

Seabed habitat mapping

**Providing insights in the distribution of habitats
protected under the EU Nature Restoration
Regulation in the Dutch North Sea**

TNO-2026-17825 – September 2026

Seabed habitat mapping

Providing insights in the distribution of habitats
protected under the EU Nature Restoration Regulation
in the Dutch North Sea

Author(s)	Bas Binnerts, Timo Constantin Gaida, Aron Schouten, Willem Dabekaussen, Bart Meijninger
Classification report	NLD ONGERUBRICEERD
Title	NLD ONGERUBRICEERD
Report text	NLD ONGERUBRICEERD
Appendices	NLD ONGERUBRICEERD
Number of pages	95 (excl. front and back cover)
Number of appendices	7
Sponsor	LVVN
Project name	North Sea habitat maps NRR
Project number	060.65180

The classification designation Ongerubriceerd is equivalent to Unclassified, Departementaal Vertrouwelijk is equivalent to NLD Restricted, Stg. Confidentieel is equivalent to Confidential and Stg. Geheim is equivalent to Secret.

All rights reserved

No part of this publication may be reproduced and/or published by print, photoprint, microfilm or any other means without the previous written consent of TNO.

© 2026 TNO

Summary

The European Union Nature Restoration Regulation (NRR) requires Member States to develop National Restoration Plans that are underpinned by spatially explicit, scientifically robust information on the distribution and characteristics of marine habitats. For the Dutch North Sea, this creates a clear need for up-to-date, consistent and policy-relevant seabed information that can support restoration planning, monitoring and reporting. Existing seabed maps provide an important baseline, but their spatial resolution, thematic detail and consistency are often insufficient for addressing NRR-specific questions, particularly for heterogeneous seabed features such as hard substrates, reef-forming structures and transitions between sediment types.

The objective of this project is to support the Ministry of Agriculture, Fisheries, Food Security and Nature (LVVN) in the elaboration of the marine component of the NRR by improving the availability and applicability of seabed habitat information for the Dutch North Sea. The project focused on generating and evaluating spatially explicit maps of seabed information that are directly relevant as abiotic habitat proxies under the NRR. Rather than providing a full ecological assessment, the emphasis was on characterising seabed properties that form the physical basis for habitat occurrence and restoration potential, using existing geological information, seabed samples, bathymetric maps and side-scan sonar data.

At North Sea-wide scale, updated seabed-sediment maps were produced using the Folk classification system and an associated mud-percentage map, building on and extending the most recent Geological Survey of the Netherlands products. These maps provide a spatially consistent baseline for the full Dutch Exclusive Economic Zone, including uncertainty information, and form a reference for large-scale assessment and reporting. The results provide more insight in the spatial variability in sediment composition across the Dutch North Sea and highlights gradients and patterns that are relevant for habitat interpretation, particularly in relation to areas with potential suitability for reef-building species.

At local scale, side-scan sonar (SSS) data were analysed for a selection of priority areas to assess fine-scale seabed heterogeneity using the added value of high-resolution acoustic mapping. The SSS analyses reveal pronounced small-scale variability in sediment properties and seabed morphology that is not resolved in North Sea-wide products. These results provide important contextual information for interpreting habitat suitability within specific areas and demonstrate the strengths and limitations of SSS for local seabed characterisation. A specific aim of the project was to assess whether acoustic indications of biogenic reef structures, in particular mussel and oyster beds, were present in the high-quality SSS data within the scanned priority areas. Although the analysed data were of sufficient quality to detect reef patches, no clear acoustic patterns indicative of mussel or oyster beds were found.

For geogenic reef features, semi-automated mapping approaches were applied to SSS data to generate stone density maps for key areas such as the Borkumse stenen, Texelse stenen and Klaverbank. For these areas, an overview of the distribution of wrecks and other anthropogenic hard-substrate objects was produced by combining the SonarReg database with targeted interpretation of SSS imagery, providing an indicative assessment of their potential contribution to habitat development or recovery.

Overall, the project results demonstrate that a multi-scale approach combining North Sea-wide sediment mapping with targeted, high-resolution side-scan sonar (SSS) analyses provides a robust and transparent basis for characterising abiotic seabed characteristics relevant to the Nature Restoration Regulation (NRR). North Sea-wide sediment products provide the necessary consistency and completeness for large-scale assessment and reporting, while SSS-based analyses add valuable local detail, structural context and a direct relationship to sediment properties in selected areas. At North Sea scale, the combination of updated Folk-based sediment maps and associated mud-percentage maps delivers a spatially consistent overview of sediment composition and gradients, including uncertainty information. In this study the SSS-based analysis was carried out separately from the North Sea-wide sediment mapping, but future work could focus on targeted integration and complementary use of these data sources, rather than on replacing one approach with another. As such the high-level of local sedimentological and morphological details revealed by the SSS data can further improve the North Sea-wide sediment maps. While SSS data of sufficient quality can, in principle, be used to map oyster and mussel reefs, no such biogenic reef structures were identified in the selected set of analysed data. The delivered map products and accompanying insights support restoration planning by revealing spatial patterns in sediment composition, mud content, hard-substrate availability and geogenic reef occurrence, while explicitly documenting data coverage, limitations and uncertainties. Together, these results support a solid foundation for future habitat-suitability assessments, targeted monitoring strategies and further methodological development in support of national and European restoration objectives.

Contents

Summary	3
Abbreviations	6
1 Introduction	7
1.1 Background	7
1.2 Project objective and scope	8
1.3 Outline report	10
2 Seabed sediment and morphology maps	11
2.1 Introduction	11
2.2 Seabed substrate types and characteristics	11
2.3 Current knowledge on Natura 2000 and KRM areas	14
2.4 Soft and hard substrate maps	15
2.5 Sonar aided seabed characterization	19
2.6 Discussion and recommendations	30
3 Geogenic and artificial reefs	32
3.1 Introduction	32
3.2 Stone density maps	32
3.3 Wreck distribution maps	36
4 Conclusion	41
4.1 Summary of key results	41
4.2 Way forward	41
References	43
Appendices	
Appendix A: North Sea wide maps	44
Appendix B: Sediment folk classification method	51
Appendix C: Sonar aided sediment and reef classification methods	52
Appendix D: Literature study oysters and mussels	65
Appendix E: Sonar data and classification examples	67
Appendix F: Overview of available data	72
Appendix G: Delivered files	95

Abbreviations

Abbreviation	Meaning
CNN	Convolutional Neural Network
EEZ	Exclusive Economic Zone
EMODnet	European Marine Observation and Data Network
EUNIS	European Nature Information System
HS	Hydrographic Service (NL: Dienst der Hydrografie)
KRM	Kaderrichtlijn Mariene Strategie (EN: Marine Strategy Framework Directive (MSFD))
LVVN	Ministry of Agriculture, Fisheries, Food Security and Nature
MBES	Multi-beam echosounder
NRR	Nature Restoration Regulation
NRP	National Restoration Plans
SBES	Single beam echo sounder
SSS	Side-Scan Sonar
SVM	Support Vector Machine
GDN	Geologische Dienst Nederland (EN: Geological Survey of the Netherlands)

1 Introduction

1.1 Background

The European Union Nature Restoration Regulation (NRR), which entered into force in 2024, establishes a legally binding framework to halt biodiversity loss and to restore degraded ecosystems across terrestrial, freshwater and marine environments. For the marine domain, the NRR places particular emphasis on the recovery of seabed habitats and ecosystem functions that have been adversely affected by long-term anthropogenic pressures, including bottom-disturbing fisheries, infrastructure development, sediment extraction, and climate-driven changes in hydrodynamics and biogeochemistry. Within the Exclusive Economic Zones (EEZs) of EU Member States, the NRR requires the development of National Restoration Plans (NRP), supported by spatially explicit, scientifically robust information on the distribution, extent and condition of relevant habitat types.

In the Dutch North Sea, the seabed forms the physical foundation for a wide range of marine habitats and ecological processes. Soft sediments, hard substrates, and both biogenic and geogenic reef structures determine habitat suitability for benthic communities and reef-building species, including mussels, oysters and polychaete reef formers. These habitats play a key role in biodiversity, nutrient cycling and ecosystem resilience, and are therefore central to the marine objectives of the NRR. At the same time, the North Sea is a highly dynamic and intensively used system, characterised by strong spatial variability in sediment composition, seabed morphology and disturbance regimes. This complexity poses a significant challenge for the large-scale, repeatable mapping that is required to support restoration planning, monitoring and reporting under the NRR.

Existing knowledge on the seabed of the Dutch North Sea is based on a combination of sediment sampling, sonar surveying and thematic mapping products developed over past decades by national authorities and research institutes, including the Geological Survey of the Netherlands (GDN). While these datasets provide a valuable baseline, their spatial resolution and thematic detail are often insufficient to address current policy questions related to habitat restoration, particularly for heterogeneous or spatially limited features such as hard substrates, reef structures and transitions between sediment types. Moreover, historical datasets or out-dated maps may not fully capture present-day conditions in areas subject to strong seabed dynamics or recent anthropogenic activities.

Against this background, there is a clear need for updated, spatially consistent seabed habitat information that aligns with the habitat categories and reporting requirements of the NRR, and that can be directly applied within the context of Natura 2000 areas, Marine Strategy Framework Directive (MSFD¹) assessment areas, and other priority regions identified by the Ministry of Agriculture, Fisheries, Food Security and Nature (LVVN). In particular, insight is required into (i) the spatial distribution and characteristics of soft sediments, (ii) the occurrence and density of hard substrates as a prerequisite for reef development, and (iii) the presence of biogenic and geogenic reef features that contribute to habitat complexity and ecological value.

¹ NL: Kaderrichtlijn Mariene Strategie (KRM)

Recent developments in acoustic remote sensing and data-driven analysis provide new opportunities to address these information needs. Side-scan sonar (SSS) and multibeam echosounder (MBES) data, collected routinely in the Dutch EEZ by the Hydrographic Service and other authorities, enable large-area, higher-resolution characterisation of seabed characteristics and morphology. When combined with advanced processing techniques and machine-learning-based classification approaches, these datasets can be used to derive spatially explicit maps of sediment types, seabed structures and potential habitat features at resolutions that are directly relevant for restoration planning and evaluation.

TNO has previously demonstrated the applicability of sonar-based mapping and semi-automated classification methods for the detection and quantification of reef structures and sedimentary patterns in several regions of the Dutch North Sea (Gaida, Binnerts, & Bos, 2025) (Bos, et al., 2025). Building on this experience, the present study was initiated to support LVVN in the elaboration of the marine component of the NRR. The focus is on generating and evaluating seabed habitat substrate maps that are consistent with NRR habitat categories and that provide a scientifically sound basis for assessing current conditions, identifying restoration opportunities, and designing effective monitoring strategies.

This report therefore situates sonar-aided seabed habitat substrate mapping within the broader policy and ecological context of the NRR, linking state-of-the-art acoustic mapping techniques to concrete information needs for the Dutch North Sea. The results contribute to improved understanding of the spatial distribution of key seabed habitat substrates, and form a building block for the development of a coherent, long-term strategy for habitat restoration and monitoring in support of national and European restoration objectives.

1.2 Project objective and scope

The objective of this project is to support LVVN in the elaboration of the marine component of the European Union NRR for the Dutch North Sea. In particular, the project aimed to improve the availability and applicability of spatially explicit seabed habitat information required for the development, implementation and evaluation of the Dutch National Restoration Plan within the marine domain.

To achieve this objective, TNO applied and further developed its expertise in seabed habitat mapping, combining existing geological and sediment datasets with SSS and bathymetric maps. The focus was on (1) providing North Sea-wide seabed-sediment maps, and (2) assessing the quality, spatial coverage and thematic suitability of available data and mapping methods for characterising NRR-relevant habitats within the Dutch Exclusive Economic Zone (EEZ), with particular attention to Natura 2000 sites and areas designated under the Marine Strategy Framework Directive.

