and echinoderms, Ammodytes spp., Callionymus spp., Pomatoschistus spp., Echiichtys vipera, Pleuronectes platessa, Limanda limanda). Central Atlantic Islands (Macaronesian Islands) - Fish, crustacean, polychaeta, hydrozoan, burrowing bivalves, irregular echinoderms. Baltic Sea - Invertebrate and demersal fish communities of sandy sublittoral (fine and medium grained sands, coarse sands, gravely sands), e.g. polychaetes: Scoloplus armiger, Pygospio elegans, Nereis diversicolor, Travisia sp., e.g. bivalves: Macoma balthica, Mya arenaria, Cerastoderma sp., e.g. crustaceans: Crangon crangon, Saduria entomon, e.g. fish species: Platichthys flesus, Nerophis ophidion, Pomatoschistus spp., Ammodytes tobianus. Mediterranean - Invertebrate communities of sandy sublittoral (e.g. polychaetes). Banks are often highly important as feeding, resting or nursery grounds for sea birds, fish or marine mammals.

3) Sandbanks can be found in association with mudflats and sandflats not covered by seawater at low tide (1140), with Posidonia beds (1120) and reefs (1170). Sandbanks may also be a component part of habitat 1130 Estuaries and habitat 1160 Large shallow inlets and bays.

5.2.2 Reefs (1170)

1) Reefs can be either biogenic concretions or of geogenic origin. They are hard compact substrata on solid and soft bottoms, which arise from the sea floor in the sublittoral and littoral zone. Reefs may support a zonation of benthic communities of algae and animal species as well as concretions and corallogenic concretions. Clarifications: - "Hard compact substrata" are: rocks (including soft rock, e.g. chalk), boulders and cobbles (generally >64 mm in diameter). - "Biogenic concretions" are defined as: concretions, encrustations, corallogenic concretions and bivalve mussel beds originating from dead or living animals, i.e. biogenic hard bottoms which supply habitats for epibiotic species. - "Geogenic origin" means: reefs formed by non biogenic substrata. - "Arise from the sea floor" means: the reef is topographically distinct from the surrounding seafloor. - "Sublittoral and littoral zone" means: the reefs may extend from the sublittoral uninterrupted into the intertidal (littoral) zone or may only occur in the sublittoral zone, including deep water areas such as the bathyal. - Such hard substrata that are covered by a thin and mobile veneer of sediment are classed as reefs if the associated biota are dependent on the

hard substratum rather than the overlying sediment. - Where an uninterrupted zonation of sublittoral and littoral communities exist, the integrity of the ecological unit should be respected in the selection of sites. - A variety of subtidal topographic features are included in this habitat complex such as: Hydrothermal vent habitats, sea mounts, vertical rock walls, horizontal ledges, overhangs, pinnacles, gullies, ridges, sloping or flat bed rock, broken rock and boulder and cobble fields.

2) Plants:
North Atlantic including North Sea and Baltic Sea: - A large variety of red, brown and green algae (some living on the leaves of other algae). Atlantic (Cantabric Sea, Bay of Biscay): - Gelidium sesquipedale communities associated with brown algae (Fucus, Laminaria, Cystoseira), and red algae (Corallinaceae, Ceramiceae, Rhodomelaceae). Central Atlantic Islands (Macaronesian Islands) and Mediterranean: - Cystoseira/Sargassum beds with a mixture of other red algae (Gelidiales, Ceramiales), brown algae (Dictyotales) and green algae (Siphonales, Siphonacladales). Animals - reef forming species: North Atlantic including North Sea: - Polychaetes (e.g. Sabellaria spinulosa, Sabellaria alveolata, Serpula vermicularis), bivalves (e.g. Modiolus modiolus, Mytilus sp.) and cold water corals (e.g. Lophelia pertusa). Atlantic (Gulf of Cádiz): - Madreporarians communities: Dendrophyllia ramea community (banks), Dendrophyllia cornigera community (banks); white corals communities (banks), (Madrepora oculata and Lophelia pertusa community (banks). Solenosmilia variabilis community (banks). Gorgonians communities: Facies of Isidella elongata and Callogorgia verticillata and Viminella flagellum; Facies of Leptogorgia spp.; Facies of Elisella paraplexauroides; Facies of Acanthogorgia spp. and Paramuricea spp. Filigrana implexa formations. Central Atlantic Islands (Macaronesian Islands): - Warm water corals (Dendrophilia, Anthiphates), serpulids, polychaetes, sponges, hydrozoan and briozoan species together with bivalve molluscs (Sphondillus, Pinna). Baltic Sea: - Bivalves (e.g. Modiolus modiolus, Mytilus sp., Dreissena polymorpha). Mediterranean: - Serpulid polychaetes, bivalve molluscs (e.g. Modiolus sp. Mytilus sp. and oysters) Polychaetes (e.g. Sabellaria alveolata). South-West Mediterranean: - Dendropoma petraeum reefs (forming boulders) or in relation with the red calcareous algae Spongites spp or Litophyllum lichenoides. Filigrana implexa formations. Gorgonians communities: Facies of holoaxonia gorgonians (Paramuricea clavata "forest", Eunicella Interpretation Manual - EUR28 Page 14 singularis "forest"), mixed facies of gorgonians (Eunicella spp, P. clavata, E. paraplexauroides, Leptogorgia spp). Facies of Isidella elongata and Callogorgia verticillata; Facies of scleroaxonia gorgonians (Corallium rubrum). Madreporarians communities: Cladocora caespitosa reefs, Astroides calycularis facies. Madreporarians communities: Dendrophyllia ramea community (banks); Dendrophyllia cornigera community (banks); white corals communities (banks): Madrepora oculata and Lophelia pertusa community (banks). West Mediterranean: - Polychaetes (exclusively Sabellaria alveolata). Animals - non reef forming: North Atlantic including North Sea: - In general sessile invertebrates specialized on hard marine substrates such as sponges, anthozoa or cnidaria, bryozoans, polychaetes, hydroids, ascidians, molluscs and cirripedia (barnacles) as well as diverse mobile species of crustaceans and fish. Central Atlantic Islands (Macaronesian Islands): - Gorgonians, hydrozoans, bryozoan and sponges, as well as diverse mobile species of crustacean, molluscs (cephalopoda) and fish. Baltic Sea: - Distribution and abundance of invertebrate species settling on hard substrates are limited by the salinity gradient from west to east. Typical groups are: hydroids, ascidians, cirripedia (barnacles), bryozoans and molluscs as well as diverse mobile species of crustaceans and fish. Mediterranean: - Cirripedia (barnacles), hydroids, bryozoans, ascidians, sponges, gorgonians and polychaetes as well as diverse mobile species of crustaceans and fish.

3) Reefs can be found in association with "vegetated sea cliffs" (habitats 1230, 1240 and 1250) "sandbanks which are covered by sea water all the time" (1110) and "sea caves" (habitat 8830).

Reefs may also be a component part of habitat 1130 “estuaries” and habitat 1160 “large shallow inlets and bays”

6 Results

The results of the geophysical and biological investigations are shown on maps in Appendix A and here is a list of their content:

A1 Overview – The map gives an overview of the mapping area with the Natura 2000-area and the sea chart of the area

A2 Map of investigations – The map shows the biological investigations along with the geophysical survey lines (a track plot) in the area

A3 Bathymetry – The map shows the bathymetry of the area obtained from the EdgeTech-system

A4 Substrates – The map of the substrates interpreted from the data from the EdgeTech-system and the Innomar validated with the biological ground truthing

A5 Habitat directives nature types – The map of the habitat directives nature types interpreted from the substrates and the bathymetry along with the Innomar data. On this map is also a bobbling reef 1180 found during the survey in 2012.

A6 Habitat directives nature types – The map shows the same as Appendix A5 apart from that the habitat directives nature types are transparent so the sea chart and the water depths shines through.

A7 Sediment/geological map – The map shows the stony glacial till deposits at the sea bed surface along with the lateglacial Yoldia deposits also where it crops to the sea bed surface. This has been interpreted on the background of the Innomar data.

A8 Side scan sonar mosaic – The map shows a mosaic of the side scan sonar data that gives an indication of differences in material and texture of the seabed according to the reflectivity of the seabed. On the map is also given the position of a large object (possible wreck) and traces from sand extraction from the seabed.

A9 Design and location of reefs – The map shows the design and location of the proposed reefs. Two locations have been chosen for reestablishing (restoring) of the stone reef in the investigated areas. The locations are at approximately 3.5 and 5 km distance NW of Gilleleje harbour at 10m and 15 m depth respectively (PR1 and PR2). The northern reef PR2 is a submerged dam 600 m long and the southern reef PR1 consists of 18 cones of 4 m height each.

6.1 Mapping of seabed substrates and extension of the stone reef

The acoustic images was processed and interpreted with dedicated software to produce the substrate map of the seabed. The substrate classification was performed on the basis of a definition given by the SVANA Denmark in 2012 (see Chapter 5.1).

For a brief explanation: the seabed was divided into four substrate types following the stone-% per unit area. Substrate 4 represents areas with >25% stones of more than 10 cm size, substrate 3 areas with 10-25% stones, substrate 2 of <10% stones, and 1 is soft sediment that ranges from mud to sand. An example is shown in Figure 6-1.

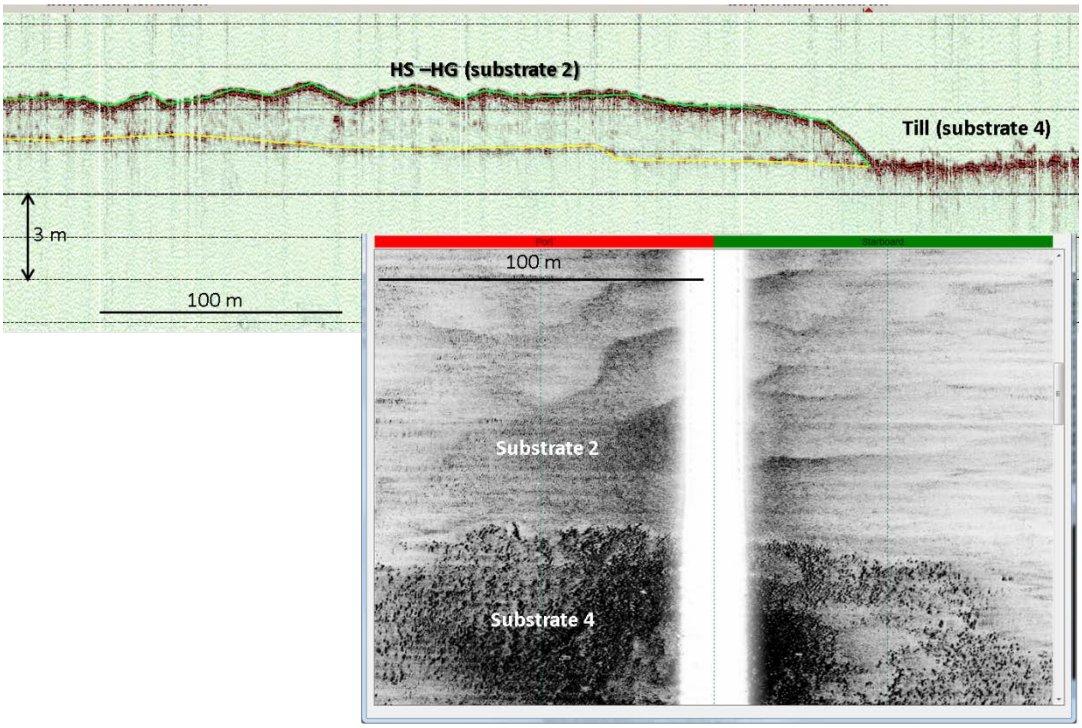


Figure 6-1 Innomar seismic profile example showing the Holocene sandbanks (HS-HG) and the glacial till at the seabed surface. Below is a side scan sonar example from the same area showing how the sandbanks and the till surface looks and how they are substrate classified accordingly (substrate 2 and 4).

After a preliminary interpretation using acoustic data only, ground truth validation points were chosen from areas of the acoustic images that is not very clear or areas that shows significant features and structures.

In order to obtain a high confident substrate map the interpretation was based on: the seabed imagery, the ground truth data, and the seismic profile of the survey line that was obtained from the sub-bottom profiler (Figure 6-2). By combining information from these three layers the seabed substrate maps were produced. From the substrate map and the bathymetry map the seabed nature types, sandbanks and stone reefs (substrate 4 and substrate 3 attached with substrate 4) and their spatial extents were accurately delineated.

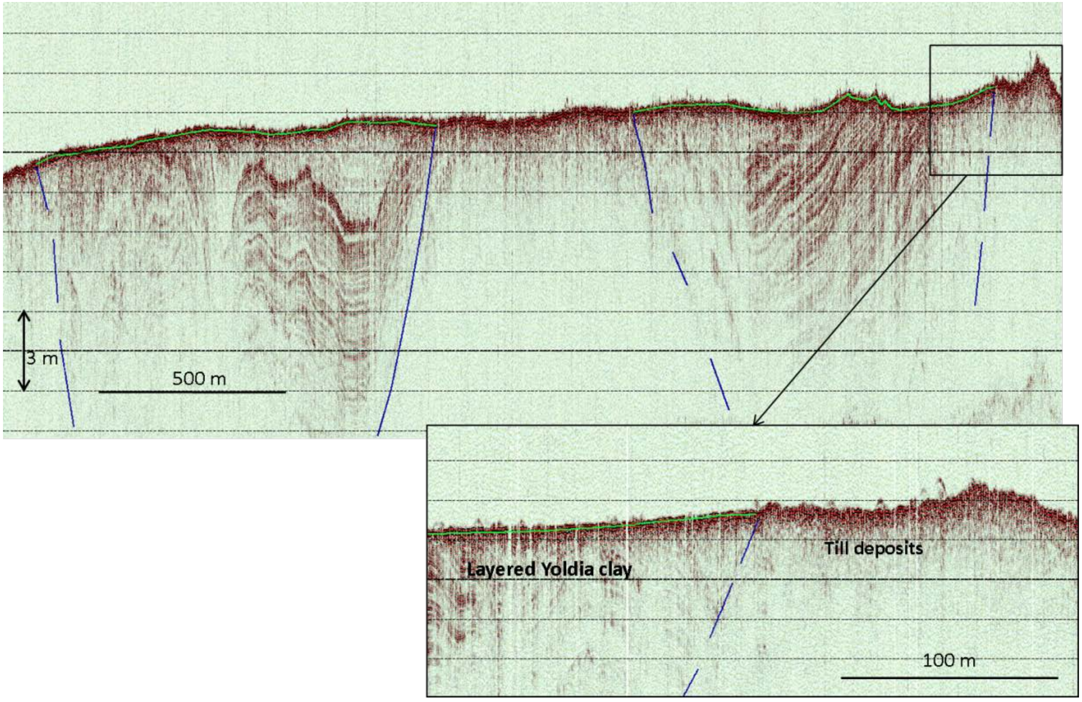


Figure 6-2Innomar seismic profile example showing the layered stony Yoldia clay and the stony glacial till units. Note the spiky seabed appearance indicating abundant stones on the seabed in the close up.

Figure 6-3 shows the substrate map of the Gilleleje area and Figure 6-4 shows the Habitat Directive nature types extracted from the substrate type as explained earlier.

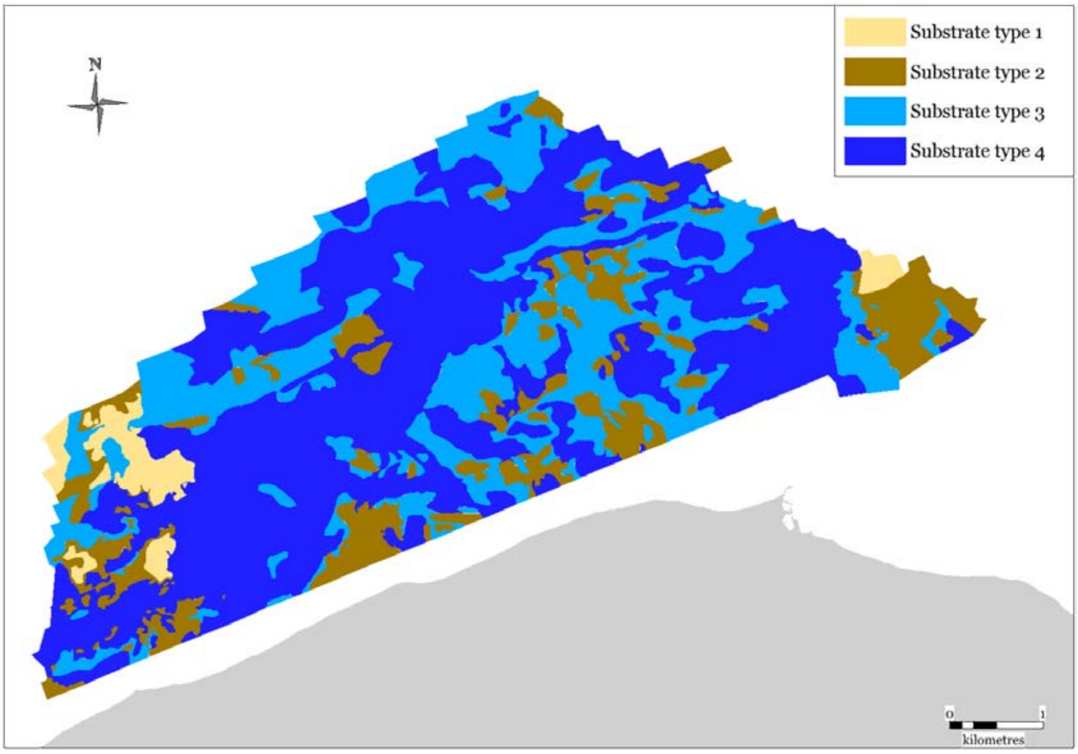


Figure 6-3 Substrate map of the area

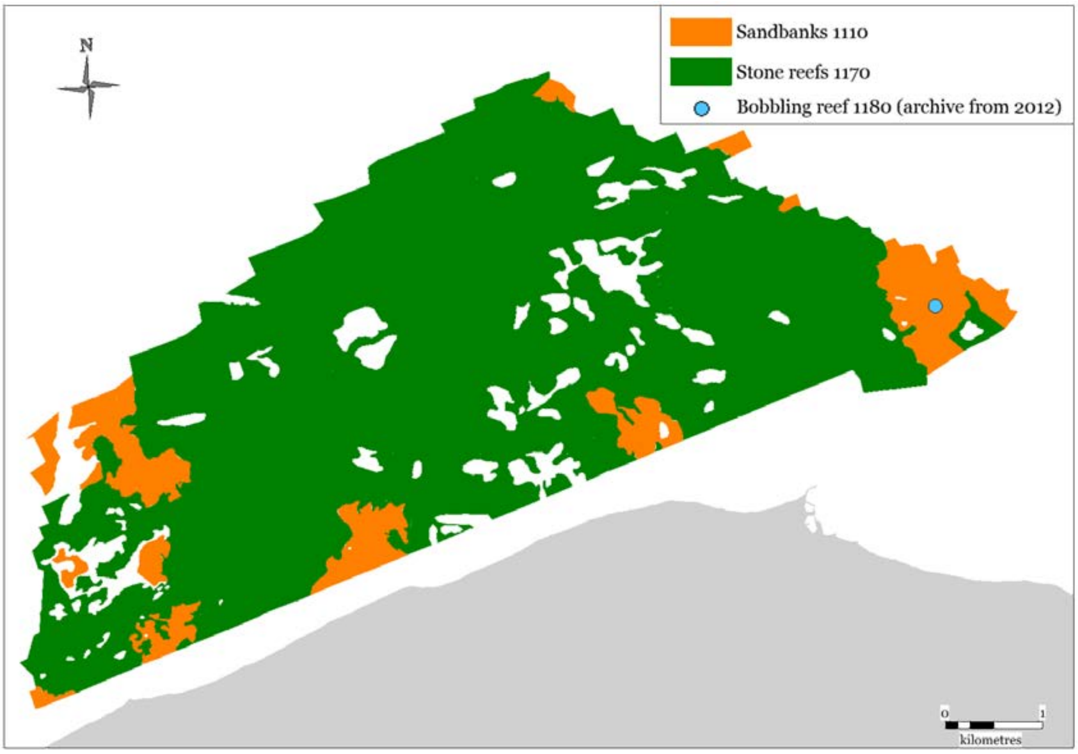


Figure 6-4 Map of the Habitat Directives nature types found in the survey area

The interpretation of the side scan sonar combined with the ground truth data show, that the substrate types of the mapped area has the following distribution:

- The substrate type 1b comprises 3% of the total area
- The substrate type 2 comprises 14% of the total area
- The substrate type 3 comprises 28% of the total area
- The substrate type 4 comprises 55% of the total area

These two figures show that the 1170 stone reef comprises 82% of the total area with stone percentage that can reach up to 60% in some regions. Stone ridges also exist at few locations. The rest of the area consists of smaller sandy patches and the nature type 1110 sand banks.

6.2 Waves, currents and sediment transport

In principle stone reefs, as they earlier existed on places like Gilleleje Flak, reduce the wave erosion of the coast by forcing the waves partly to break earlier on their way towards the coastline.

In Appendix B model results are shown:

- Since only wave simulations are conducted – a calculation of the bed shear stress induced by 3 knots current speed is presented representing the observed strong current primarily at NW storms (Figure 6-5)

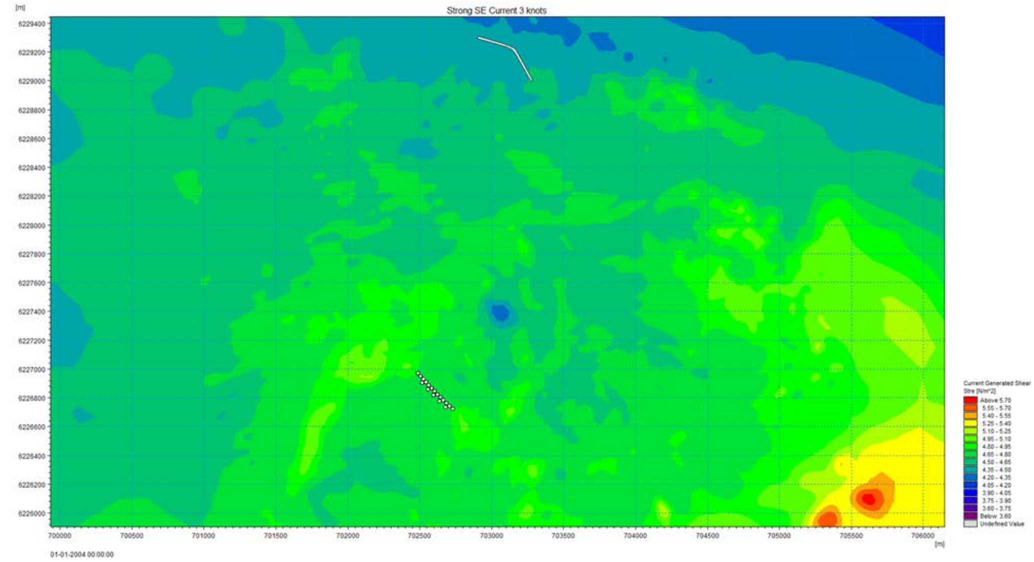
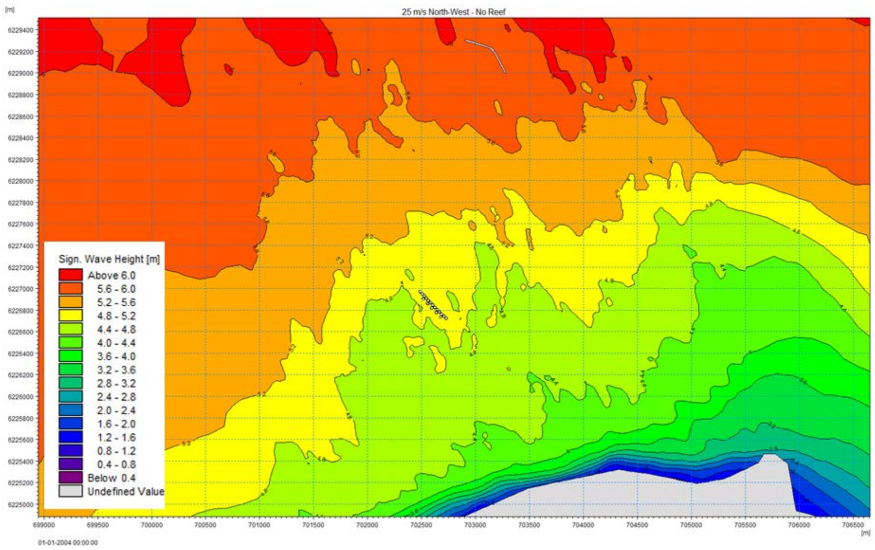


Figure 6-5 Bed shear stress calculated at 3knots current. Northern reef (PR2) is a 600 m dam type. Southern reef (PR1) consists of 18 cones.