Scope of habitats and habitat proxies

Within the framework of the NRR, the project concentrated on habitat types that are both ecologically significant and technically feasible to map at large spatial scales using the available data. The following NRR habitat groups and related proxies were addressed:

- › Mussel and oyster beds (NRR habitat group 3), as key biogenic reef habitats contributing to biodiversity and ecosystem functioning;
- › Hard substrate, including stones, cobbles, shell beds and other coarse or consolidated seabed features, considered a critical proxy for the potential occurrence and restoration suitability of mussel and oyster beds (NRR habitat group 3) as well as a habitat suitable for sponge, coral and coralligenous fields (NRR habitat group 5);

- Soft sediments (NRR habitat group 7), encompassing clay, silt, sand and mixed sediments, which form the dominant habitat substrate matrix of the Dutch North Sea and strongly influence benthic community composition and habitat suitability for mussel and oyster beds (NRR habitat group 3).

Rather than providing a full ecological assessment of habitat condition, the emphasis was placed on mapping abiotic characteristics of the seabed that are directly relevant for habitat identification, suitability assessment and restoration planning under the NRR. The basis of the seabed habitat substrates of the NRR habitat groups is the Folk sediment classification system which was as such implemented for the generation of the North Sea-wide seabed-sediment maps.

Spatial focus and prioritisation

The spatial scope of the project covered the Dutch North Sea, with a prioritised focus on areas identified by LVVN as relevant for NRR implementation. These include a selection of Natura 2000 sites and KRM assessment areas, and additional offshore regions of ecological interest where formal protection status is under development. Priority areas addressed in this study are shown in Table 1.1, where the area size and status of analysis for the regions of interest is shown. Regarding the mapping of soft sediments and hard substrates, seabed-sediment maps are generated for the full Dutch EEZ. A map showing the different regions is shown in Figure A.1 and Figure A.2 in Appendix A.

Table 1.1: Prioritized areas for the NRR provided by LVVN, including a selection of KRM & Natura 2000 areas and yet undefined unprotected areas offshore. The last four (10, 11, 12 and 13) were identified but the areas were not defined or no priority was given at this stage.

Priority	Area name (size)	Area size (km ²)	Analysed in project
1	Friese Front (Natura2000/KRM)	3246	Yes, partial
2	Texelse Stenen	1020	Yes, partial
3	Borkumse Stenen (KRM)	684	Yes
4	Doggersbank (Natura 2000)	4726	Yes, partial
5	Bruine Bank (Natura 2000)	1365	No
6	Klaverbank (Natura 2000)	1533	Yes, partial
7	Noordzeekustzone (Natura 2000)	1435	No
8	Vlakte van de Raan (Natura 2000)	174	No
9	Centrale Oestergronden (KRM)	2093	No
10	Gasfonteinen	Area not defined	No
11	Zeeuwse banken	Area not defined	No
12	Historische oestergronden	Area not defined	No
(13)	Voordelta (Natura 2000)	835	No

Deliverables and intended use

The project resulted in a set of spatial data products (including GeoTIFF maps and vector layers), methodological descriptions and insights that together provide a basis for seabed habitat substrate characterisation under the NRR. These outputs are intended to support the:

- preparation and substantiation of the Dutch National Restoration Plan;
- identification of areas with high restoration potential;
- design of targeted monitoring strategies and follow-up studies;
- future development of habitat suitability and probabilistic restoration models.

The scope of the project imposes several limitations on the interpretation and use of these deliverables. Not all NRR-relevant areas within the Dutch North Sea were analysed, and coverage varies between regions. In addition, the SSS based products were primarily generated to assess the value, feasibility and robustness of sonar-aided mapping approaches for different habitat proxies, rather than to produce fully harmonised, operational habitat maps for all areas.

Furthermore, sediment information derived from SSS data has not yet been structurally integrated into the North Sea-wide habitat substrate maps, which currently rely on MBES derived bathymetric data and seabed-sample-based sediment models. As such, SSS-based sediment and habitat indicators should be interpreted as complementary and exploratory, providing added local detail and methodological insight rather than a replacement of existing national mapping products.

Finally, due to the sensitive nature of parts of the underlying SSS data, not all processed data and underlying algorithms can be made publicly available. However, the applied methodologies, assumptions and limitations are documented in this report to ensure transparency and reproducibility within the constraints of data confidentiality.

1.3 Outline report

To guide the reader from the policy and ecological context of the NRR to the applied mapping results and their relevance for restoration planning and monitoring in the Dutch North Sea, the report is structured as follows:

Chapter 2 presents the mapping of seabed sediments and morphology, following a multi-scale structure. It starts with an overview of North Sea seabed characteristics and their relevance for NRR habitat interpretation, followed by the presentation of North Sea-wide seabed-sediment maps based on sediment samples and bathymetric data. Subsequently, the chapter presents targeted, high-resolution side-scan sonar (SSS) analyses for selected priority areas, illustrating local-scale seabed heterogeneity and the added value and limitations of sonar-aided seabed characterisation. The chapter concludes with a discussion of data quality, methodological constraints and implications for habitat mapping under the NRR.

Chapter 3 focuses on geogenic reefs and other hard-substrate features relevant for NRR habitat assessment. It describes the applied methods for mapping stone density and wrecks using sonar data, presents the resulting maps for the selected priority areas, and discusses their interpretation, uncertainties and relevance as habitats or habitat proxies.

Chapter 4 summarises the main results and provides an integrated discussion of their implications for NRR implementation. This chapter reflects on the applicability of sonar-based habitat mapping for large-scale restoration planning, identifies knowledge gaps and methodological limitations, and provides recommendations for future monitoring, data integration and follow-up studies.

The appendices provide detailed methodological descriptions, supplementary analyses and supporting information, including sediment classification methods, sonar processing and classification workflows, literature reviews on biogenic reefs, examples of sonar data and noise characteristics, and map overviews of available datasets for the North Sea and for the Natura2000 / KRM areas. The appendices are added to keep the main report focused on results and policy-relevant insights.

2 Seabed sediment and morphology maps

2.1 Introduction

Seabed substrate (i.e. sediment type and condition) and seabed morphology form the physical basis for marine habitats and strongly influence the distribution, suitability and resilience of NRR-relevant habitat types in the Dutch North Sea. Characteristics such as seabed-sediment composition, seabed sediment mobility and the presence of morphological features determine habitat conditions for benthic communities and reef-building species, and therefore provide essential context for habitat identification and restoration planning.

This chapter presents the results of seabed-sediment and -morphology mapping carried out within the framework of this study. Using a combination of existing geological information, MBES-derived bathymetric data, seabed-sediment samples and SSS products, spatially explicit maps are generated to characterise soft and hard substrates, seabed structures and acoustic indicators relevant for NRR habitat assessment. The chapter focuses on the interpretation of these abiotic and structural seabed properties, their spatial variability at North Sea-wide and local scales, and their relevance as inputs for habitat mapping and restoration under the NRR.

2.2 Seabed substrate types and characteristics

Seabed habitats in the Dutch North Sea are shaped by the interaction between seabed sediment composition, hydrodynamic forcing and seabed morphology. At broad spatial scales, these factors give rise to a characteristic set of habitat types, ranging from extensive soft-sediment environments dominated by sand and mud to more spatially restricted hard-substrate and structurally complex seabed features. Together, these habitat types form the physical and ecological framework within which NRR-relevant habitats occur.

This section provides an overview of the main seabed habitat types (i.e. seabed sediment substrate types) and seabed characteristics that are typical for the Dutch North Sea, with a focus on their abiotic properties and spatial organisation. Emphasis is placed on sediment types, seabed mobility and morphological features that are expected to influence benthic community composition and the suitability of the seabed for reef-building species. The aim is not to provide a detailed ecological classification, but to establish a common reference framework for interpreting the sediment and morphology mapping results presented in the subsequent sections.

By outlining the dominant seabed habitat types and their key physical characteristics, this section sets the broader context for the North Sea-wide sediment maps presented in Section 2.4 and the local-scale, high-resolution analyses based on side-scan sonar presented in Section 2.5.

The seabed habitat substrates of the NRR habitat groups are based on the EUNIS habitat classification, which itself draws on the Folk sediment classification system, specifically the

Folk 16 and Folk 5 system. The numbers indicate how many sediment classes each system contains. In the Folk classification triangle, the relative proportions (as ratios or percentages) of gravel, sand, and mud (the latter being a heterogeneous mix of clay and silt) determine the sediment class (Figure 2.1). Table 2.1 presents the grain sizes of the various sediment particle types referenced throughout the text.

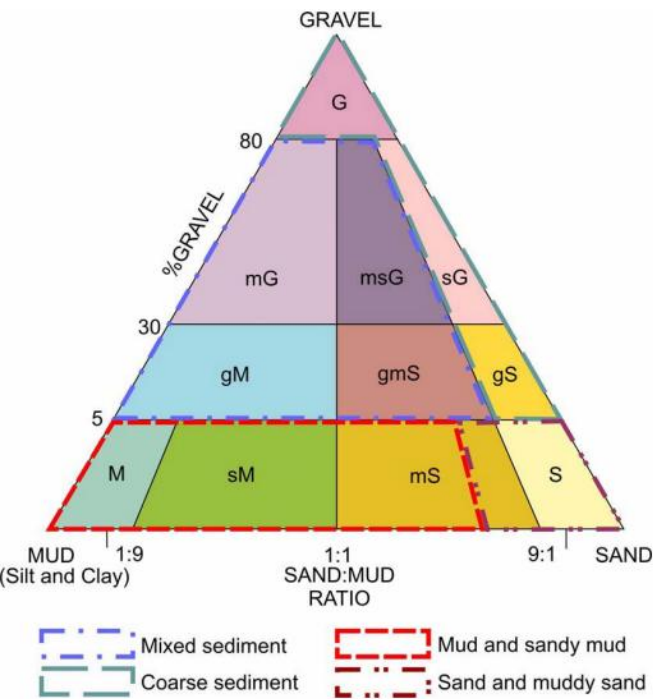


Figure 2.1: Folk 16 classification triangle and sediment classes. Overlay of the outlines of the EUNIS habitat classes (different colours). From Evan et al., 2016.

Table 2.1: Grain size fractions of sediment according to ISO 14688.

Grain size fraction sediment		
Category	Grain size fraction	Grain size range (mm)
very coarse	large boulder	>630
	boulder	200 - 630
	cobble	63 - 200
coarse	gravel	2 - 63
	sand	0.063 - 2
fine	clay and silt	<0.002 - 0.0063

For the EUNIS habitat classification, the Folk sediment classes are grouped together ((Evans, et al., 2016); see Figure 2.1). One minor difference between the systems is the sand-to-mud ratio: the Folk classification uses a 9:1 ratio for the sand and muddy-sand classes, whereas EUNIS applies a 3:1 ratio for the mud–sandy mud and sand–muddy sand classes. Following consultation with LVVN and Deltares, it was agreed to retain the original Folk class ratios.

The Folk sediment classification was therefore implemented for the production of the North Sea-wide seabed-sediment maps (see Section 2.4). These maps can subsequently serve as input for updates of specific habitat maps, such as the EMODnet Seabed Habitats map, a broad-scale seabed habitat map for Europe (EUSeaMap).

The North Sea-wide seabed-sediment maps are based on seabed samples and cores collected across the Dutch North Sea over several decades for a variety of purposes. The distance between sampling locations can be considerable, meaning that spatial coverage is not uniform. As a result, the maps provide a broad regional overview of the distribution of seabed substrate types rather than fine-scale detail. To obtain higher-resolution information on seabed characteristics, especially features not captured by discrete sediment samples, additional methods such as SSS-assisted seabed characterization are required (see Section 2.5).