For each wind direction and speed, the following parameters were simulated with and without reefs:

- Effect on the coast. A comparison of the wave height in 11 points approximately 100 meter from the coastline.
- Significant wave height (direct output)
- Bed shear stress
- Critical grain size due to wave motions

Figure 6-6 shows the modelling results for the NW 25 m/s wind speed which is considered as the worst case scenario (storm). The other scenarios modelling results are found in Appendix B.



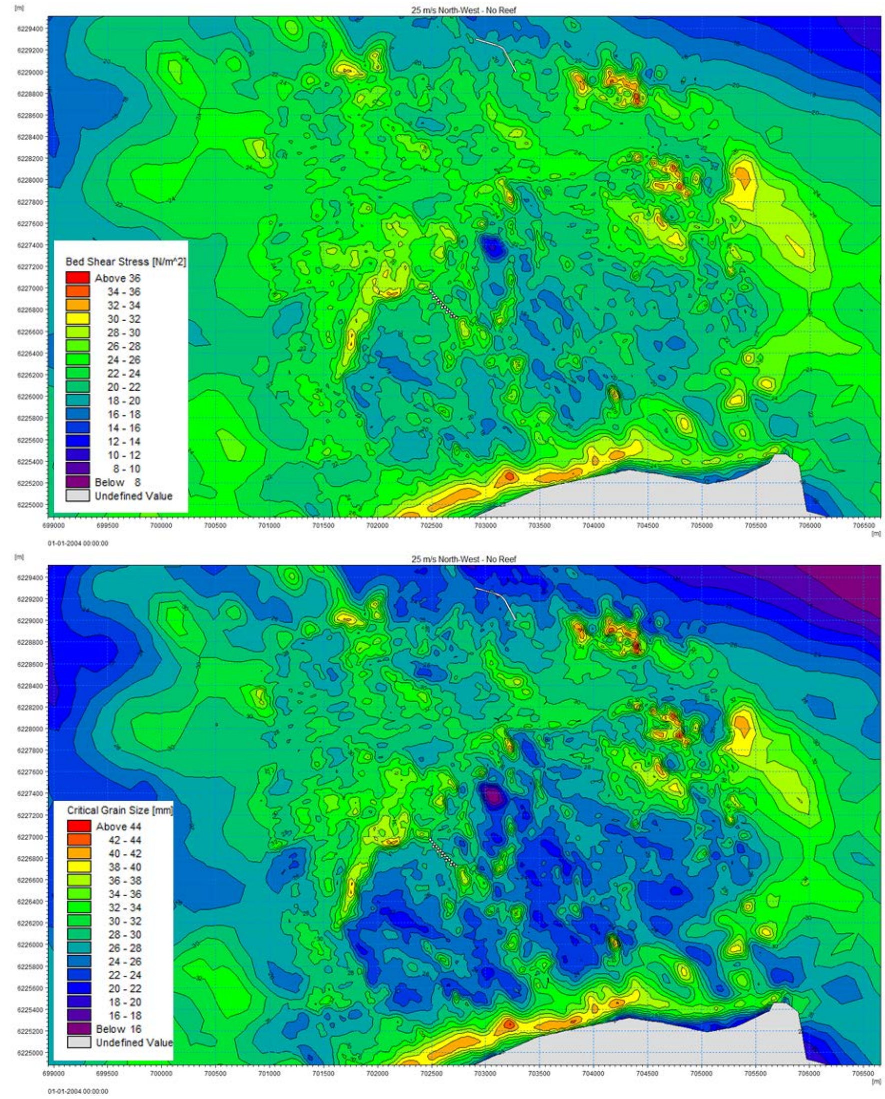


Figure 6-6 All three figures show different parameters with a NW wind at a speed of 25 m/s. Northern reef (PR2) is a 600 m dam type. Southern reef (PR1) consists of 18 cones. First: Significant wave height. Second: Wave generated bed shear stress. Third: Critical grain size corresponding to the wave generated bed shear stress.

The hydrographic model for waves and waves generated current shows that the area is stable, because only the smallest sediment fractions are mobile under maximum conditions. Furthermore, the results show that the reef itself is stable under all circumstances. The effect of the proposed reefs on the wave height is minimal and only very local reductions of wave heights can be expected.

The length of the northern deep-water reef was modelled with a length of 500 m as first projected. The effect of the reef is seen to be very local and only giving rise to a very small reduction of the wave heights. After the modelling, it has been decided to extend this reef to 600 m instead. The effect of this change will still only have negligible influence on the waves and the modelling results will be valid for this extension as well.

6.3 Bathymetry

The bathymetry in the area is relatively flat with depths reaching 18 m at 5 km north-west of the harbour of Gilleleje (Figure 6-7 and Appendix A3). The top of the moraine layer in the eastern part of the area is at 4.6 m water depth (the pink area in Figure 6-7).

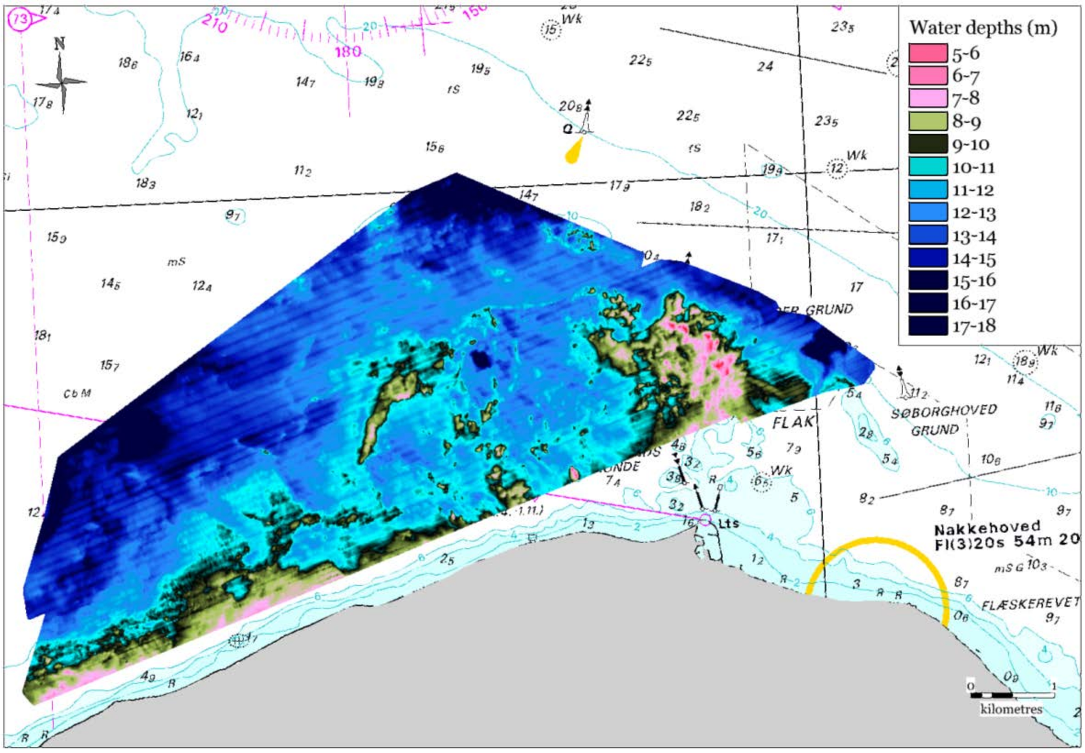


Figure 6-7 Map of the bathymetry of the area collected with the EdgeTech-system. The background is the sea chart from the Danish Geodata Agency.

The bathymetry shows a rather rugged terrain in the middle of the area that reduces in depth as we move towards the south eastern and southern part of the Gilleleje Flak. The area is generally flat but slopes gradually towards the east and the north-west.

To get a better vision of the area morphology a 3D-presentation was made and shown in Figure 6-8. Shallow structures with stones are shown in the south eastern part and small ridges of stones are found at the central part of the area.

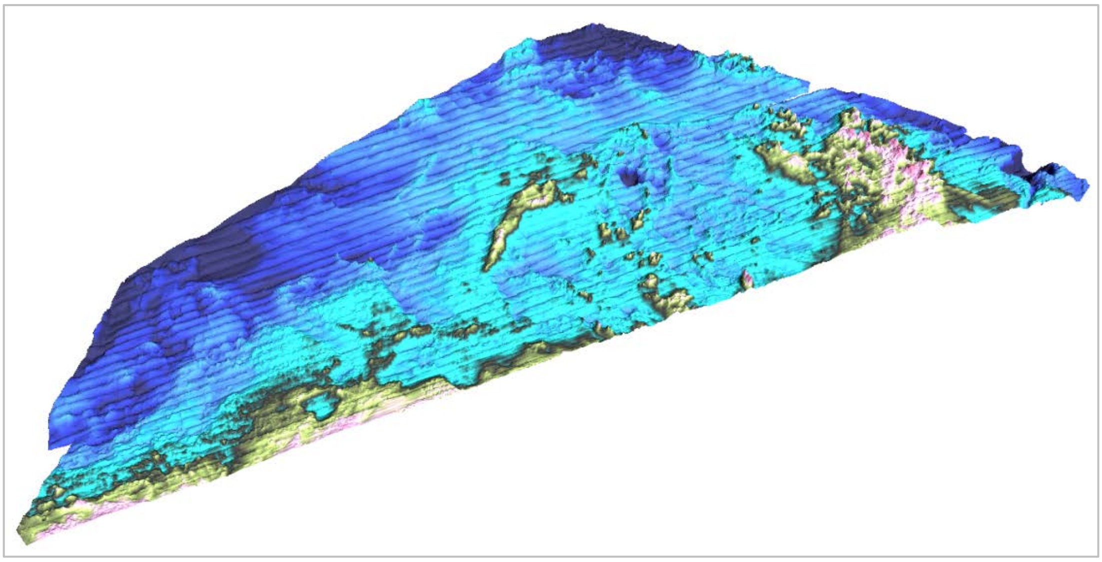


Figure 6-8 3D-manifestation of the seabed morphology.

A deep hole is noticed in the eastern part with an approximate depth of about 18 m. The origin of this hole is not yet known and requires more investigation.

6.4 Load bearing capacity

The substrate bearing capacity is an important factor that affects the stability of new reef establishments, especially when a cavernous stone reef composed of few overlaying layers of large stones is required. One way of evaluating the bearing capacity of the seabed substrate is to construct the geological model of the area from the seismic profiles obtained by the sub-bottom profiler. These profiles were interpreted with expert judgment (as there are no core samples from the area) and previous knowledge of the geological development of the area. The seismic profiles reveal the geological stratigraphic composition of the area and the different units outcropping at the sea bed (Figure 6-9 and Appendix A7).

The geological model of the area shows that the bearing capacity of the suggested sites for stone reef re-establishment is suitable for holding the weight of the stone layers. These suggested sites are characterized by till deposits cropping out at the sea bed (green colour in Figure 6-9). The risk of subsidence is limited because till deposits typically consist of over-consolidated sediments, which have been compacted by ice-loading during the previous glacial period. It is worth mentioning here, that the bearing capacity is obtained from acoustic measurements only and not from coring and geotechnical investigations.

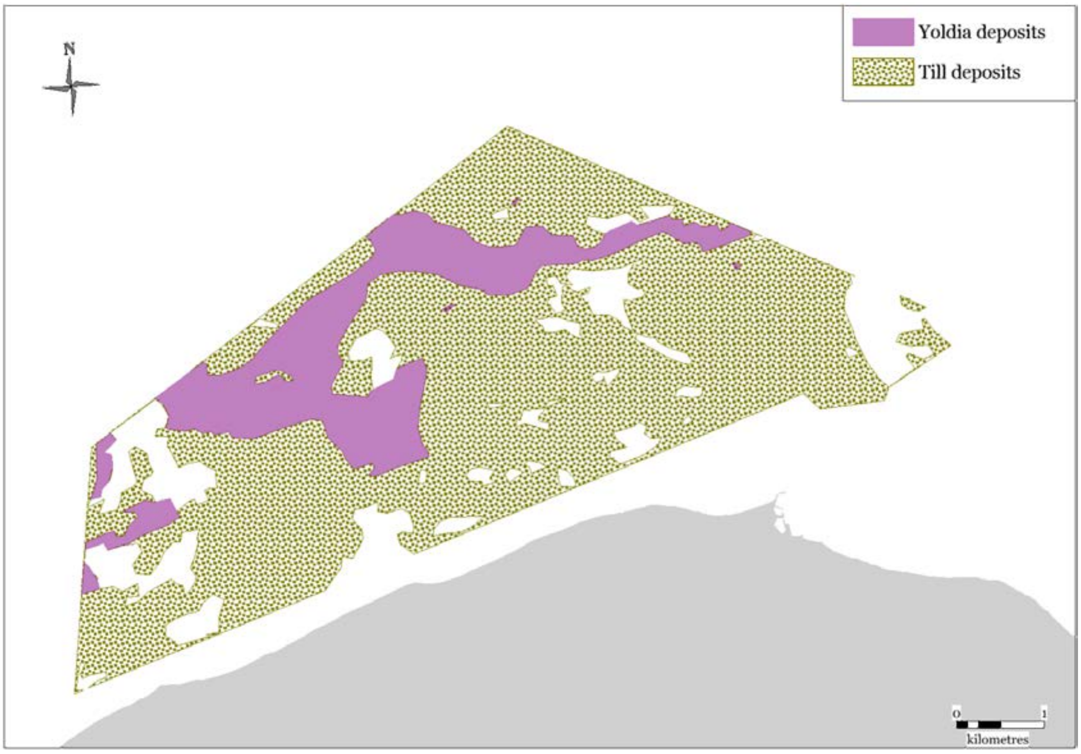


Figure 6-9 Map of the area showing where the glacial deposits (till deposits) and the Yoldia deposits are at the surface of the seabed. White areas are characterised by sand accumulations.