The North Sea-wide seabed-sediment maps primarily correspond to NRR habitat group 7, soft sediments, which include mud, sand, and mixed sediments. In this context, soft sediments refer to unconsolidated mud and loosely packed sands, which make up the majority of the Dutch North Sea seabed. Hard and firm substrate types associated with NRR habitat groups 3 and 5, such as (soft) rock, firm to hard clays, artificial hard substrates (e.g. shipwrecks and debris), and biogenically formed substrates (e.g. shell beds), generally occur only locally on the seabed. These small-scale features cannot be reliably identified from the North Sea-wide sediment maps. However, areas mapped as containing gravels or gravelly sediments may indicate the presence of local hard or firm substrate types such as shell beds, gravel beds, cobbles and boulders, or outcropping consolidated strata (e.g. glaciogenic deposits). To accurately determine the location and extent of such substrates, dedicated seabed assessment methods, such as SSS aided seabed characterization, are required.

The seabed is additionally characterized by the presence of seabed morphological structures (subaqueous bedforms) occurring across multiple spatial scales. Large-scale bedforms are clearly discernible on basin-wide bathymetric maps of the North Sea and are primarily of geological origin. In contrast, small-scale features are less distinct, and in many cases not visible, on regional overview maps.

Bedforms at the meso- and micro-scale show a strong relationship with the spatial distribution of seabed sediment types, in particular for fine grained sediments and sand fractions. These structures are dynamic and can migrate under the influence of wave action, tidal currents, and other hydrodynamic processes. Table 2.2 provides an overview of different bedform types in the Dutch North Sea, including their dimensions and estimated migration rates. The occurrence, density, and spatial distribution of bedforms may also exert influence on the characteristics and functioning of the NRR habitats.

To date, a comprehensive understanding of the temporal variability of the seabed in the Dutch North Sea is lacking. Existing research has been limited to small-scale investigations targeting specific locations within the North Sea, and no studies have been conducted at a broad regional or multi-area scale. Time-separated Sonar imagery, collected of the same area but over multiple years, offers a promising means of assessing the extent and nature of seabed dynamism and may significantly improve the insight into these spatial and temporal patterns and may attribute to our understanding of potential impact on NRR habitats.

Table 2.2: Relevant morphological seabed features or subaqueous bedforms. Modified after Van Dijk et al. (2011), with respect to the Dutch North Sea. *Ridges generally have steeper crests.

Subaqueous bedform		Wavelength [m]	Height [m]	Orientation (degrees to tidal current)	Migration speed [m/year]	Time scale (order of years)
macro- scale	sand bank / (tidal) ridge*	1000-10000	5-50	0-30	<<1	centuries
	long bed waves	1000-2000	1-10	60	unknown	centuries
micro- and meso-scale	sand waves	100-1000	1-10	90	1-10	years-decades
	mega ripples	7-40	<1	90	100-1000	hours-days
	ripples	0.1-1	<0.1	90	100-1000	hours

2.3 Current knowledge on Natura 2000 and KRM areas

The Dutch North Sea includes a number of Natura 2000 sites and KRM assessment areas that are of particular relevance for the implementation of the NRR. For many of these areas, existing knowledge on seabed characteristics, habitat distribution and ecological functioning is derived from a combination of historical surveys, targeted studies and national mapping programmes. However, the level of detail, spatial coverage and thematic focus of this information vary considerably between areas.

Rather than offering a comprehensive ecological assessment for each area, this section aims to capture the current knowledge of seabed conditions that is relevant for habitat mapping and restoration planning. These are briefly summarised in Table 2.3. The subsequent sections build on this baseline by presenting updated, spatially explicit sediment and morphology maps and by refining the level of detail available for selected areas.

Table 2.3: Brief summary of the seabed characteristics in the Natura 2000 / KRM priority areas and the Texelse Stenen area within the scope of this study.

Area name (NL)	Description
Frieze Front	Fine-grained sediments (mud and fine sand) dominated area due to relatively low hydrodynamic energy. The seabed is mostly plane, dipping north and flat to weakly rippled, with pronounced biogenic modification through bioturbation. The area forms the transitional zone between the sand-dominated southern North Sea and the muddy central basin towards the north. Sandbanks are present in the southwestern and southeastern parts of the area.
Texelse Stenen	Seabed characterized by coarse sand, gravel and shelly sand. Frequent occurrences of cobbles, boulders from sub-cropping glaciogenic sediments (glacial till). High-energy conditions prevail due to strong tidal currents, and storm waves, that lead to erosion and transportation of seabed sediment and the formation of micro- and meso-scale bedforms. The currents limit the deposition and accumulation of fine sediments. The seabed is dominated by sand waves and mega ripples, superimposed on both coast-parallel sandbanks and in the troughs and shoals.

Area name (NL)	Description
Borkumse Stenen	Characterized by sand, gravel and locally sandy or gravelly mud, with frequent occurrences of cobbles and boulders originating from out- and sub-cropping glaciogenic sediments (glacial till). In the northern part the seabed is mostly plane, terrace-like bed. The southern part is similar but with superimposed west-northwest to east-southeast trending sand banks and swales, shaped by tidal currents, with locally mega ripples on top.
Doggersbank	Dominated by sand to gravelly sand and locally areas with muddy sediments. Gradual shallowing towards the crest of the Doggersbank. Locally, gravel patches and relict deposits occur on the crests of the bank. Mega ripples and ripples are the defining seabed features, reflecting active sediment transport.
Bruine Bank	Distinctive north-south trending sandbanks and swales. Superimposed east-west trending sand waves and mega ripples occur, most pronounced on the banks, which reflect a moderate to strong hydrodynamic regime. The seabed is mainly characterized by sand and gravelly sand, but in the swales also muddy sand occurs. Also presence of biogenic structures (shell beds, reef fragments) and relicts (fossils, a.o. mammoth) in the deepest throughs.
Klaverbank	Lithologically highly heterogeneous, the sediment type is tightly related to the complex geomorphology. Gravelly lag sediments with frequent occurrences of cobbles, boulders and outcropping glaciogenic sediments (glacial till) occur on the central Klaverbank. Muddy sediments are present in the Botney Cut channel and other bathymetric lows. Relict tidal banks are composed of well-sorted sand. Limited presence of mobile bedforms; sand ribbons and sand patches migrate over coarse-grained lag deposits during storm conditions only.
Noordzeekustzone	Highly-dynamic nearshore zone dominated by shelly sand. Offshore of the lower shoreface the seabed is characterized by ripples, mega ripples and sand waves, with relatively rapid migration due to waves and tides. The inner shoreface is dominated by longshore currents and wave action, resulting in wave breaker bars and rip currents. Highly-dynamic ebb-tidal delta systems with migrating tidal channels occur around the barrier island inlets to the Wadden Sea. Continuous erosion and redeposition of sand characterizes these areas.
Vlakte van de Raan	Shoal characterized by sandy sea bed. Near the coasts tidal channels and shoals are present that migrate in response to strong tidal currents. Generally low-relief bedforms (ripples and mega ripples). Influence of shipping-line dredging along the northern and southern border of the area.
Centrale Oestergronden	Relatively deeper waters, dominated by muddy fine sand and sandy mud, to mud, with abundant shell material. Largely plane beds with strong biogenic influence (historical oyster beds). Low-energy depositional environment where only fine-grained sediments accumulate.
Voordelta	Characterized by shell-bearing sands. Highly-dynamic environment with ever-changing tidal channels and shoals in response to strong tidal currents. Generally low-relief superimposed bedforms (ripples and mega ripples)..

2.4 Soft and hard substrate maps

2.4.1 Introduction

TNO-GDN published the most recent seabed-sediment map in 2023 on www.dinoloket.nl.

This map provides insight into the composition of the sediment in the upper 0.5 metres of the

seabed, using sediment classes according to the Folk classification system. We updated and extended this information by:

- › An update of Folk sediment-class maps (Folk 16 and derived Folk 7 and Folk 5), including class probability (likelihood) of the mapped class;
- › A mud-percentage map, including interquartile range (IQR) as uncertainty;
- › Point layers indicating potential hard-substrate occurrences (shell/gravel-rich samples).

2.4.2 Available data

For this study, both public and confidential sample data from the TNO-GDN DINO database were used, as well as recently available data that will be added to the DINO database in due course. In the Dutch part of the North Sea, there are 14,857 locations where the Folk sediment class in the upper 0.5 metres of the seabed can be determined (Figure F.15). This is an increase of 861 locations compared with the seabed-sediment map published in 2023. These include 321 sample locations from offshore wind farms (Borssele, IJmuiden Ver, Ten Noorden van de Wadden eilanden, Nederwiek Zuid, and Hollandse Kust-Zuid, -Noord and -West). This expanded dataset improves local detail especially in and around offshore wind-farm areas. Of this dataset, 10,404 sample locations contain a quantitative indication of mud percentage (Figure F.16), based on grain-size analyses or visual estimates.

2.4.3 Seabed-sediment map – Folk classification system

For the construction of the seabed-sediment maps according to the Folk classification system (hereafter: Folk maps), the same method was applied as for the existing seabed-sediment map. Technical details are provided on TNO-GDN, 2023 (see www.dinoloket.nl for methodological background). Based on the available data points, the bathymetric grid, and derived variables from the bathymetry, a model was built using the random forest algorithm (264 trees). This resulted in a Folk 16 map with a grid resolution of 100 m x 100 m (Figure A.3), from which Folk 7 and Folk 5 maps were subsequently derived (Figure A.4). Compared with the 2023 Folk maps, the following adjustments were made:

- › New sample locations are included;
- › Bathymetry was updated from EMODnet bathymetry 2020 to EMODnet bathymetry 2024;
- › The map is now fully continuous up to the coastline, unlike the 2023 version;
- › A noise filter was applied to remove isolated grid artefacts, almost always caused by irregularities in the bathymetric grid.

2.4.4 Seabed-sediment map – mud-percentage map

For modelling the mud-percentage map, the same techniques were used as for the Folk map, with the following adjustments:

- › The random forest model consists of 128 trees;
- › Spatial information was not used as an explanatory variable.

Mud percentage was modelled such that it remains consistent with the Folk sediment classes. In practice, this means we estimate mud percentage within each Folk 16 class using the mud observations belonging to that class, and combine them using the predicted probability of each Folk class at that location. This avoids local contradictions such as predicting 'sand' while simultaneously predicting a mud percentage outside the sand range. Mud-percentage maps include a map of the most likely mud percentage (Figure A.5), and uncertainty as the interquartile range (Figure A.6). The technical details of this percentile-weighting procedure are provided in Appendix B. All maps have a grid resolution of 100 m x 100 m.

The predicted mud percentage in relation to the bathymetry is shown in Figure 2.2, both for the area around the Botney Cut and for the coastal area near IJmuiden. The mud percentage follows the patterns of the Folk map, but shows additional lithological detail within individual Folk classes. In both areas, for example, a clear lithological gradient is visible within sand banks and sand waves: troughs contain a higher mud percentage, the crests a lower percentage, while this variation in the Folk map generally falls entirely within the sand class. Because of the high level of detail and the strong relationship between mud percentage and bathymetry, irregularities in the bathymetric grid become visible. For certain areas, this results in distinct linear patterns in the predicted mud percentage that reflect the “striping” in the underlying bathymetric grid, as can be seen in the south-eastern part of Figure 2.2 (left). Users should interpret narrow linear anomalies with caution, especially where they align with known edges of MBES surveys from which the bathymetry was derived.