The lateglacial deposits, which are interpreted as mainly glacio-marine, fine-grained, layered sediments with scattered stones crops out at the seabed surface in a distinct zone across the mapped area (purple color in Figure 6-9). Similar to the till deposits, the late glacial layers has been subject to erosion leaving high percentages of large stones *in situ* on the sea bed. However, the late glacial deposits have not been loaded by glacial ice, and therefore these may be less suitable for new reef establishment.

As mentioned earlier, the combination of the results from the sub-bottom profiler (geological model) and the seabed image is crucial for interpreting the substrate types. In some regions, and due to dynamics and sediment transport, the stony seabed surface is covered with a thin layer of sand that can be deceptive in the side scan image. But the seismic interpretation will identify that, preventing false interpretations of the subsurface lithology (Figure 6-10).

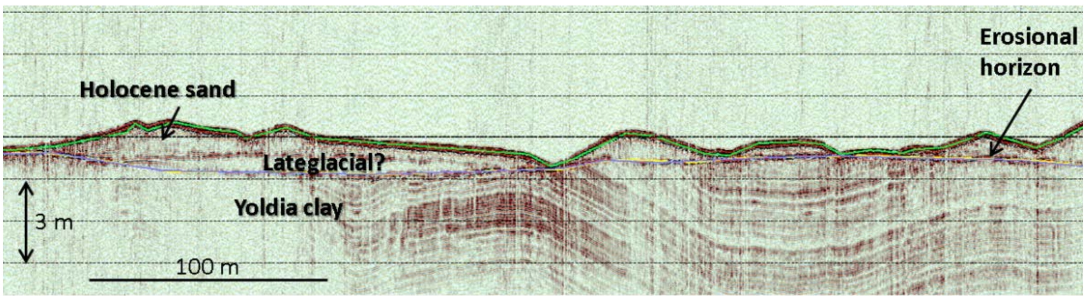


Figure 6-10 Innomar seismic example profile showing stratified Yoldia deposits that have been eroded and covered by Holocene sand banks at the seabed surface.

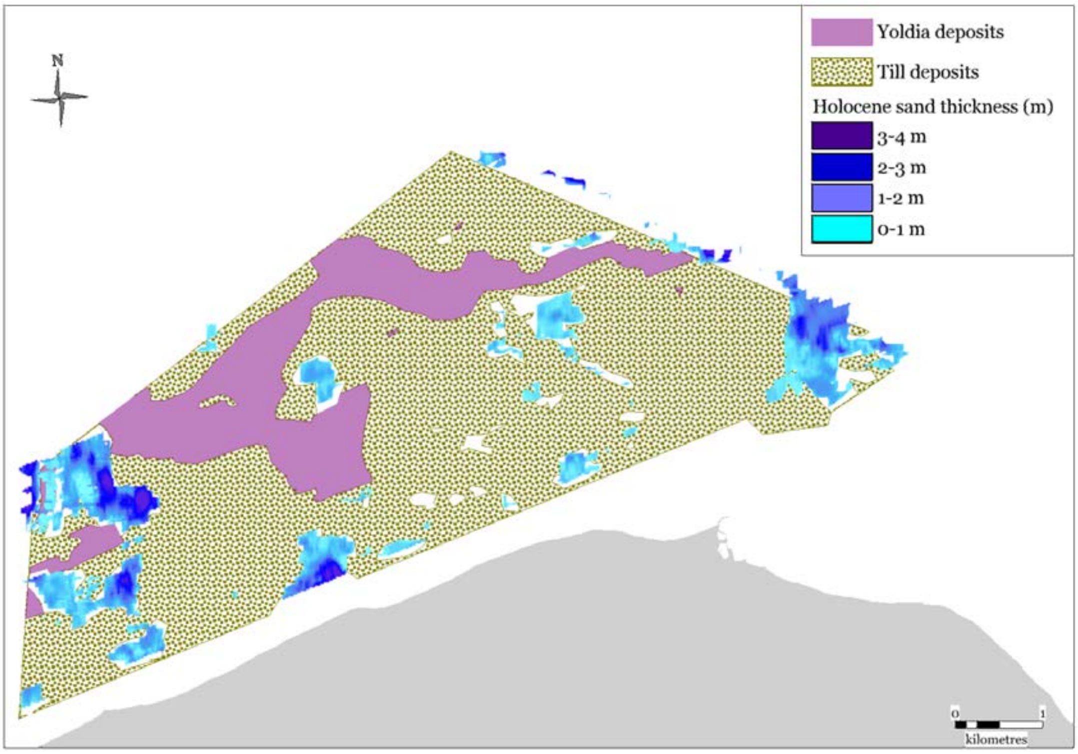


Figure 6-11 Map of the Holocene sand thickness in the area

As shown in Figure 6-9 the till deposits outcrop at the areas designated by substrate type 3 and 4 and these areas are considered to have sufficient bearing capacities for sustaining the establishment of a cavernous stone reef. Comparing the distribution of the substrates (Figure 6-3) and the outcropping geological units (Figure 6-9) reveal that high stone concentrations (substrate 3 and 4) are found on top of both the till deposits and the Yoldia deposits. However the load bearing capacity of the Yoldia deposits are likely to be less stable compared to the till deposits.

Full geotechnical investigations are needed to quantify this realisation. Core samples from the designated areas are needed for performing bearing test in the laboratory as well as other geotechnical measurements described in Chapter 7.9.

6.5 Macro algae

Macro algae require suitable substrate, such as stones, to grow on. Thus, the most diverse and abundant macro algae community were observed in areas with high coverage of stones especially areas with stone reefs.

Thirty-four species of macro algae were registered during the vegetation dives with frames on 12 different locations – 18 species of red algae, 11 species of brown algae and 5 species of green algae. In general, the macro algae communities within the investigation area were in good condition.

The combination of species of macro algae changes with depth, as they prefer different depth intervals. The number of species registered in the two depth intervals <10 m and >10 m is almost similar with a slight difference in types of species (Table 6.5-1) and coverage of the species. The brown algae Sea Lace (*Chorda filum*), Tiny Wrack Bush (*Elachista fucicola*) and Toothed Wrack

(*Fucus serratus*) as well as the green algae Green Tarantula Weed (*Acrosiphonia arcta*) were only observed at depths <10 m. Whereas species of brown algae such as *Desmarestia aculeate*, *Desmarestia viridis* and *Punctaria* as well as the green algae *Cladophora sericea* were observed at depths >10 m (Table 6-1).

Table 6-1 Species observed in the depth intervals <10 m and >10 m during the vegetation dives.

Species	<10 m	>10 m	Species	<10 m	>10 m
Red algae			**Brown algae**		
Ahnfeltia plicata	X	X	*Chorda filum*	X	X
Brongniartella byssoïdes	X	X	*Desmarestia aculeata*	-	X
Callithamnion corymbosum	X	X	*Desmarestia viridis*	-	X
Ceramium nodulosum	X	X	*Dictyosiphon foeniculaceus*	X	X
Chondrus crispus	X	X	*Ectocarpus/Pilayella*	X	X
Coccotylus truncatus	X	X	*Elachista fucicola*	X	-
Corallina officinalis	X	X	*Fucus serratus*	X	-
Cystoclonium purpureum	X	X	*Halidrys siliquosa*	X	X
Delesseria sanguinea	X	X	*Laminaria digitata*	X	X
Dilsea carnosa	X	X	*Laminaria saccharina*	X	X
Furcellaria lumbricalis	X	X	*Punctaria*	-	X
Membranoptera alata	X	X	**Green algae**		
Palmaria palmata	X	X	*Acrosiphonia arcta*	X	-
Phycodrys rubens	X	X	*Bryopsis plumosa*	X	X
Polysiphonia elongata	X	X	*Chaetomorpha melagonium*	X	X
Polysiphonia fibrillosa	X	X	*Cladophora rupestris*	X	X
Rhodomela confervoides	X	X	*Cladophora sericea*	-	X
Spermothamnion repens	X	X	**Total no. species**	**30**	**30**

The most abundant group of macro algae were red algae, especially species such as *Coccotylus truncatus*, *Cystoclonium purpureum*, *Furcellaria lumbricalis*, *Phycodrys rubens*, *Polysiphonia fibrillosa* and *Ceramium virgatum*. The high abundance of these species were found both <10 m and >10 m water depth and some of the species covered up to 60 % of the suitable substrate.

The brown algae species were less abundant than the red algae and the largest observed coverage (35 %) on depths < 10 m was the species *Laminaria saccharina*. *Ectocarpus/Pilayella* was the most abundant brown algae at depths >10 m which covered up to 20 % of the suitable substrate.

The less abundant group of macro algae was green algae, which only covered up to 1 % of the suitable substrate. Additionally, the total coverage of macro algae associated to suitable substrate (> 10 cm) was registered during the transect dives:

- As expected the macro algae community on the sandy substrate type (substrate type 1) was very sparse due to the lack or very low coverage (≤ 1 %) of suitable substrate for the macro algae to grow on.

- The coverage of suitable substrate for macro algae were slightly increased (2-8 %) in areas with more coarse sand and gravel (substrate type 2) compared to the sandy habitats. Thus, macro algae were observed at all transects observations of substrate type 2 covering 1- 97 % of the suitable substrate. There were no differences in the coverage percentage with depth.

- Areas with large stones covering 10-20 % of the habitat (substrate type 3) were dominated by macro algae covering up to 95 % of the suitable substrate. There were no differences in the coverage percentage with depth.

- The stone reef areas with > 25 % coverage of large stones (substrate type 4) were highly dominated by macro algae covering up to 95 % of the suitable substrate.

In general, macro algae were the dominating biological element in the investigation area with the densest communities in areas with coverage of stones. The area was dominated by perennial macro algae, which were common for Kattegat. The most flourishing macro algae communities were seen at shallow water.

6.6 Epi fauna

Bottom dominated by sand (substrate type 1) were only observed twice during the vegetation ground truth monitoring – one observation at depths < 10 m and one at depths > 10 m. This habitat did not contain any epifauna species.

Substrates with more coarse sand and gravel (substrate type 2) were observed at four locations during the vegetation dives – one at depths < 10 m and three at depths > 10 m. In general, the fauna was sparse especially at depths < 10 m where starfish (*Asterias rubens*), lugworms (*Arenicola marina*) and shrimps occurred. Starfish (*Asterias rubens*), sinistral spiral tubeworm (*Spirorbis spirorbis*), moss animal (Bryozoa), hermit crab (*Pagurus bernhardus*) and barnacles occurred at this habitat type at depths > 10 m.

Areas with large stones covering 10-20 % of the habitat (substrate type 3) were only observed at depths > 10 m during the vegetation dives. The habitat included seven different epifauna elements such as moss animal (Bryozoa), Porifera, sinistral spiral tubeworm (*Spirorbis spirorbis*), hermit crab (*Pagurus bernhardus*), starfish (*Asterias rubens*), Cnidaria and chiton (*Leptochiton asellus*).

The fauna in the stone reef areas with > 25 % coverage of large stones (substrate type 4) were observed at the majority of the vegetation dives both at depths < 10 m and > 10 m. Ten species of epifauna were observed at depths < 10 m, whereas 14 species were observed at depths > 10 m. The fauna at this habitat type at depths < 10 m consisted primarily of, starfish (*Asterias rubens*), moss animal (Bryozoa) and Porifera but also sinistral spiral tubeworm (*Spirorbis spirorbis*), Cnidaria, plumose rose (*Metridium senile*), shrimps, shore crab (*Carcinus maenas*), common limpet (*Patella vulgata*) and common periwinkle (*Littorina littorea*). The fauna at depths > 10 m were dominated by the same species however plumose rose, shrimps and common limpet were only seen at depths < 10 m. The fauna at deeper water (> 10 m) was more diverse and consisted besides of the abovementioned species also of species like keelworm (*Spirobranchus triqueter*), species of Cnidaria, hermit crab (*Pagurus bernhardus*), edible crab (*Cancer pagurus*), green sea urchin (*Psammechinus miliaris*), chiton (*Leptochiton asellus*), blue mussel (*Mytilus edulis*) and anomiids.

Table 6-2 Species of epifauna observed in the depth intervals <10 m and >10 m during the vegetation dives and along transects.

Species – common name	**Species - Latin name**	**<10 m**	**>10 m**
Polychaeta			
Sinistral spiral tubeworm	*Spirorbis spirorbis*	X	X
Lugworm	*Arenicola marina*	X	X
Keelworm	*Spirobranchus triqueter*	-	X
Moss animal	***Bryozoa***	X	X
Cnidaria		X	X
Plumose anemone	*Metridium senile*	X	-
Crustacea			
Hermit crab	*Pagurus bernhardus*	X	X
Shrimps	*Decapoda*	X	-
Barnacles	*Balanidae*	-	X
Shore crab	*Carcinus maenas*	X	X
Edible crab	*Cancer pagurus*	-	X
Sandy swimming crab	*Liocarcinus depurator*	-	X
Echinodermata			
Starfish	*Asterias rubens*	X	X
Green sea urchin	*Psammechinus miliaris*	-	X
Mollusca			
Common limpet	*Patella vulgata*	X	-
Chiton	*Leptochiton asellus*	-	X
Common periwinkle	*Littorina littorea*	X	X
Blue mussel	*Mytilus edulis*	-	X
Anomiids	*Anomiidae*	-	X
Ocean quahog	*Arctica islandica*		X
Sand gaper	*Mya arenaria*	X	-
Razor shells	Solenidae	X	-
Horsemussel	*Modiolus modiolus*	-	X
Common whelk	*Buccinum undatum*	-	X
Porifera		X	X
Hydrozoa		-	X
Total no. species		**14**	**21**

Additionally, the total coverage of fauna was registered during the transect dives:

The total coverage of fauna at sandy substrates (substrate type 1) were in general low covering 2-20 % of the bottom at depths < 10 m and 1-10 % at depths > 10 m. The fauna were dominated by lugworm (*Arenicola marina*), starfish (*Asterias rubens*) and crab. The ocean quahog (*Arctica islandica*) were often observed at depths ≥ 13.5 m. Additionally, there were few observations of sand gaper (*Mya arenaria*), razor shells (Solenidae) and hermit crab (*Pagurus bernhardus*). There were no significant differences in the species combination of fauna observed above and below 10 m depth on the sandy substrates.

Starfish (*Asterias rubens*) was the most abundant species in areas with more coarse sand and gravel (substrate type 2). The fauna covered 1-5 % at depths < 10 m whereas 1-10 % of the bottom at depths > 10 m was covered with fauna. Beside starfish the fauna consisted of lugworm

(*Arenicola marina*), Porifera, crab such as sandy swimming crab (*Liocarcinus depurator*) and hermit crab (*Pagurus bernhardus*). The species composition did not differ with depth.

The fauna in areas with large stones covering 10-20 % of the habitat (substrate type 3) consisted of starfish (*Asterias rubens*), Porifera, crabs and lugworms (*Arenicola marina*). Edible crab (*Cancer pagurus*) and hermit crab (*Pagurus bernhardus*) were only seen at depths > 10 m.

The fauna in the stone reef areas with > 25 % coverage of large stones (substrate type 4) was sparse and consisted mainly of starfish (*Asterias rubens*). Other fauna elements like Porifera and crabs eg. hermit crab (*Pagurus bernhardus*) were also observed. Horsemussel (*Modiolus modiolus*), common periwinkle (*Littorina littorea*), lugworms (*Arenicola marina*), Hydrozoa and common whelk (*Buccinum undatum*) were only seen at depths > 10 m.

6.7 Fish

No fish species were observed during the vegetation dives at sandy habitats (substrate type 1). Few individuals of flatfish and gobies like two-spotted goby (*Gobiusculus minutus*) were associated with areas with the more coarse sand and gravel (substrate type 2) at depths > 10 m. Wrasse were the only fish observed in areas with large stones covering 10-20 % of the habitat (substrate type 3) during the vegetation dives.

Fish like wrasses (eg. goldsinny wrasse - *Ctenolabrus rupestris*), gobies (eg. two-spotted goby - *Gobiusculus minutus*) were dominant in areas with stone reefs (substrate type 4). Furthermore, Lotidae were observed at depths > 10 m, whereas species like ballan wrasse (*Labrus bergylta*), turbot (*Scophthalmus maximus*), sand/common goby (*Pomatoschistus minutus/microps*), species of cod fish and Cottidae were observed at depths > 10 m.

Table 6-3 Species of epifauna observed in the depth intervals <10 m and >10 m during the vegetation dives and along transects.

Species – common name	**Species - Latin name**	**<10 m**	**>10 m**
Labridae			
Ballan wrasse	*Labrus bergylta*	X	X
Goldsinny wrasse	*Ctenolabrus rupestris*	X	X
Corkwing wrasse	*Symphodus melops*	X	X
Wrasse	-	X	-
Gobiidae		X	X
Two-spotted goby	*Gobiusculus minutus*	X	X
Sand/common goby	*Pomatoschistus minutus/microps*	-	X
Gobies			
Gadidae			
Cod fish sp.	-	X	X
Cod	*Gadus morhua*	X	X
Lotidae		X	X
Cottidae			
Shorthorn sculpin	*Myoxocephalus scorpius*	X	X
Agonidae			
Hooknose	*Agonus cataphractus*	X	-
Flatfish		X	X
Turbot	*Scophthalmus maximus*	X	X
Common dab	*Limanda limanda*	X	X
Plaice	*Pleuronectes platessa*	-	X
Common sole	*Solea solea*	-	X
Trachinidae			
Greater weever	*Trachinus draco*	X	X
Dragonet	**Callionymidae**	-	X
Pholidae			
Rock gunnel	*Pholis gunnellus*	-	X
Total no. species		**15**	**18**

Different fish types were observed during the transect dives:

The occurrence of fish associated with sandy substrate (substrate type 1) was sparse and consisted of gobies, hooknose (*Agonus cataphractus*), greater weever (*Trachinus draco*) and species of flatfish eg. flounder (*Platichthys flesus*), common dab (*Limanda limanda*) and plaice (*Pleuronectes platessa*).

Gobies and goldsinny wrasse (*Ctenolabrus rupestris*) were the most abundant species at in areas with more coarse sand and gravel (substrate type 2). Other fish observed at this habitat type were greater weever (*Trachinus draco*), corkwing wrasse (*Symphodus melops*), flounder (*Platichthys flesus*) and common dab (*Limanda limanda*). Common sole (*Solea solea*), dragonets (Callionymidae) and rock gunnel (*Pholis gunnellus*) were only seen along transects at depths > 10 m.

The fauna in areas with large stones covering 10-20 % of the habitat (substrate type 3) were dominated by fish species as gobies and goldsinny wrasse (*Ctenolabrus rupestris*). Ballan wrasse (*Labrus bergylta*), corkwing wrasse (*Symphodus melops*), turbot (*Scophthalmus maximus*), flounder (*Platichthys flesus*) and greater weever (*Trachinus draco*) were also registered in this habitat. Common sole (*Solea solea*), plaice (*Pleuronectes platessa*), common dab (*Limanda limanda*), dragonets (Callionymidae) and shorthorn sculpin (*Myoxocephalus scorpius*) were only seen along transects at depths > 10 m.

Fish species as gobies (eg. two-spotted goby - *Gobiusculus minutus*) and goldsinny wrasse (*Ctenolabrus rupestris*) dominated the fauna in areas with stone reefs (substrate type 4). Other species observed were ballan wrasse (*Labrus bergylta*), corkwing wrasse (*Symphodus melops*), species of cod fish eg. cod (*Gadus morhua*) and shorthorn sculpin (*Myoxocephalus scorpius*) were associated to this habitat type. Plaice (*Pleuronectes platessa*), dragonets (Callionymidae) and rock gunnel (*Pholis gunnellus*) were only seen along transects at depths > 10 m.

Fish were the most abundant fauna element in areas with stones. The most abundant fish in the investigated area were gobies and goldsinny wrasse (*Ctenolabrus rupestris*), especially in areas with many stones and stone reefs. Other species of eg. wrasses were also abundant in areas with many stones. In general, the diversity of fish species was higher at depths > 10 m and in areas with large amount of stones but the abundance was highest at shallow water.

In addition, several harbour seals and harbour porpoises were observed in the investigation area during the surveys. Marine mammals are described in Chapter 8.1.

7 Design of stone reef

As we have no or only little information about the original structure of the reef (before the stones were fished out) with regard to location, size of stones as well as depth conditions, we have used the available information, the new survey has given us, the biological data, the hydrographic setting and the accumulated knowledge to propose two position sites for reef reestablishment. This involves building cavernous reefs for enhancing biodiversity in the benthic as well as the pelagic realm, and to establish blue corridors that ensures the continuity of the habitat flow.

7.1 Location

Two locations have been chosen for reestablishing (restoring) of the stone reef in the investigated areas. The restoration areas are located approximately 3.5 km and 5 km NW of Gilleleje harbour at 10 m and 15 m depth respectively (PR1 and PR2 in Figure 7-1). The northern reef PR2 is a submerged dam 600 m long and 3m height, and the southern reef PR1 consists of 18 cones of 4 m height each. The northern deep-water reef (PR2) was first projected with a length of 500 m but after further evaluation of the budget, SVANA decided to extend this reef to 600 m.

The choice of the locations was a function of several geological and biological/environmental parameters. From the geological point of view the chosen areas bearing capacity is adequate for reef restoration, as it is composed of a thick layer of stony till. The hydrodynamic model shows that the proposed reef sites will have no significant effect on wave heights even at high wind speed (up to 25 m/s), though wave generated bed shear stress shows that sediment transport of sand and small gravel of 2.5 cm in size can be initiated at that extreme weather condition and by such high wind speed. So using the recommended stone size and structure the risk of reef collapse due to wind action is insignificant.

From a biological point of view, the creation of cavernous stone reefs in the two different depth intervals will contribute to the different biological communities. Macro algae communities will benefit from the new stone areas – especially the most shallow reef, where multi layered macro algae communities will be expected. However, especially fauna and fish communities will benefit from the cavernous reefs in both depth intervals – because new habitats (small caves and crevices) will be introduced, that more or less lack today. It is expected that different fauna and fish species will inhabit the two reef areas in regard to the different species depth preference – but it is also expected that species diversity and abundance will increase (pers. com. Associate professor Peter Rask Møller – Natural History Museum). R1 reef is connecting two large stone reef bodies acting as a bridge for securing habitat connectivity in the area.

Shallow reef (PR1, 10 m water depth):

Flora and fauna: The reef is expected to have diverse, multi-layer macro algae vegetation in all parts of the reef, dominated by perennial red and brown macro algae species plus a wide range of filamentous red and brown species.

The cavernous elements of the new reef will benefit a number of fauna species, which today have a hard time finding hiding places in the existing reefs. Large parts of the stones in a cavernous reef (under side of the stones and in the caves) will have insufficient light to macro algae – which means that epi-fauna species are expected to be able to find suitable habitats that is not available today, due to competition with macro algae - eg. edible crabs, shore crabs, sea squirts, sea anemones, and perhaps black lobster plus various fish species associated with reefs – wrasse species, goby species, cod species etc.

Deep reef (PR2, 15 m water depth):

Flora and fauna: In the lowest parts of the reef, there will possibly be a less pronounced stratification in macro algae vegetation. Perennial species of red algae will dominate plus a number of red and brown filamentous species.

At the deepest parts of the reef macro algae will still be the dominant species group. However, due to reduced light epi-fauna associated with the hard substrate will play a more dominant role in these depths - eg. sea anemones, sea squirts, barnacles, saddle oysters, horse mussels and other species such as edible crab and possibly black lobster who prefer deeper and more cold and salty water, since we expect to be below the thermocline.