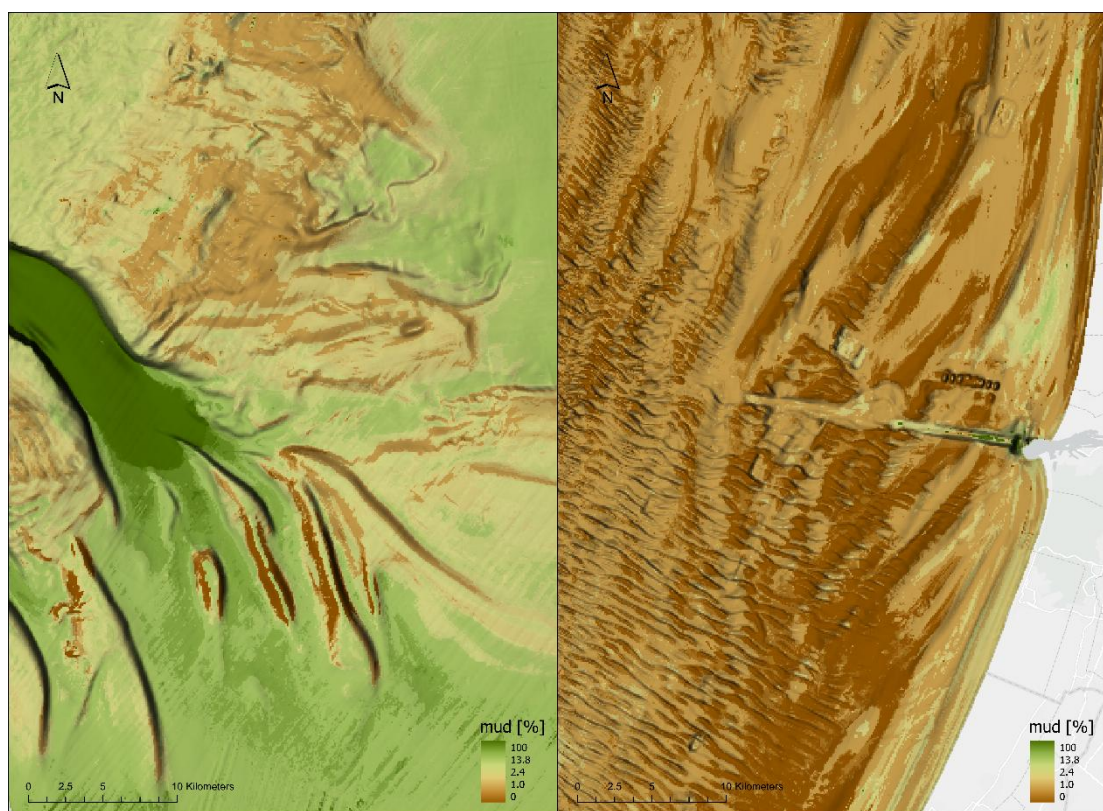


Figure 2.2: Interaction between bathymetry (hill shaded relief) and overlain mud percentage at the Botney Cut (left) and off the coast of IJmuiden (right). The linear patterns (“striping”) in the background of the left figure are an artefact in the bathymetric data. Grid resolution is 100 m x 100 m.

The quality of the prediction was evaluated with ten-fold cross-validation (repeatedly training on 90% of samples and testing on 10%). This yielded a predicted mud value for each sample location, which was compared with the measured value (Figure 2.3). Overall, predictions follow the observed mud values, while mud percentages above 40-50% tend to be underestimated (see also Table 2.4). This mainly reflects the dominance of low values in the dataset with most of the samples having a mud content of lower than 5%, causing predictions at locations with a high value to often be influenced by nearby lower values. Values around 10% mud are underrepresented, which is related to the threshold between the Folk classes Sand and muddy Sand. Like most statistical models, predictions are smoother than the raw data, causing less frequent predictions around class transitions.

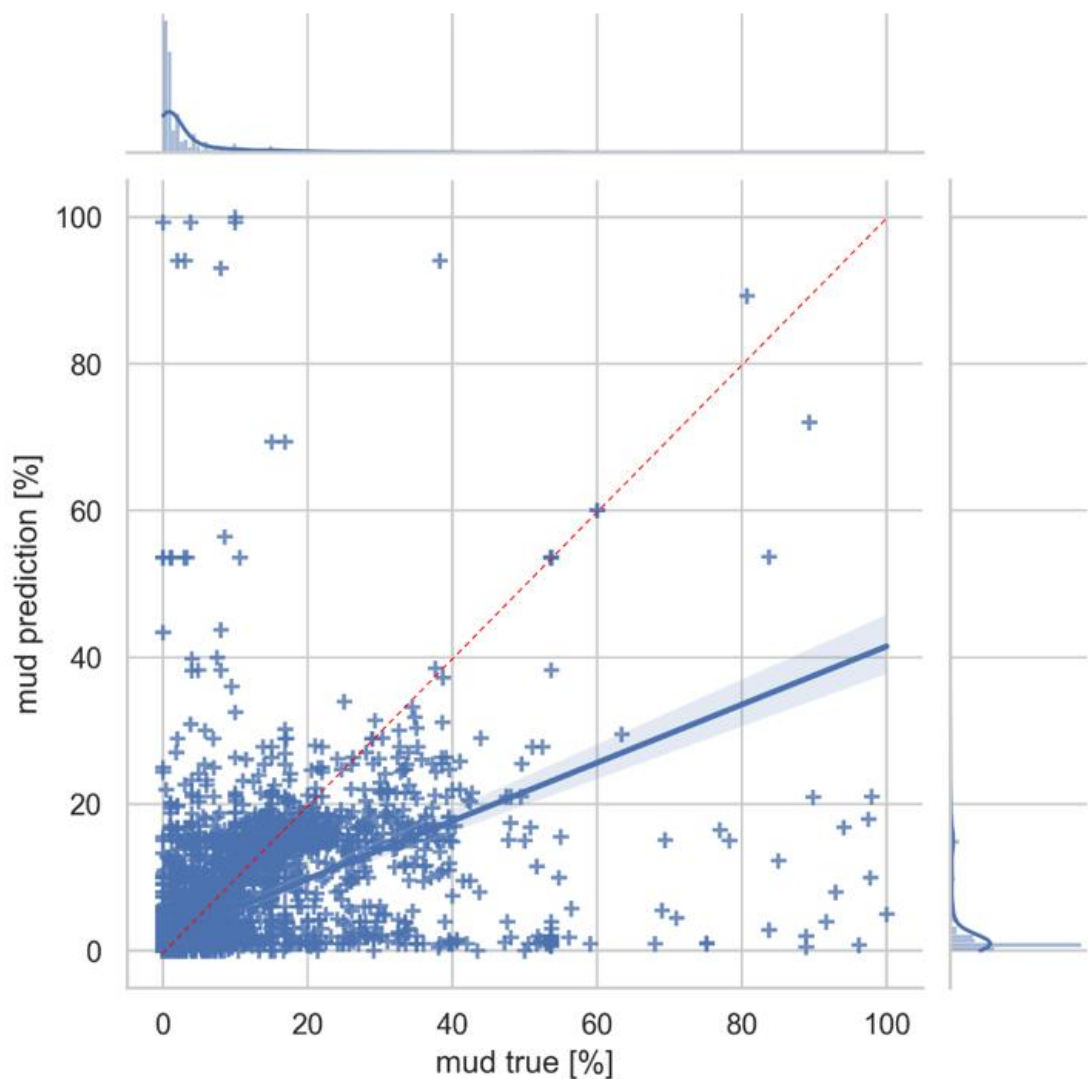


Figure 2.3: Cross-validation results with linear regression line; mud prediction indicates the predicted mud percentage at a sample location, mud true the actual value of the sample.

Table 2.4 presents the mean absolute error (MAE) for the Folk 16 classes with more than 50 samples. The deviations found are smallest for Folk classes with a relatively low mud percentage and increase for classes with a high mud percentage. This may result both from greater uncertainty in the Folk class prediction and from a larger spread in mud percentage among the data points within these Folk classes.

Table 2.4: Mean absolute error (MAE) in cross-validation between predicted mud percentage and the actual sample value, broken down by Folk 16 class, for Folk 16 classes with more than 50 samples, where S = Sand, mS = muddy Sand, (g)S = slightly gravelly sand, gS = gravelly sand, sG = sandy gravel, sM = sandy Mud.

Folk 16 class	Number of samples	MAE [%]
S	5340	1.6
mS	998	8.4
(g)S	805	1.1

Folk 16 class	Number of samples	MAE [%]
gS	390	1.6
sG	123	2.1
sM	54	42

2.4.5 Indication of hard substrate

The DINO database contains descriptions and analyses of North Sea seabed samples, including locations with high concentrations (>30%) of shells or coarse sediment (gravel or coarser) at or just below the seabed. These concentrations are based on grain-size measurements or estimates and descriptions of the sediment samples. This may indicate the presence of a hard seabed substrate, such as a shell bed or a deposit containing gravel or coarser sediment. In total, this concerns 550 sample locations with public data in the DINO database. These locations, including metadata, were extracted from the database and converted into point-location files showing occurrences of high concentrations of shells or coarse sediment (gravel).

These sediment samples have been collected, described and analysed over past decades. Because the seabed (and its composition) may change over time due to sediment movement, particularly in areas with bedforms, it is recommended to verify the presence of a hard substrate at these locations. Verification can, for example, be carried out using SSS images or MBES backscatter data of the seabed. Figure A.7 shows the locations with high concentrations (>30%) of shells or coarse sediment (gravel) at or just below the seabed. The locations with coarse sediment are mainly clustered in the Klaverbank area, north-west of Texel (also known as the Texelse Stenen area) and in a small area offshore Ameland. At the other locations, high concentrations are mainly related to shells.

2.5 Sonar aided seabed characterization

2.5.1 Introduction

This section presents the results of the side-scan sonar (SSS)–based seabed mapping carried out for a selection of priority areas within the Dutch North Sea. The primary aim of this analysis is to provide detailed, local-scale insight into seabed sediment characteristics and seabed patterning that cannot be resolved by North Sea-wide mapping products alone. The focus is therefore on identifying fine-scale spatial variability, sediment heterogeneity and acoustic patterns that are relevant as abiotic context for habitat interpretation under the Nature Restoration Regulation (NRR).

The SSS-based mapping was applied to selected areas where suitable data were available and where increased spatial detail was considered particularly relevant for NRR-related questions. As such, the results presented in this section do not provide continuous coverage of the Dutch North Sea and are not intended to represent a comprehensive or uniform seabed characterisation at national scale. Instead, they serve to illustrate the added value and limitations of SSS for local seabed mapping, and to support interpretation of seabed characteristics within specific areas of interest. The SSS products described here are complementary to the North Sea-wide seabed sediment maps derived from seabed samples and bathymetric maps, which are presented in Section 2.4. While the sample and bathymetry-based products provide a consistent baseline for the full Dutch Exclusive

Economic Zone, the SSS-based results offer enhanced local detail and insight into small-scale seabed variability and transitions that are relevant for habitat interpretation and further methodological evaluation.

This section therefore focuses on (i) an overview of the SSS-derived data and mapping products, (ii) the key local-scale sediment and seabed patterns observed in the analysed areas, and (iii) the limitations and constraints that should be considered when interpreting SSS-based results. In Appendix C, a detailed description of the SSS processing methodology is included.

2.5.2 Overview of SSS-derived maps

The SSS-based seabed mapping presented in this section is based on side-scan sonar data acquired during hydrographic surveys carried out by the Hydrographic Service and made available to TNO. These datasets consist of multiple survey blocks per area, acquired over different years and using comparable sonar configurations, and provide high-resolution acoustic imagery of the seabed surface.

For each selected area, the SSS data were processed and georeferenced to generate spatially consistent backscatter mosaics at resolutions suitable for local-scale analysis. Depending on data quality and survey characteristics, the processed products include full-coverage backscatter maps (25 m x 25 m resolution) and high-resolution sonar images (20 cm x 20 cm resolution) used for the spatial mapping of relevant seabed morphological or reef-like patterns. The spatial resolution of these products is substantially higher than that of North Sea-wide sediment maps, allowing small-scale seabed variability and transitions to be resolved.

The spatial coverage of SSS data varies between areas and survey blocks, reflecting differences in survey design, acquisition year and data availability. As a result, SSS-based products do not provide uniform coverage across all priority areas, nor do they form a continuous dataset at the scale of the Dutch Exclusive Economic Zone. The products are therefore interpreted on an area-by-area basis, with explicit consideration of local data density and coverage.