The reef is also expected to be home for a larger number of fish species that would benefit from hide, shelter and food etc. Furthermore a reef in this area will be influenced by current, which generally provide better conditions for the marine communities

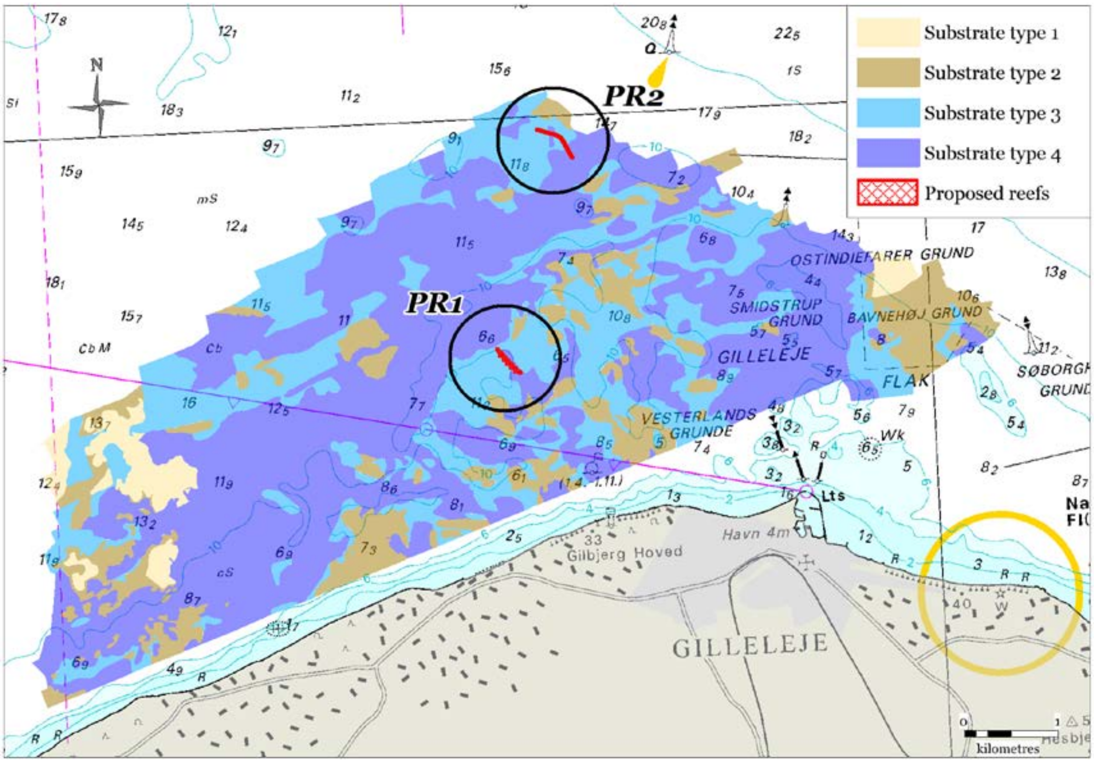


Figure 7-1 Location of the proposed reefs northwest of Gilleleje Harbour. Northern reef (PR2) is a 600 m dam type. Southern reef (PR1) consists of 18 cones.

7.2 Design/geometry of the reefs

Natural reefs in Denmark were formed during the last Weichselian glacial period. The glacial movements and the melting were responsible for deposition of the till and glaciofluvial deposits. The glacial period and the following erosion, due to changes in relative sea levels, have shaped the seabed as we know it today. Stone reefs vary considerably in shape and structure, from tightly packed collections of stones that arise abruptly from the surrounding seabed, to mosaic rocky bars, or more scattered structures with dispersed stones on sand or gravel bed (Dahl et al., 2013).

The purpose of creating artificial reefs is to enhance the biodiversity in the area. Artificial reefs can consist of various materials, for example boulders, concrete or iron. Ship wrecks, which are favoured destinations for divers, can also function as reefs (Dahl et al., 2013). The design of the reefs should meet two general demands:

- The surface (or the surface stone layer) of the reef should be irregular with large voids (cavernous) in order to be ideal habitat for pelagic animal (fish) and enhance biological activities of benthic flora and fauna just like the naturally existing reefs.

- The reef should be physically stable to resists the wave action from the most severe storms occurring with a mean return period of 30 – 100 years, and the reef-building materials should have a corresponding service life.

Based on this and after consulting marine engineers of high expertise in the field of breakwater construction and windmill engineering, as well as off-shore constructing companies and stone providers, it is recommended a design of the reefs as follows:

- The southern reef (PR1) consists of 18 elements formed as circular truncated cones with a height of 4 m, bottom-diameter of 20 m and a top-diameter of 2 m (Figure 7-3).

- The northern reef (PR2) is a 600 m long submerged dam with a height of 3,0 m and trapezoidal cross-section with a bottom-width of 15,0 m and a top-width of 3,0 m (Figure 7-2).

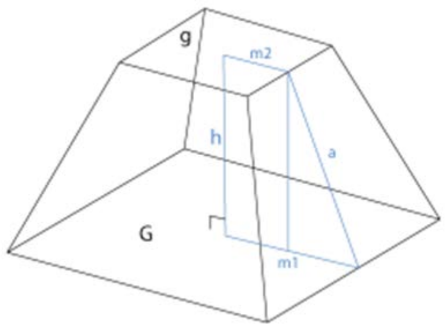


Figure 7-2 PR2 is a 600 m long submerged dam with a height of 3,0 m and trapezoidal cross-section with a bottom-width of 15,0 m and a top-width of 3,0 m

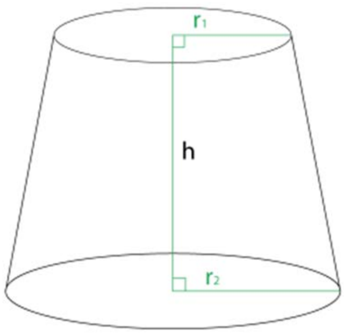


Figure 7-3 PR1 consists of 18 element formed as circular truncated cones with a height (h) of 4 m, bottom-diameter (r_2=10 m) of 20 m and a top-diameter (r_1=1 m) of 2 m.

Basically a stone reef can physically be considered as submerged breakwaters that are often used for coastal protection. Significant scientific and technical knowledge on the subject is available for example from the EU project DELOS (Environmental Design of Low Crested Coastal Defense Structures) carried out by 18 European research organizations within marine biology and coastal engineering. Reef re-establishment information and Best Practice was obtained from the Blue Reef project that had the same objectives in establishing reefs in the Læsø Trindel area in Northern Kattegat.

In principle a stone reef (corresponding to a submerged rubble mound breakwater) can be constructed of a number of layers of granular materials, with a core of smaller and cheaper boulders inside the reef. This gives the most economical solution because the finer materials are cheaper and can be dumped directly from a barge, whereas the larger blocks in some cases (decided by the contractor) must be placed individually.

The cover-layer as well as the total reef element should be designed according to generally accepted engineering principles known from breakwater design, where impacts from the storm waves are the most important load. Stone reefs based on these principles seem to fulfill the above mentioned demands.

7.2.1 Type of stones

The stone reefs are preferably built of large-grained stone materials, similar to natural reefs, in order to make the new stone reef as close to the original stone reef as possible, with regard to type and size of the stones. This ensures a surface structure towards which benthic animals and macroalgae have optimised their attachment structure through millennia of evolution.

There are several possible sources of natural stones (Dahl et al, 2013):

- The best solution is to reuse "sea boulders" from piers in connection with harbour expansion. Sea boulders originate from stone reefs and are typically very rounded in shape and have the greatest degree of originality.
- Another possible source is "fieldstones", which can be procured from construction works or from farmers. This type of stone also typically has rounded shapes.
- The third alternative is to use "quarry stones" from quarries in Sweden or Norway, for example. Compared with sea boulders and fieldstones, quarry stones have irregular shape and sharp edges.

Most recommendable for the reef elements are quarry stones (from Norway or Sweden) which have irregular shape and sharp edges that ensure large surfaces compared to sea boulders and fieldstones. From the Blue reef project experience the quarry stones are most suitable for reef restoration, but we recommend a thorough discussion with the offshore construction and breakwater building companies to optimize the effort and choose the most suitable type of stones for the job.

7.2.2 Stone sizes

The size of the stones used should reflect the physical environment and a large biodiversity must have many micro habitats where the individual species can settle. Varying bottom conditions and high physical complexity ensure this.

Cavernous boulder reefs have an extra quality in their high physical complexity and thus greater biological diversity. They make the area more attractive to both the pelagic animals (fish) and the benthic flora and fauna. Using similar-sized boulders placed in several layers, will ensure the formation of more interstitial spaces.

In the area of interest, the common stone sizes ranges for tens of centimeters to over 1m, and that will be the recommended sizes for re-establishing the reef. All these suggestions and recommendations will depend highly on the budget, the availability, and the recommendation from the experienced construction company.

The hydrodynamic model shows that the wave generated bed shear stress at high wind speed (up to 25 m/s) will cause sediment transport of sand and small gravel of 2.5 cm in size, so the stones must have a size more than tens of centimetres.

7.3 Method for placement of the stones

Acquiring and placing stones will typically be the activity that claims the highest budget in the project, and the organisation of this is of great importance to the project's financial framework and to the quality of the restored stone reef.

- Costs for transporting and placing the stones are lower in periods with quiet weather. In open and exposed areas, the weather may affect total costs significantly.
- The most important objective of this project is to have as much reef as possible within the project's financial framework, so the stones are not to be placed with pinpoint accuracy with regard to position.
- A method for placement of the stones that ensures the complex cavernous elements and following the reef design is important. Such an assignment requires a specialised vessel.
- Choosing when to deploy the stones should take into account the season and the weather conditions to allow for subsequent biological development.

All these suggestions and recommendations will depend highly on the budget and the recommendation from the experienced construction company.

7.4 Assessment of wave and current

The effect of storms and current on the proposed reefs was thoroughly considered in this project. The status of wave height was calculated in a hydrodynamic model (Appendix B) for different wind speed coming from different directions before and after the re-establishment of the stone reefs PR1 and PR2. The wave generated bed shear stress was calculated for the same scenarios for the area before and after the establishment of the reef.

A total of 18 scenarios were modelled for wind speed and direction and corresponding water level conditions. The results indicated that with increasing wind speed from 12-25 m/s the critical sediment grain size below which the sediment will be transported rises from 1 to 22 mm respectively (Figure 7-4).

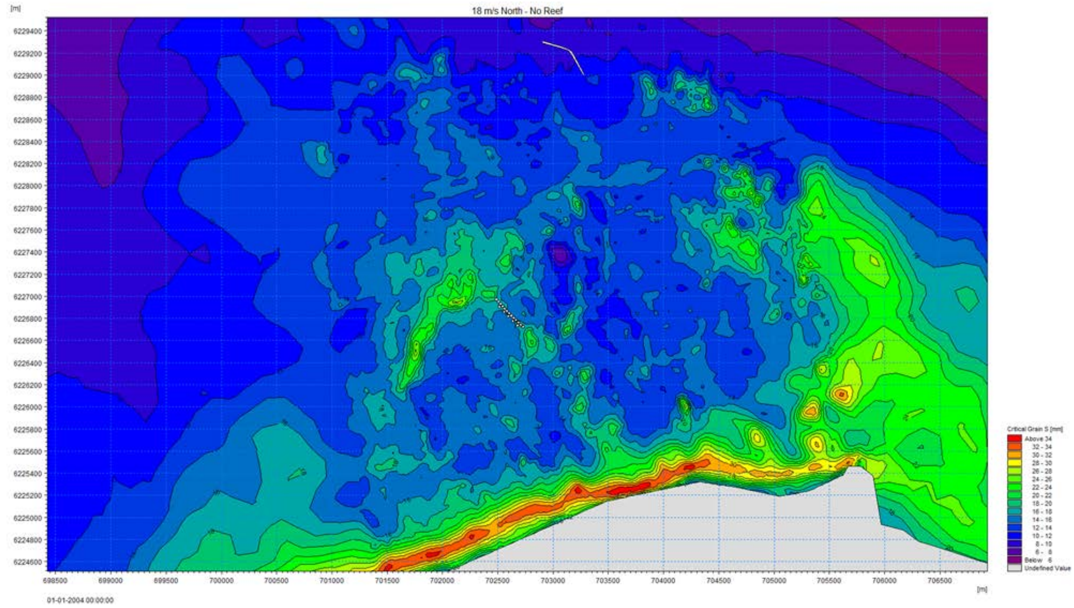


Figure 7-4 Critical grain size corresponding bead shear stress generated at to wind speed of 18m/s.

Wave height on the other hand will have insignificant changes after the re-establishment of the proposed reef (Figure 7-5).

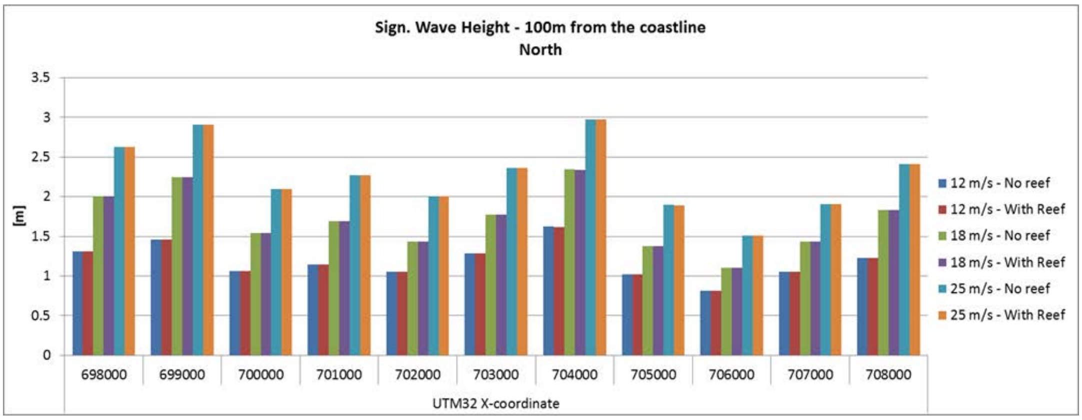


Figure 7-5 Wave height effect on coast for Northern wind at different wind speed with and without reef.

7.5 Impact of reefs on surrounding waters

Preliminary investigations have shown that the reef under normal condition with wind speed of 12–25 m/s do not have any noticeable effect on the surrounding waters. Only during severe storms from the northern sector the reefs give a slight reduction of the wave height and bottom shear stress on the lee-side of the reef, but not enough to induce any significant damage of the reef structure (Appendix B).

7.6 Impact of reefs on coast erosion or longshore sand transport

Preliminary investigations have shown that the reefs under normal condition with wind less than 15–20 m/s do not have any noticeable effect on wave energy transported towards the coastline neither in respect to energy transported or to the direction the wave energy moves.

Only during severe storms from the northern sector the reefs give a slight reduction of the wave transported towards the coast line. Accordingly a small and marginal reduction of the coast erosion (coast line regression) and similar reduction of the east-going sand transport can be expected theoretically, but in practice no impact will be experienced (Appendix B).

7.7 Biology

The aim with the restoration of stone reefs in the area is to improve the biodiversity of macro algae, epifauna and fish by restoring cavernous stone reefs.

Reestablishment of a reef at deep water:

The current in the location of the new stone reef in the northern deep part of the area is strong which will benefit the biological conditions.

It is expected that the stratification of macro algae will be less pronounced at the shallowest part of the reef. Perennial red algae such as sea beech (*Delesseria sanguinea*), clawed fork weed (*Furcellaria lumbricalis*), carrageen moss (*Chondrus crispus*), *Coccotylus truncatus* as well as red and brown bushes such as Polysiphonia and Ceramium and brown algae like Desmarestia will dominate.

Macro algae will still occur at the deeper part of the reef, primarily species like sea beech (*Delesseria sanguinea*), *Coccotylus truncates* and *lithothamnium* eg. (*Corallina officinalis*). However, it is expected that species associated to the hard substrate will be more dominant at these depths eg. sea anemones (Actiniaria), ascidians, sessile, tube-building annelid worms (Serpulidae), barnacles, anomiids, horsemussel (*Modiolus modiolus*) and other species like edible crab (*Cancer pagurus*). Perhaps even lobster (*Hommarus gammarus*), which prefer deeper more cold and saline water may occur as the deepest parts of the reef may be below the pycnocline.

Furthermore, this deep reef will be favourable for many fish species such as gobies, wrasses and cod fish as the reef will provide shelter from predators and current. Furthermore, fish will fourage on the many food items associated with the reef. The reef might also function as a nursery area for juvenile fish.

Reestablishment of several small reefs at shallow water:

The macro algae composition at the shallow water reefs is expected to be diverse and multilayered dominated by perennial species like oarweed (*Laminaria digitata*), toothed wrack (*Fucus serratus*), sea beech (*Delesseria sanguinea*), clawed fork weed (*Furcellaria lumbricalis*) and *Coccotylus truncatus* as well as several red and brown filamentous algae like species of Ceramium, Polysiphonia and purple claw weed (*Cystoclonium purpureum*).

Currently it is difficult for many species of fauna to find shelter in an area without cavernous reefs and the competition for space on the stones is high. Reintroducing cavernous structure will accommodate many fauna species as they can find shelter and substrate to settle on. Fauna species associated with hard substrate like edible crab (*Cancer pagurus*), shore crab (*Carcinus maenas*), ascidians, sea anemones and sessile, tube-building annelid worms (Serpulidae) may settle at the shadow full parts of the reef (eg. caves), at spaces lacking currently eg. due to the competition with macro algae. The reef will attract fish species of eg. wrasses, gobies and cod fish. The reef might also function as a nursery area for juvenile fish.

7.8 Risks for the ship traffic

The stone reef to be established in Gilleleje waters is basically outside the ships route and will be of 7-8 m deep. The exact positions of the reefs and its exact depth will be forwarded to the responsible authority to issue warning signs and mark the new reef on the sea chart.

7.9 Pre-monitoring

The pre-monitoring phase is divided into three main parts:

- The geotechnical,
- The physical monitoring and,
- The biological monitoring

As Gilleleje Flak is a location where stone reefs still exist but might have been damaged or partially excavated, the seabed will most likely be able to carry the weight of the new stones, but as a precaution geotechnical testing on cores taken from the area should be carried out. It is also recommended to do tri-axial tests on the core samples to ensure sediment stability.

Before the placement of the stones, the area should be mapped geophysically to produce very detailed bathymetry and side scan sonar images of cm accuracy for the area of establishing the new reefs. The geophysical monitoring should be performed immediately prior to the stone placing activity. This will give a robust reference of the area before the establishment of the stone reef from the physical aspects.

The biological monitoring programme should consist of vegetation dives similar to those conducted in this study in accordance with the NOVANA guidelines, to describe the occurrence of macro algae and epifauna in the area, as well as a separate fish survey to monitor the occurrence of fish as fish species are targets for the reestablishment of the stone reefs.

It is suggested that the biological monitoring is carried out when the exact location of the new stone reefs are designated. This will be a baseline monitoring conducted before the project is commenced.

7.10 Post-monitoring

This is a rather important act after the laying down of the stones and finishing the first stage of the reef re-establishment. It will give solid indication of the reef structure and integrity (size, extent, and height), the new seabed morphology, the effect of the energy (sediment transport), and on the long run, the assessment of the benthic and pelagic biological development of the new reef.

Monitoring is considered as a complementary part in assuring the functionality of the established reef and its physical integrity. With the implementation of a monitoring program, it will be possible to document what the restoration project has meant for fauna, benthic animals, fish, etc. and whether the project has realized its objective. The monitoring program should be designed so that the results can be used to evaluate whether the reef has had the intended favorable impact (Dahl et al, 2013).

On the basis of the expected colonization by algae, benthic fauna or fish, the monitoring program should be designed with a view to collecting information about the occurrence of these organisms. The methods may vary according to species, the physical structure and depth of the reef, etc. Monitoring is divided into two main parts:

- The physical monitoring and,
- The biological monitoring

The physical (geophysical) monitoring should be performed immediately after the stone placing activity, to produce the new bathymetry map of the newly established reef. After 5 years of the placement of the stones another geophysical monitoring is recommended. This will show the development of the reef structure from the physical point of view. It will also reveal the dynamics of the area and the volume of sediment transport and direction that took place after the construction of the reef.

The purpose with the reestablishment of stone reefs at Gilleleje Flak is to increase the biodiversity and the abundance of fish in the area. Thus, the biological monitoring programme is based on collecting data to describe the development in the biological communities of macro algae, epifauna and fish in the areas around the new stone reefs.

The biological monitoring programme should consist of vegetation dives similar to those conducted in relation of this study in accordance with the NOVANA guidelines to describe the occurrence of macro algae and epifauna in the area as well as a separate fish survey to monitor the occurrence of fish as fish species are targets for the reestablishment of the stone reefs.

The biological monitoring should be in 2022. It is important that all monitoring endeavours are conducted at approximately the same time of the year due to the annual cycle of flora and fauna and in a control area with similar biological conditions. This will strengthen the comparison of monitoring data from different year.

However, previous studies in relation to Blue Reef have shown that the development of biomasses of benthic animals and plants on boulders that were restored to the reef was assessed to be far from complete after four years. They conservatively estimated that the process of migration to the area, succession and development of biomasses corresponding to a climax community would take at least eight to ten years (Dahl et al. 2013).

The monitoring of macro algae can be used to evaluate the stability of the reestablished stone reefs.

8 Impact assessment of Natura 2000

The project area is situated within the marine Natura 2000 area 195 Gilleleje Flak and Tragten, and covers 150 km^2. The area is designated as habitat area 171 due to the occurrence of sandbanks (1110) and reefs (1170) habitat types. In addition harbour porpoise, *Phocena phochena* (1351) is on the designation. In 2013, a bubbling reef (1180) was identified within the Natura 2000 area but it is not on the designation, yet. The bubbling reef is observed in the eastern part of the project area (Figure 6-4).

The reefs (1170) are primarily found in the western coastal part of the Natura 2000 area (Figure 8-1). Stone fishery in the past has impacted the area and it is lacking cavernous structures. The aim with this project is to improve the habitat type reef (1170) by establishing cavernous reefs in order to strengthen the biodiversity in the area.

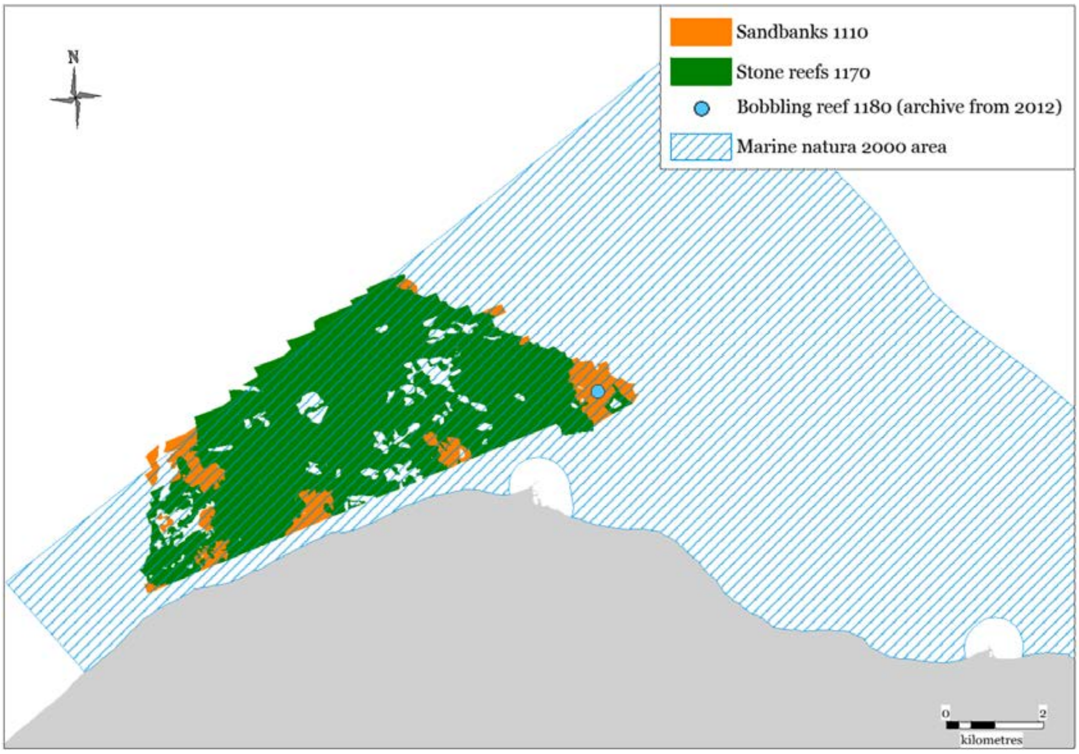


Figure 8-1 Map with Natura 2000 area and the habitat nature types found in the area.

According to the mapping of the Natura 2000 area in 2012 the sandbanks (1110) consists of sand with shell gravel in the wave ripples. Shells of common cockle (*Cerastoderma edule*) covered up to 15 % of the bottom. The fauna consisted of shore crab (*Carcinus maenas*), common starfish (*Asterias rubens*), netted dog whelk (*Tritia reticulata*) and hermit crabs (*Pagurus bernhardus*). Dab and sand gobies were the only fish observed on the sandbanks. The vegetation consisted of single specimens of sea beech (*Delesseria sanguinea*).