The SSS-derived mapping products described here form the basis for the local-scale analysis of sediment heterogeneity and seabed patterning presented in the subsequent sections.

Figures in this section illustrate representative examples of SSS backscatter mosaics and derived products for the analysed areas, highlighting the level of spatial detail available from these datasets. Interpretation of the observed patterns and their relevance as abiotic context for habitat assessment is addressed in Sections 2.5.3 and 2.5.4, while methodological limitations and constraints are discussed in Section 2.5.5.

Figure 2.4 provides an overview of the spatial coverage of the processed and georeferenced SSS survey data for the analysed priority areas. It illustrates the distribution of available SSS track lines per area, highlighting differences in coverage density and overlap between survey blocks.

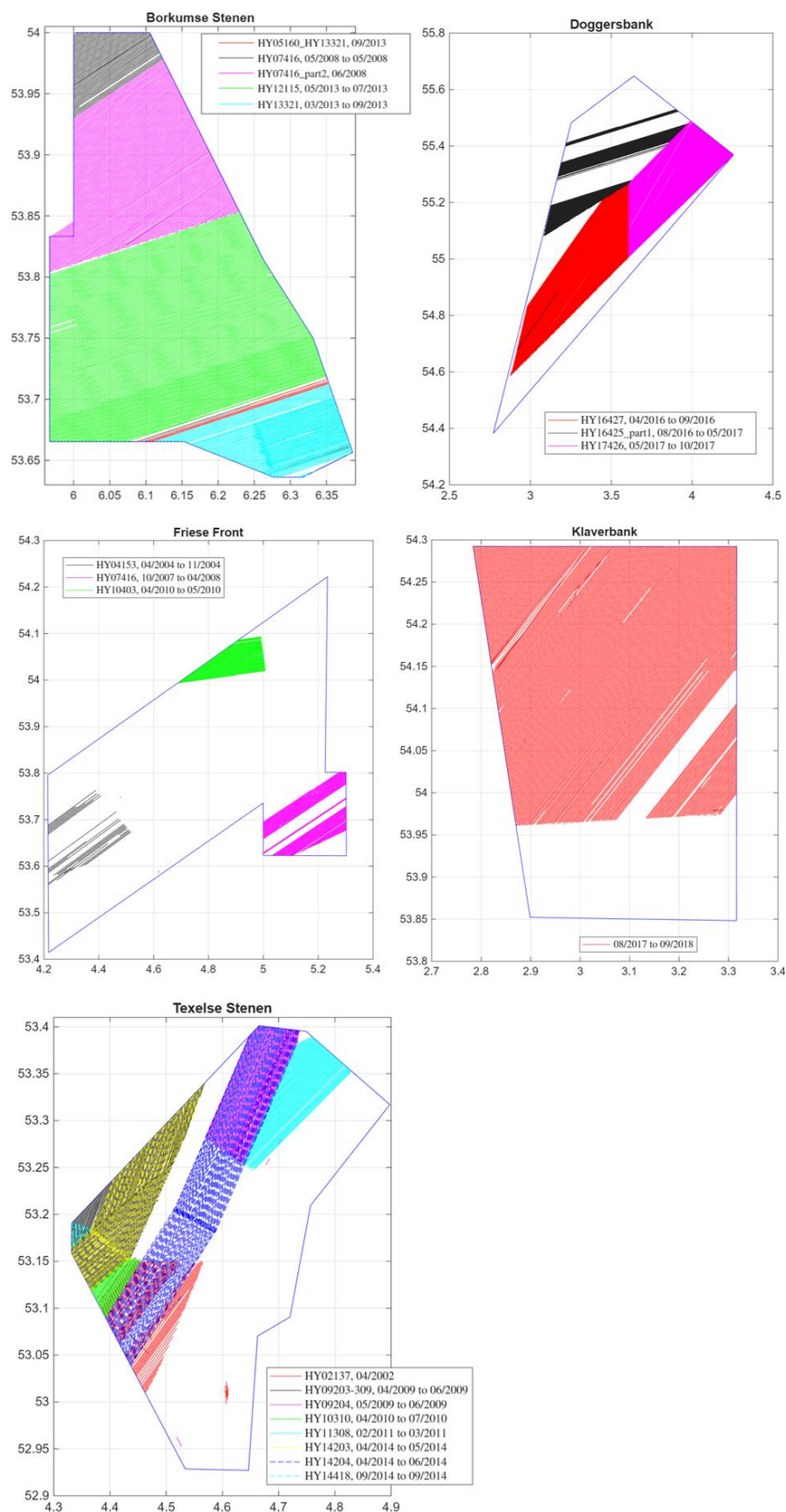


Figure 2.4: Overview of the 5 areas with processed and georeferenced sonar survey lines.

2.5.3 Key results: fine-scale sediment distribution and seabed patterns

The SSS-based mapping results reveal pronounced spatial variability in seabed sediment characteristics and seabed patterning within the analysed priority areas. At the local scale, the high spatial resolution of the SSS data allows the identification of sediment heterogeneity, patchiness and transitions that are not resolved in North Sea-wide mapping products. These patterns reflect variations in sediment composition, seabed texture and the presence of small-scale morphological features.

Across the analysed areas, SSS backscatter mosaics show clear contrasts between acoustically homogeneous zones and areas characterised by strong spatial variability. Homogeneous backscatter patterns are typically associated with relatively uniform sediment conditions, whereas heterogeneous backscatter patterns indicate mixtures of sediment types, local enrichment in coarser material, or transitions between sedimentary environments. In several areas in the Borkumse Stenen, elongated or patchy features are observed, highlighting fine-scale sedimentary structures and boundaries that are smoothed or absent in coarser-resolution datasets (Figure 2.6). The gravel-rich sediments identified in the Klaverbank area of the North Sea-wide sediment map closely align with regions of high reflectivity observed in the SSS backscatter map (Figure 2.7). This correlation between low reflectivity and fine sediments is also evident in the Botney Cut; however, the SSS data suggests that the section of the Botney Cut containing fine (muddy) sediments is narrower than indicated by the broader North Sea sediment map. These observations demonstrate how SSS backscatter can offer substantial enhancements to the accuracy of North Sea-wide sediment mapping. In addition to sediment heterogeneity, shown by the SSS backscatter mosaics with a reduced resolution of 25 m x 25 m, the original SSS images with a resolution of 20 cm x 20 cm, provide even more detailed insights into local seabed patterns and morphology. Depending on the area, characteristic patterns such as ripples, megaripples, small-scale sedimentary boundaries, trawl marks and other seabed textures are visible in the sonar imagery (Figure 2.5). These features vary in spatial extent and expression between areas, reflecting differences in hydrodynamic regime, sediment mobility and seabed disturbance. The ability to resolve such features illustrates the value of SSS for characterising seabed structure at spatial scales relevant for local interpretation.

Within several of the analysed areas, the SSS imagery also reveals acoustic patterns indicative of hard substrates and reef-relevant seabed features, such as stones, cobbles, shell-rich patches and other coarse or consolidated elements at the seabed surface (Figure 2.5). These features are of particular relevance as abiotic proxies for NRR habitat groups associated with reef-building species, including mussel and oyster beds (NRR habitat group 3) and other reef-forming communities. The observed patterns provide spatially explicit information on the local distribution and heterogeneity of potential attachment substrates, which is a key precondition for the occurrence and restoration suitability of these habitats. While *Lanice/Loimia* reefs were detected and mapped in the Borkumse Stenen in a previous project (Bos, et al., 2025) (Figure C.9), indicators for the presence of mussel or oyster beds were not found in the processed SSS images as described in Section C.1. An overview of the scanned area is shown Figure 2.4, however, not all lines have sufficient data quality for reef inspections, because weather and sea conditions, use of different sonar systems, tow fish stability or interference with other acoustic systems were variable over the 16 years (2002 to 2018) of data acquisition.

It is important to note that reef-relevant acoustic patterns in SSS data do not provide direct evidence of biogenic reef habitats or the presence of specific NRR species. Instead, they primarily indicate seabed surface properties such as roughness, coarseness or elevation relative to surrounding sediments. SSS should therefore be regarded as an indirect observation method, unlike direct validation methods such as optical imagery or grab sampling. Rather, the SSS-based results provide abiotic context by identifying seabed conditions that may facilitate or constrain reef development, such as substrate type, surface roughness and local stability. Detailed identification and classification of geogenic reefs, including their spatial extent and density, are addressed separately in Chapter 3.

The SSS-based results further demonstrate that sediment characteristics and reef-relevant features within individual priority areas can vary substantially over short distances. This intra-area variability emphasises that locally observed seabed conditions cannot be assumed to be spatially uniform, even within areas that appear homogeneous in North Sea-wide sediment maps (see Figure 2.6 to Figure 2.8). As such, the SSS-derived products provide important local-scale context for interpreting habitat suitability and seabed dynamics in selected locations.

Overall, the key results of the SSS-based mapping underline the strongly heterogeneous nature of the seabed at local scale and highlight the co-occurrence of sedimentary, morphological and reef-relevant features such as rocks and outcrops that are not captured by coarser-resolution mapping approaches. These observations form the basis for the subsequent assessment of the added value of SSS-based mapping and for the discussion of methodological limitations and interpretation constraints in the following sections.

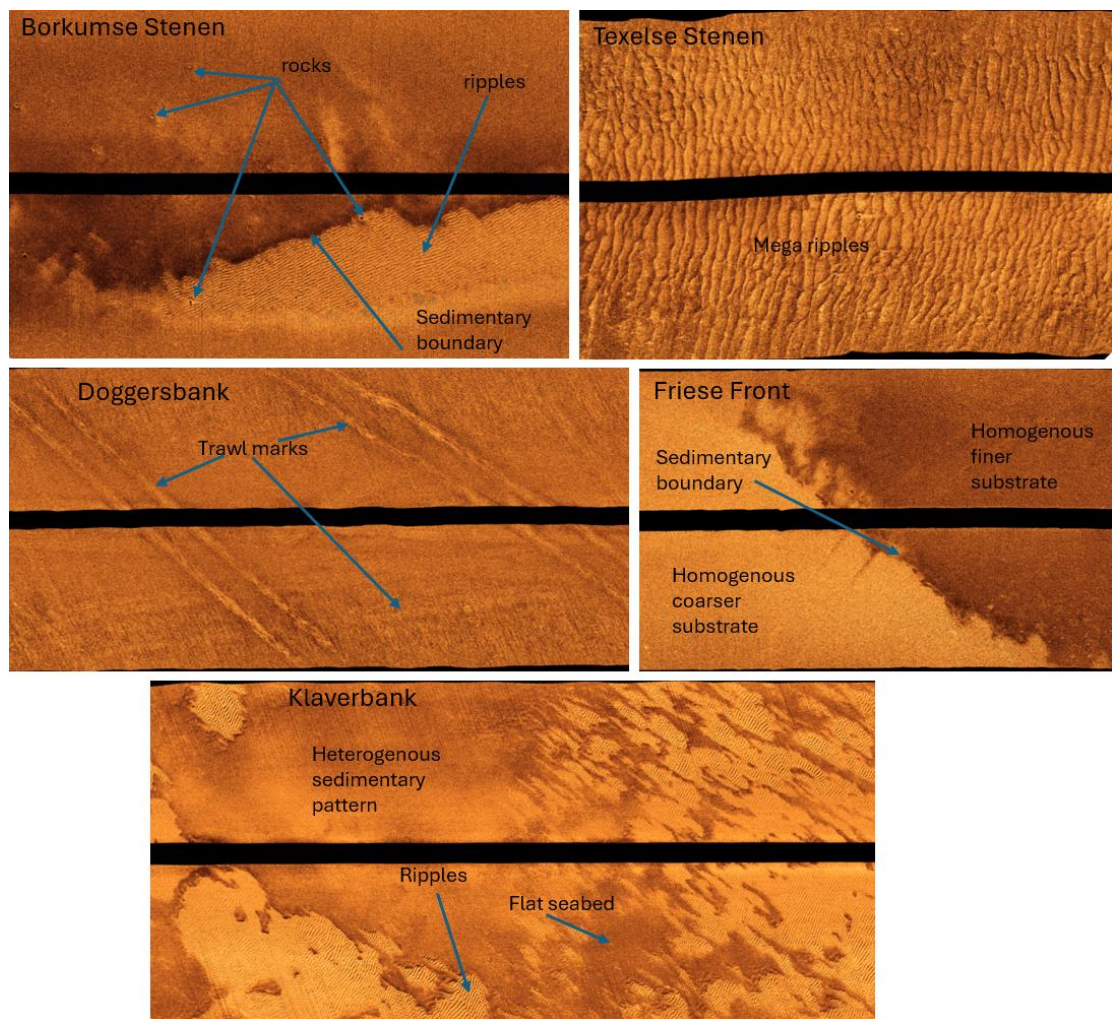


Figure 2.5: Representative examples of processed SSS backscatter mosaics and derived products, demonstrating the level of spatial detail available from these datasets. High-resolution backscatter processing was applied to reveal fine-scale seabed features. The black gap in the centre of each figure is the nadir gap below the sonar fish where low-quality data is removed. It also indicates the sonar survey line.

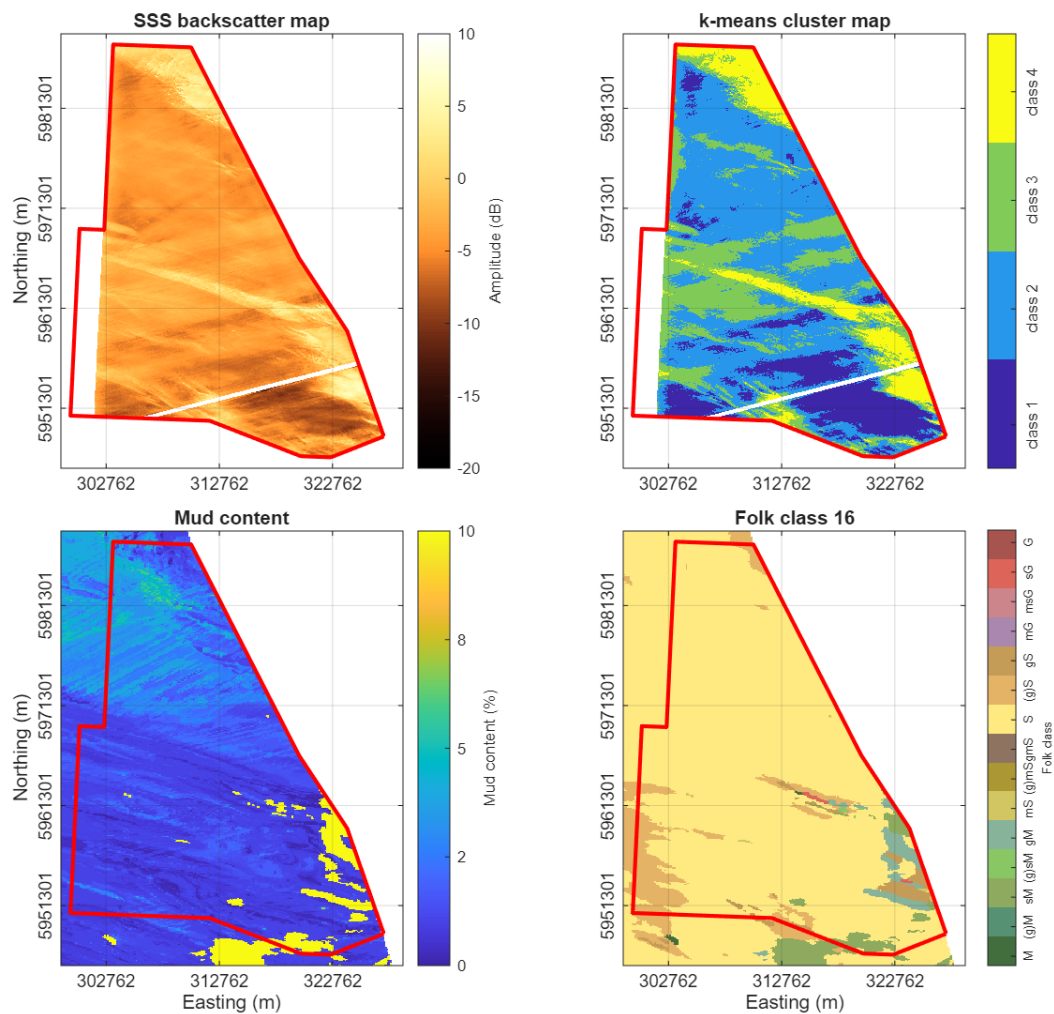


Figure 2.6: Seabed maps of Borkumse stenen compiled from various data sources. (Top left) SSS backscatter map with a resolution of 25 m x 25 m and generated from the Hydrographic Service data; the amplitude values indicate the coarseness and hardness of the seabed. (Top right) k-means clustered SSS backscatter map with classes 1 to 4 illustrating patterns of increasing coarseness and hardness. (Bottom left) Mud content and (bottom right) Folk class map both produced using the methodology outlined in Section 2.4. All maps are shown in ETRS89 UTM 32N.

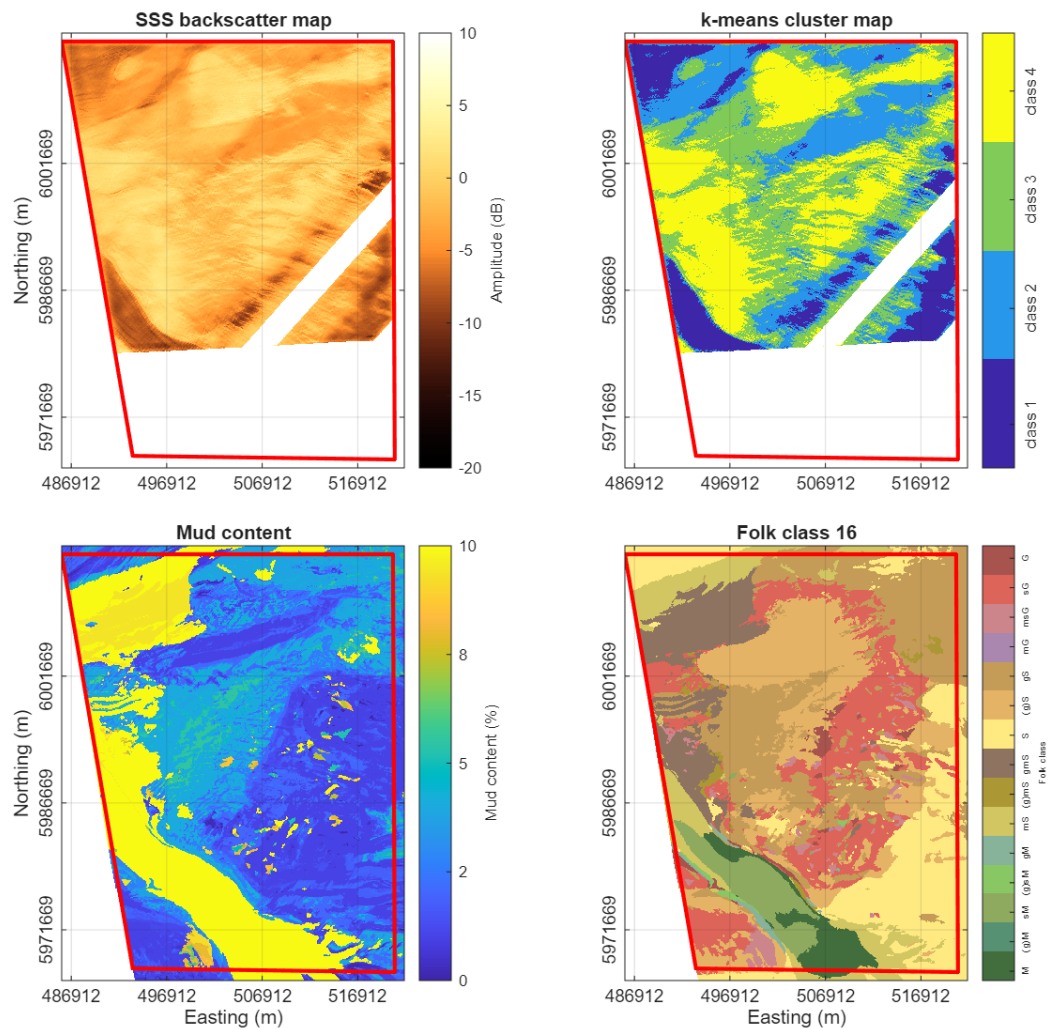


Figure 2.7: Seabed maps of Klaverbank compiled from various data sources. (Top left) SSS backscatter map with a resolution of 25 m x 25 m and generated from the Hydrographic Service data; the amplitude values indicate the coarseness and hardness of the seabed. (Top right) k-means clustered SSS backscatter map with classes 1 to 4 illustrating patterns of increasing coarseness and hardness. (Bottom left) Mud content and (bottom right) Folk class map both produced using the methodology outlined in Section 2.4. All maps are shown in ETRS89 UTM 31N.

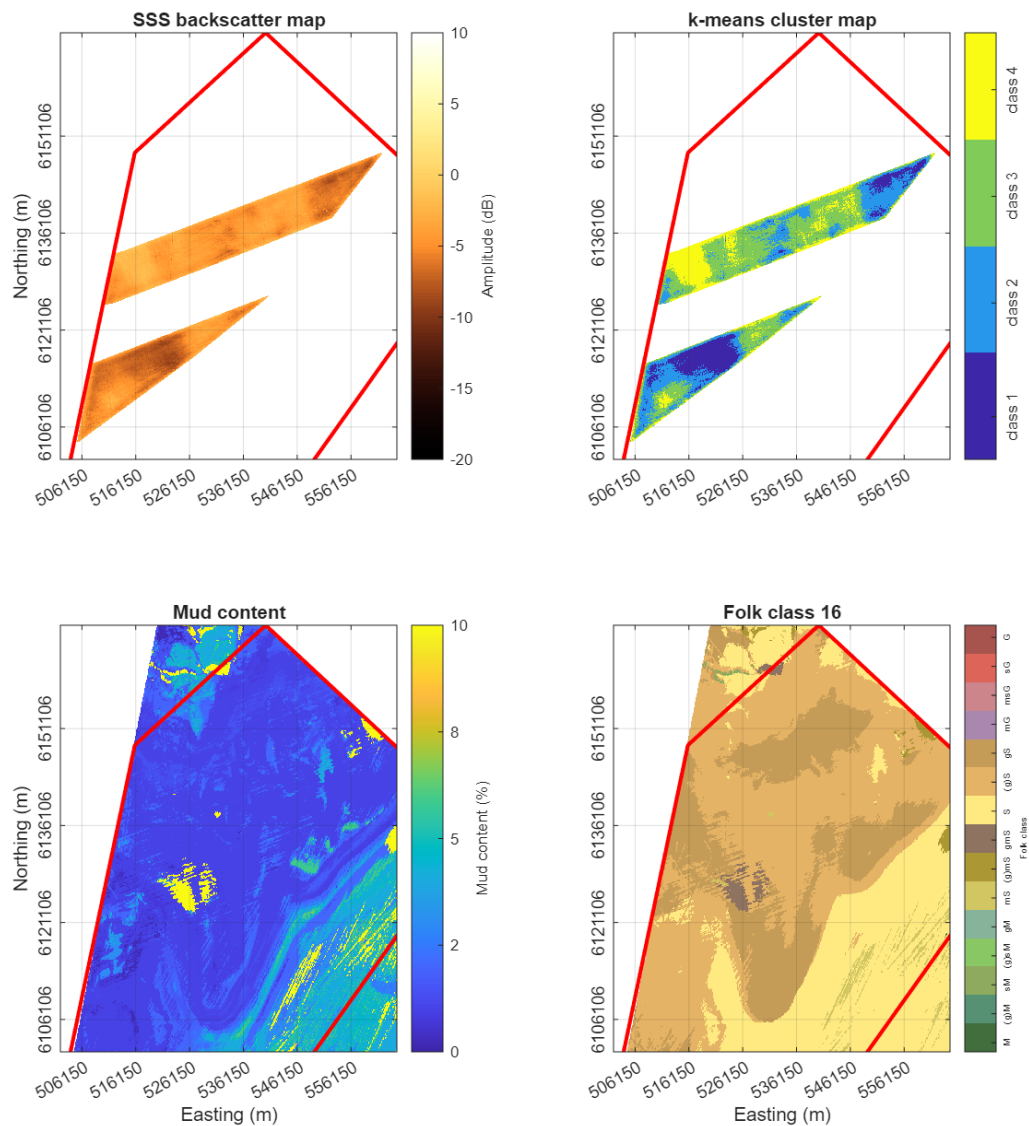


Figure 2.8: Seabed maps of the northern area of the Doggersbank compiled from various data sources. (Top left) SSS backscatter map with a resolution of 25 m x 25 m and generated from the Hydrographic Service data; the amplitude values indicate the coarseness and hardness of the seabed. (Top right) k-means clustered SSS backscatter map with classes 1 to 4 illustrating patterns of increasing coarseness and hardness. (Bottom left) Mud content and (bottom right) Folk class map both produced using the methodology outlined in Section 2.4. All maps are shown in ETRS89 UTM 31N.