The reef habitat type consists of a dense coverage of pebbles between 2 – 10 cm (50-60 %) and larger stones (35 %). Cavernous stone reefs were not observed during the mapping in 2012. The coverage of fauna was in general low (few %) and consisted of mobile animals such as common starfish (*Asterias rubens*), shore crab (*Carcinus maenas*) and blue mussels (*Mytilus edulis*).

Common limpet (*Patella vulgata*), Porifera, ascidians and moss animals (Bryozoa) were observed in the larger stones with macro algaes. Fish such as goldsinny wrasse (*Ctenolabrus rupestris*), juvenile cod and gobies were found in the reef areas. The coverage of macro algae was dense (70-90 %) and consisted of species such as toothed wrack (*Fucus serratus*), clawed Fork Weed (F*urcellaria lumbricalis*), oarweed (*Laminaria digitate*), bush shaped red algae, sea beech (*Delesseria sanguinea*), sea oak (*Halidrys siliquosa*) and landladies' wig (Desmarestia aculeata). The species were primarily perennial (Jensen et al. 2012).

The overall objective of the Natura 2000 area is to ensure a rich diversity of plants and animals in the habitat types in the area with occurrence of characteristic species of the designation. The area is ensured as a good habitat for harbour porpoise. The habitat types and the species must ensure favorable conservation status. Furthermore, the ecological integrity is ensured by good water quality through reduced nutrient loading and environmental hazards, which is regulated through the water management plans.

In the long term habitats and species should achieve a favorable conservation status. The overall area of habitat types reefs and sand banks, and the area of the harbour porpoise habitat should be stable or increasing, if natural conditions allow. The objective for habitat types and species without the condition assessment system is favorable conservation status. This means that the condition and the total area of habitat for harbour porpoise are stabilized or increased as basis for sufficient suitable breeding and feeding areas.

The objective of the second plan period of the Natura 2000 area is implemented to ensure favorable conservation status of the reefs, which are affected by previous removal of stones and boulders. At the same time, a restoration project will improve the condition of species on and around the reef, eg. harbour porpoise.

8.1 Marine mammals

The area is a hotspot for harbour porpoise especially during the summer. Thus, the Natura 2000 area 195 Gilleleje Flak and Tragten are designated for harbour porpoises. Furthermore, harbour porpoises are protected under annex IV according to the Habitat Directive.

The harbour porpoise is the most common and the only breeding whale in Danish waters. The most important habitats seem to vary depending on the season. However, particularly important habitats are found in eg. the waters around Skagen, in the Great Belt around Sprogø, the waters south of Gedser Odde, the waters south of Ebeltoft near Djursland, most of Little Belt as well as the waters around Als, Sønderborg and Flensburg Fjord. Especially during summer the area around Øresundstragten north of Helsingør-Helsingborg including the Natura 2000 area 195 is an important area for harbour porpoises (Teilmann et al. 2004, Søgaard and Asferg 2007).

At present no specific breeding areas for the species in Danish waters are known. As harbour porpoise occurs in areas of high variation in depth, bottom conditions, occurrence of fish and degree of pollution, it is difficult to generalize about the type of habitat porpoise prefer (Søgaard and Asferg 2007).

Females are pregnant in 11 months and give birth in May-July. It is assumed that harbour porpoises are more sensitive to disturbances in this period as well as during the mating season in July-August.

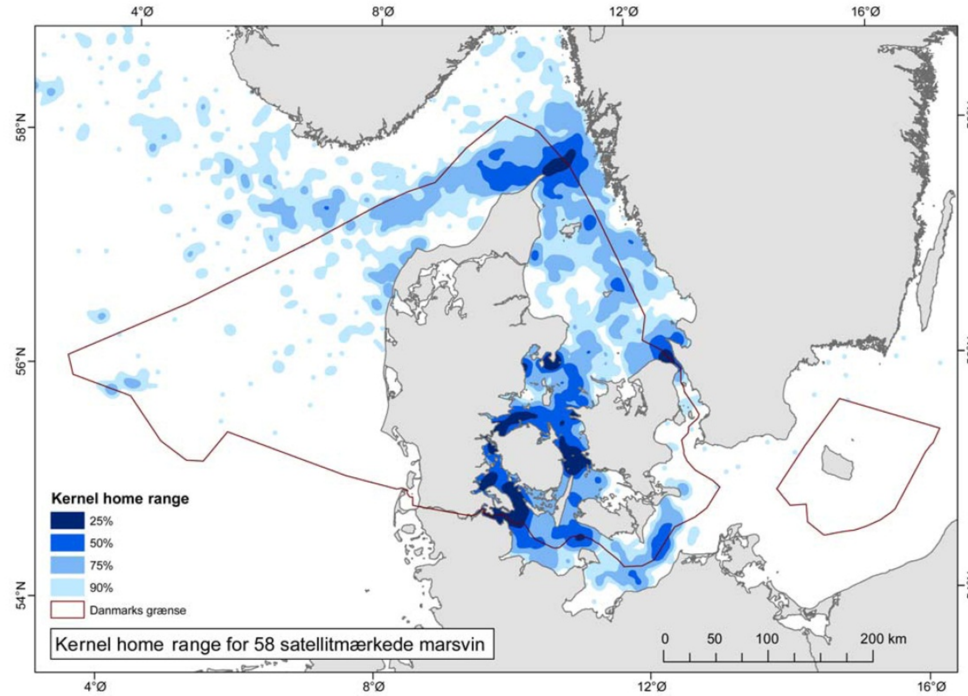


Figure 8-2 Map of kernel home range for 58 harbour porpoises tagged in Danish waters during the period 1997 to 2005. There was used one position per animal per day. The darker the colour marked on the map, the more important area for porpoises. Map from Søgaard and Asferg 2007.

Studies conducted by the National Environmental Research Institute have shown that animals often dive to the bottom, where many fish occur. Harbor porpoises are active all day and dive almost as often at night than during the day. In Danish waters harbor porpoises prefer to dive less than 40 m, but in the Skagerrak is measured diving depths down to 200 m (Søgaard og Asferg 2007).

During the relatively few large counts of whales conducted in Danish waters the stock in the Kattegat, the Great and Little Belt, the sea north of Funen and the western Baltic in 1994, was estimated to 22,127 animals, in 2005 to 13,600 animals and in 2012 to 18,495 animals (Søgaard and Asferg 2007; Sveegaard et al. 2012). An average abundance of 0.17 animals per km inside Natura 2000 areas and an abundance of 0.33 animals per km outside Natura 2000 areas were registered during acoustic tracking in 2012. The abundance at Gilleleje Flak and Tragten was estimated to 0.14 harbor porpoise per km (Naturstyrelsen 2014b).

In general, harbor porpoises are sensitive to noise, and studies have demonstrated the noise can influence the occurrence of species in impacted areas. However, it is assessed that harbor porpoises are capable of adapt to the noise from ship traffic, since the occurrence of the species is large in areas such as the Great Belt, where the ship traffic is intense. The greatest known threat to harbor porpoise are from inadvertent bycatch by net fishing but also pollution, underwater noise, heavy ship traffic and reduced amount of food can have a negative impact on the porpoises.

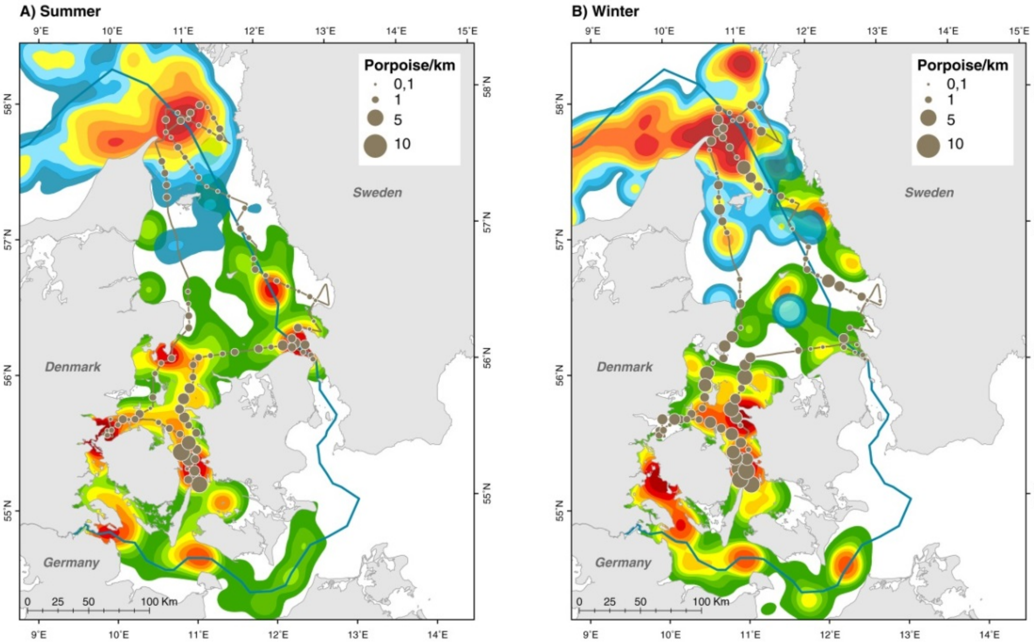


Figure 8-3 Summer and winter habitats in the inner Danish waters with high concentrations of harbour porpoises are illustrated with red. The overlaid circles are number of acoustic registrations for each 10 km along Teilmann et al. 2008.

An extensive amount of data from satellite tracking, flight- and ship counts as well as acoustic counts of harbor porpoises in Danish waters are collected in the period 1991-2007.

The most significant data sets for designation of important areas are obtained by satellite tracking of 63 harbor porpoise from 1997 to 2007. In the northern North Sea and in the inner Danish waters, including the area around North Samsø Belt, there were also used acoustic records as an independent method to verify the important areas identified from satellite tracking data.

The National Environmental Research Institute prepared a report in 2008 that collects all relevant data from these studies on the movements of porpoises and distribution in Danish and adjacent waters. The purpose was to identify and eventually protect particularly important areas with high density of harbor porpoise (Teilmann et al. 2008).

9 Discussion and recommendations

The geophysical, biological, and hydrodynamic investigations in the area of interest in Gilleleje Flak, Natura 2000 habitat area 195, indicated that the establishment of the new reefs will have significant environmental and biological improvements and that no negative physical, biological or environmental effects of any importance can be expected.

Compiling all available information, two locations are proposed for reef restoration. These two locations are most likely to be capable of withstanding the load of the stones that will be used to construct the proposed reefs as they are located at seabed areas with glacial till deposits consisting of stones and hard substrate. Nevertheless, a full geotechnical investigation to quantitatively measure the bearing capacity is recommended.

The two proposed reef positions are located in areas of respectively 10m and 15m depth. These two depths ranges were deliberately chosen to ensure enhancement in biodiversity in both the pelagic and the benthic regimes. The shallowest reef will most likely be dominated by macro algae communities with a multi layered structure, but different epi-fauna species and fish will benefit from the new cavernous reef. Macro algae will most likely also dominate the reef located on deeper water, but with a larger proportion of epi-fauna species and fish such as edible crap and cod that will benefit from the caves in the new reef placed under the thermocline.

Choosing the right design, stone types, stone size and structure is a task that has required thorough investigations and consultation with the engineering companies of related expertise as well as with individuals with long offshore construction experience. Added to that is the "Best Practice" and recommendations obtained from a similar endeavour in the Blue Reef project in Northern Kattegat.

Based upon the previous experiences we have recommended two reefs to be build in the area, the Northern PR2 is a 600 m dam of 3 m hight and the southern PR1 consists of a structure of 18 coneshaped elements that connect two existing reef structures. We recommend the use of quarry stones of about 0.5 m-1.0 m diameter.

Different construction methods for placing these stones can be used and it depends basically on the required shape of the reef, the available stone size, the required accuracy of the final design, and of course the budget. We recommend to investigate this particular subject even further when the project is accepted and time table for conducting the diffent activities is set.

We recommend a pre-construction geophysical and biological survey on the two proposed sites in order to obtain all the required measurements as accurately as possible. We also recommend a geophysical monitoring survey after the construction. This in order to map the change in the bathymetry of the newly constructed reefs and to investigate the integrity and the settelement of the errected reefs.

Biological investigations on the exact locations of the new reefs are recommended for several reasons. Before the stones are placed it is recommended to describe the communities that will be burried under the new reef, as part of the Natura 2000 impact assesment. But also to document the changes in communities – a before and after study. Further more it is recommended to do post-construction monitoring to document the settlement of the biological communities at the new cavernous reefs. By this it is possible to evaluate the goal of the project, where fish and fauna species should benefit from the cavernous structures that do not exist in the area today.

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