2.5.4 Added value of SSS-based mapping relative to existing sediment information

The SSS-based mapping provides added value relative to existing North Sea-wide sediment information by resolving seabed variability and structure at spatial scales that are not captured by grab-sample-based or MBES-derived products. While North Sea-wide sediment maps offer a consistent representation of dominant sediment classes across the Dutch Exclusive Economic Zone, the SSS results reveal fine-scale heterogeneity, patchiness and transitions within individual areas that are smoothed or generalised in coarser-resolution products.

In particular, the SSS data enhance insight into the spatial distribution of coarse substrates, shell-rich patches and other hard or consolidated seabed elements. These features are of direct relevance as abiotic context for NRR habitat groups associated with reef-building species, including mussel and oyster beds (NRR habitat group 3), as well as for other reef-forming communities. The SSS-based products allow such features to be identified and delineated locally, even where their spatial extent is limited or where they occur as small-scale inclusions within predominantly soft-sediment environments.

In addition to substrate composition, SSS imagery provides detailed information on seabed surface texture and morphology, such as ripples, megaripples, trawl marks and other small-scale seabed structures. These characteristics offer insight into local seabed dynamics and stability, which are relevant contextual factors when interpreting habitat suitability for NRR species. Such information is not explicitly represented in sediment class maps derived from samples and bathymetry alone.

The added value of SSS-based mapping is therefore primarily local and context-dependent. It does not replace existing North Sea-wide sediment products, but complements them by providing higher-resolution detail that supports local interpretation, validation and refinement of seabed characterisation in selected areas. In this role, SSS-based results contribute to a more nuanced understanding of seabed conditions and habitat-relevant variability at spatial scales that are directly relevant for site-specific assessment and analysis.

2.5.5 Limitations and interpretation considerations of SSS-based results

The interpretation of the SSS-based results presented in this section is subject to several limitations related to data coverage, data quality and the indirect nature of acoustic seabed characterisation. Spatial coverage of SSS data is uneven across and within the analysed areas, reflecting differences in survey design, acquisition year and data availability. Consequently, the SSS-based products do not provide spatially exhaustive coverage, and the absence of observed features should not be interpreted as evidence of their absence on the seabed. In addition, SSS data quality varies between survey blocks due to factors such as tow-fish stability, flying height, survey speed, environmental conditions and sonar settings. Noise artefacts and range-dependent effects can locally reduce image quality and limit the reliable detection of fine-scale seabed features. These effects constrain the interpretation of sediment transitions, seabed morphology and reef-relevant acoustic patterns in parts of the dataset. SSS-based interpretation is inherently indirect, as acoustic backscatter provides a proxy for seabed surface properties such as roughness and hardness rather than direct information on sediment composition or biological presence. Similar acoustic responses may arise from different seabed conditions, and subtle material differences may not always be acoustically distinguishable. As such, the SSS-derived results should be interpreted as indicative of abiotic seabed context.

The SSS-based products provide detailed, local-scale insight into seabed heterogeneity and hard-substrate distribution within the limits of the available data, and are best used to complement North Sea-wide sediment maps derived from seabed samples and bathymetric data. They are particularly suited for site-specific interpretation and contextualisation, but should not be extrapolated beyond their spatial coverage or used to infer habitat condition or species presence without supporting biological observations via video footage or grab samples.

2.5.6 Mapping of morphological seabed features: glacial outcrops (case study Texelse stenen)

The semi-automated machine-learning classification workflow originally developed for the mapping of biogenic reef structures in previous projects was applied in this study to map morphological seabed features, specifically glacial outcrops, in the Texelse stenen. During manual inspection of the processed side-scan sonar imagery, extensive acoustic patterns indicative of glacial outcrops were identified in the northern part of the area, in particular within survey block HY09204.

Based on these observations, the classifier was trained and applied to generate a spatially explicit map of glacial outcrop coverage. The resulting map, shown in Figure 2.9, represents the percentage coverage of the seabed surface by glacial outcrops for an area of approximately 16 km × 6 km in the northern Texelse stenen. The classification results indicate that approximately 5.7% of the seabed surface in this area is characterised by glacial outcrops, with the majority of these features concentrated in the northern part of the mapped region.

The applied workflow demonstrates that SSS-based classification techniques can be used to map specific seabed morphological features at high spatial resolution in selected areas. Details of the manual and automated processing steps underlying this classification are provided in Appendix C.3.

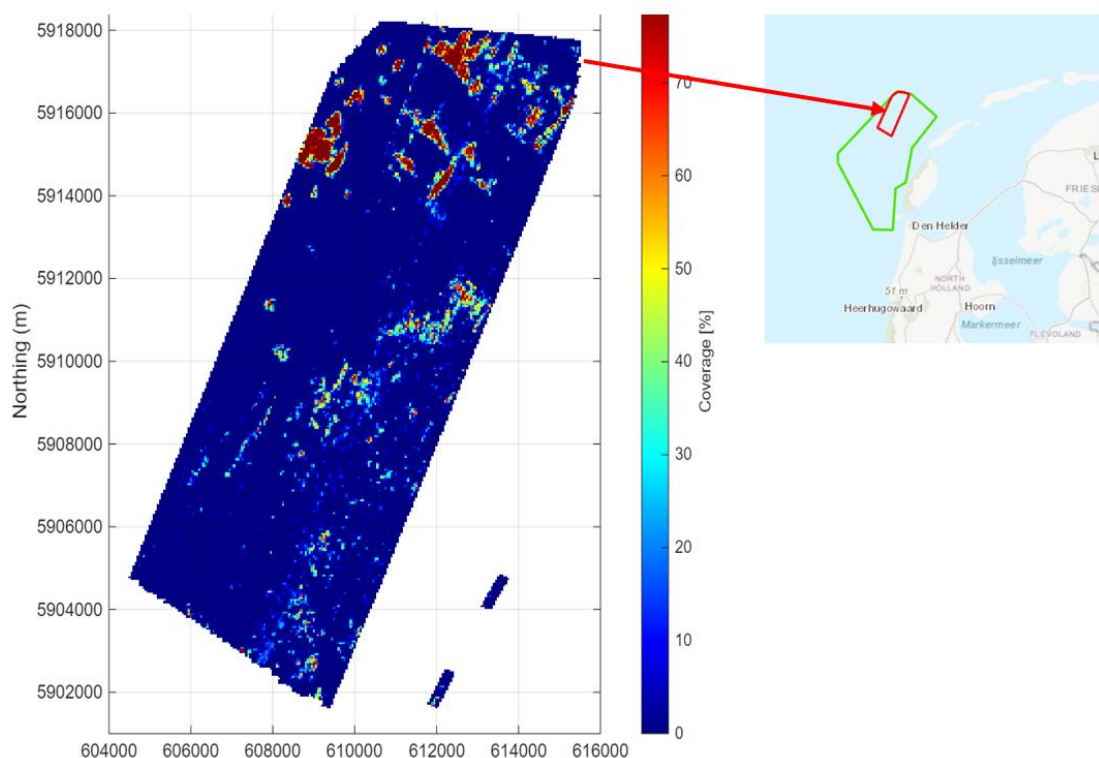


Figure 2.9: SSS based glacial outcrop map. Area is located in the north-west of the Texelse stenen in block HY09204. In that area 5.7% of the surficial seabed is classified as outcrop. The map is shown in ETRS89 UTM 31N.

2.6 Discussion and recommendations

The sediment and morphology mapping results presented in this chapter demonstrate that a combination of North Sea-wide, sample-based sediment products and local-scale SSS analyses provides a robust and complementary basis for characterising the abiotic seabed context relevant for NRR implementation. While the sample and bathymetry-based sediment maps offer spatially consistent coverage across the Dutch North Sea, the SSS-based analyses reveal fine-scale seabed variability and structural detail that are not captured by the North Sea-wide maps.

One potential avenue for further development is the integration of SSS backscatter information into the existing sediment-mapping workflow used for generating Folk-class and mud-percentage maps. The current geostatistical models primarily rely on sediment samples and bathymetric predictors, learning relationships between these inputs and sediment characteristics from ground-truth observations. Incorporating SSS backscatter as an additional predictor could provide high-resolution acoustic information on seabed texture and roughness, potentially enhancing local detail in areas. When properly processed, SSS backscatter shows a direct relationship with sediment properties and thus provides a substantial contribution to improved sediment mapping. This is especially relevant in light of the fact that the current input layer, bathymetry, serves only as an indirect proxy for sediment properties.

Further potential added value of such integration lies in the ability of SSS backscatter to resolve geomorphological patterns at spatial scales smaller than the typical sample spacing, thereby enabling sediment characterisation at finer grid resolutions. The current SSS backscatter maps were generated on a 25 m x 25 m grid (e.g. Figure 2.6), already providing more detail than the 100 m x 100 m Folk sediment map and Mud content map. However, further refinement is possible because the original SSS imagery has decimetre-scale resolution. A meters to 10th of meters scale is more closely aligned with the level of spatial detail required for local habitat interpretation and site-specific assessment. In addition, derivation of backscatter-based features analogous to bathymetric derivatives (e.g. texture metrics, focal statistics) may further enrich the predictor set used in data-driven sediment modelling.

At the same time, other prerequisites and limitations need to be considered. Successful integration of SSS backscatter requires careful harmonisation of spatial resolution between bathymetric grids and sonar products, as well as rigorous quality control of backscatter data. Even after destriping and radiometric corrections, linear artefacts and survey-specific amplitude differences may persist and could propagate into sediment maps if not adequately addressed. Differences in acquisition settings between surveys may also introduce artificial boundaries between adjacent areas if absolute backscatter values are used directly. Moreover, SSS backscatter data are not available with uniform coverage across the entire Dutch North Sea. As a result, high-resolution sediment maps based on backscatter integration would necessarily be limited to areas with sufficient data coverage, or would require the use of mixed-resolution products where detailed local maps are combined with coarser North Sea-wide baselines. Such hybrid approaches may be suitable for targeted applications but require careful communication of scope and limitations.

The current sample and bathymetry-based sediment maps, most recently updated using additional samples and improved modelling approaches, already provide a good baseline for North Sea-wide sediment characterisation. The addition of a mud-percentage product and associated uncertainty estimates offers further opportunities for refining habitat interpretation

and for identifying areas where additional data collection could most effectively improve map quality.

Overall, the results of this chapter highlight that seabed sediment and morphology mapping benefits from a multi-scale approach. North Sea-wide sediment products provide the necessary consistency and completeness for large-scale assessment and reporting, while SSS-based analyses add valuable local detail, structural context and a direct relationship to sediment properties in selected areas. Future work should therefore focus on targeted integration and complementary use of these data sources, rather than on replacing one approach with another.

3 Geogenic and artificial reefs

3.1 Introduction

Geogenic reef features, such as stone fields, boulders and other hard-substrate seabed elements of geological origin, form an important component of the seabed habitats relevant under the Nature Restoration Regulation (NRR). These features increase structural complexity of the seabed and provide stable attachment surfaces that can support diverse epifaunal communities and reef-building species. As such, geogenic reefs and hard substrates play a key role both as its own habitat and as abiotic preconditions for the occurrence and restoration of biogenic reef habitats.

In the Dutch North Sea, geogenic hard substrates occur in a limited number of distinct regions, often associated with glacial deposits and lag sediments. Their spatial distribution is highly heterogeneous and typically patchy. Therefore, they cannot be easily sampled by a typical sediment sampling device, such as a Box corer, or via an ROV with a video camera. Accurate information on the presence, density and spatial organisation of these features is therefore essential for assessing habitat availability, restoration potential and monitoring needs under the NRR.

This chapter presents the results of geogenic reef mapping carried out within the framework of this study, with a focus on stone fields and other hard-substrate features detected using side-scan sonar data. Building on the abiotic seabed characterisation presented in Chapter 2, the analyses in this chapter aim to identify, quantify and spatially describe geogenic reef features in selected priority areas. The emphasis is on the detection and mapping of physical hard-substrate elements; interpretation in terms of ecological functioning or species presence is addressed only when supported by existing knowledge.

The chapter first presents the results of the applied mapping approaches for stone density. The focus is on presenting the resulting maps for the areas where stones were identified, followed by discussion of their interpretation, limitations and relevance for NRR implementation, with methodological details provided separately. Wrecks and other anthropogenic hard-substrate features are addressed in the following section, acknowledging their distinct characteristics and management context.

3.2 Stone density maps

The stone maps were produced using a Deep Learning approach, in which a Convolutional Neural Network (CNN) is applied to the SSS imagery to automatically detect small-scale seabed features. In this specific case it has been trained to recognize stones. The CNN analyses local image patterns in the processed and georeferenced SSS data and identifies characteristic acoustic signatures of stones, such as bright reflections accompanied by acoustic shadows. Figure 3.1 provides an example of a processed and georeferenced SSS image containing stones embedded in different sediment types, serving as a visual reference for the automated detections that form the basis of the stone density maps. A detailed description of this Deep Learning methodology is provided in Appendix C.4.

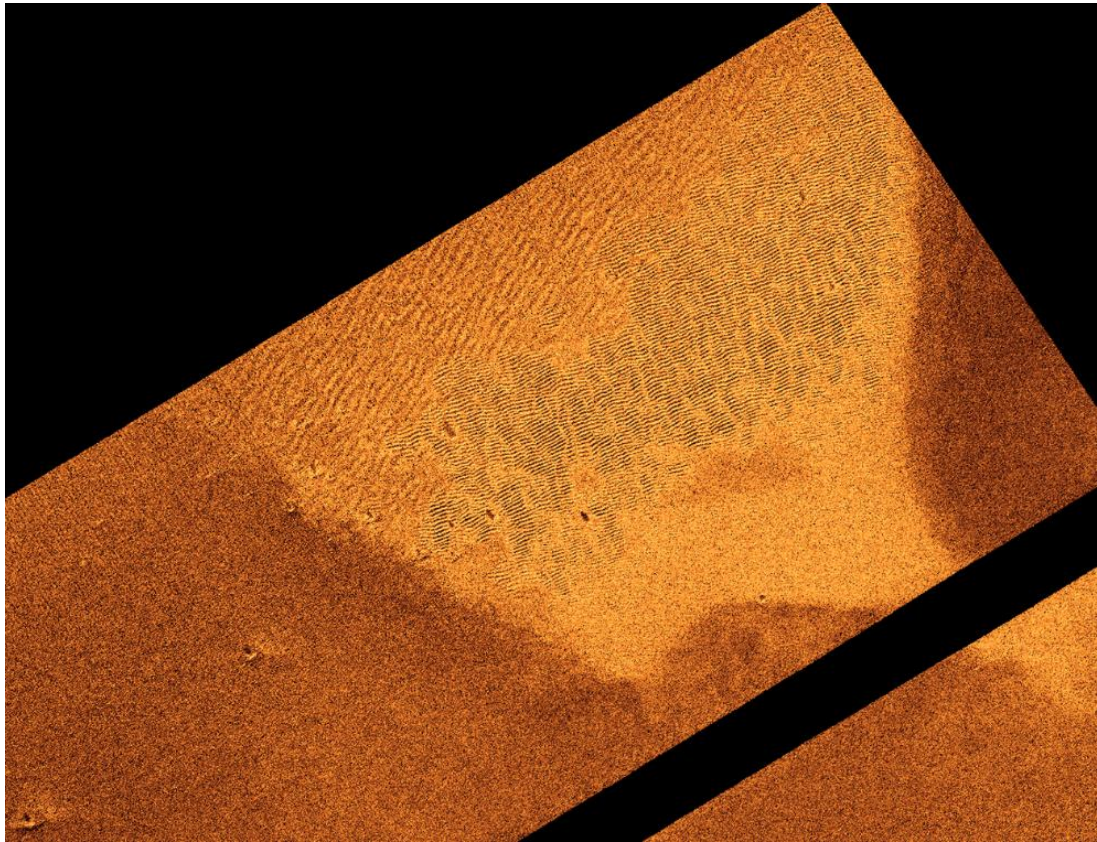


Figure 3.1: Example of processed and georeferenced side-scan sonar (SSS) imagery showing a few stones embedded in different sediment types. Stones are characterised by bright acoustic reflections and associated acoustic shadows, which form the visual basis for the automated stone detections used in this study.

3.2.1 Distribution of stones across the study areas

Stone density maps were generated for the areas where the presence of stones was confirmed after manual inspection of the SSS data (see Appendix C.1). Following this manual pre-selection, three areas were analysed in detail: Borkumse Stenen, Texelse Stenen, and Klaverbank. Some locations are covered by multiple overlapping SSS tracks. To avoid artificially inflating densities in these areas, a weighting procedure is applied: for each hectare cell, the total number of detected stones is divided by the number of SSS tracks covering that same cell. The resulting Weighted Stone Density maps thereby represent an estimate of stone abundance that is comparable across the entire survey area. Stone density maps were produced by applying the trained classifier to all available SSS data in the selected areas and aggregating the detected stone locations on a hectare-scale grid. An example for the Borkumse Stenen area is shown in Figure 3.2. The coverage map (left panel) shows the spatial variation in the number of processed SSS tracks, with most grid cells covered by one to three tracks. The corresponding weighted stone density map (right panel) indicates that, after normalisation for track overlap, the spatial distribution of stones becomes homogeneous and easy to interpret. Distinct clusters of higher stone density are visible in the northern and southern parts of the area. Equivalent maps were generated for the Texelse Stenen area (Figure 3.3) and the Klaverbank (Figure 3.4). These maps reveal spatially heterogeneous stone distributions within each area, with locally elevated stone densities that are consistent with field expectations for geogenic reef structures.

For the Borkumse Stenen area, a hand-picked stone map from earlier work (Bos, et al., 2025) was available for comparison. The overall spatial patterns show strong agreement between the two datasets, with zones of elevated stone density occurring in the same regions. This correspondence provides confidence that the automated classification approach yields realistic and reproducible estimates of stone abundance.

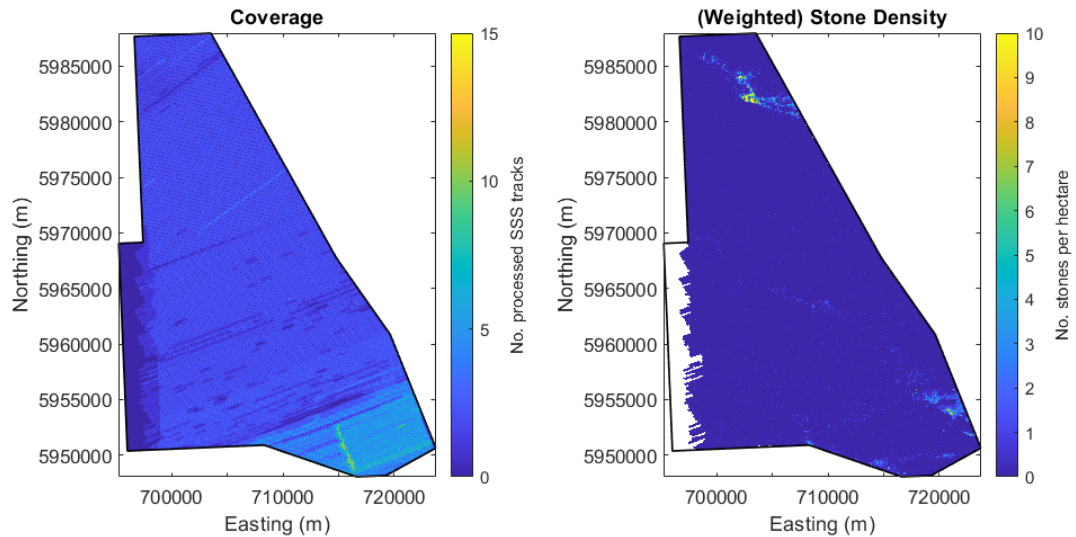


Figure 3.2: Coverage (left) and weighted stone density (right) maps for the Borkumse Stenen area. Colours indicate the number of SSS tracks (coverage) and the number of detected stones per hectare (stone density), with blue representing low values and yellow representing high values. Maps are displayed in ETRS89 UTM Zone 31N, with coordinates in metres.

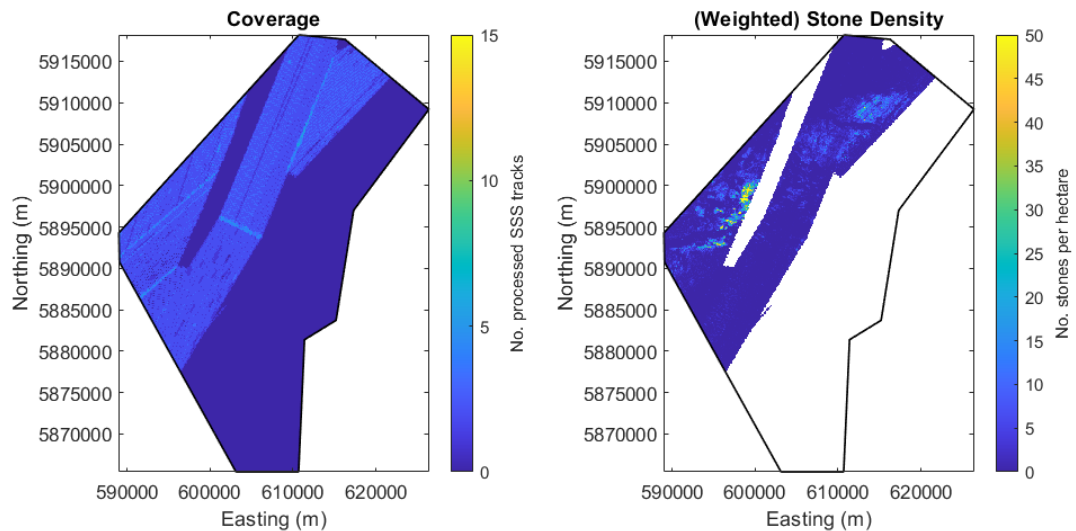


Figure 3.3: Coverage (left) and weighted stone density (right) maps for the Texelse Stenen area. Maps are displayed in ETRS89 UTM Zone 31N, with coordinates in metres.

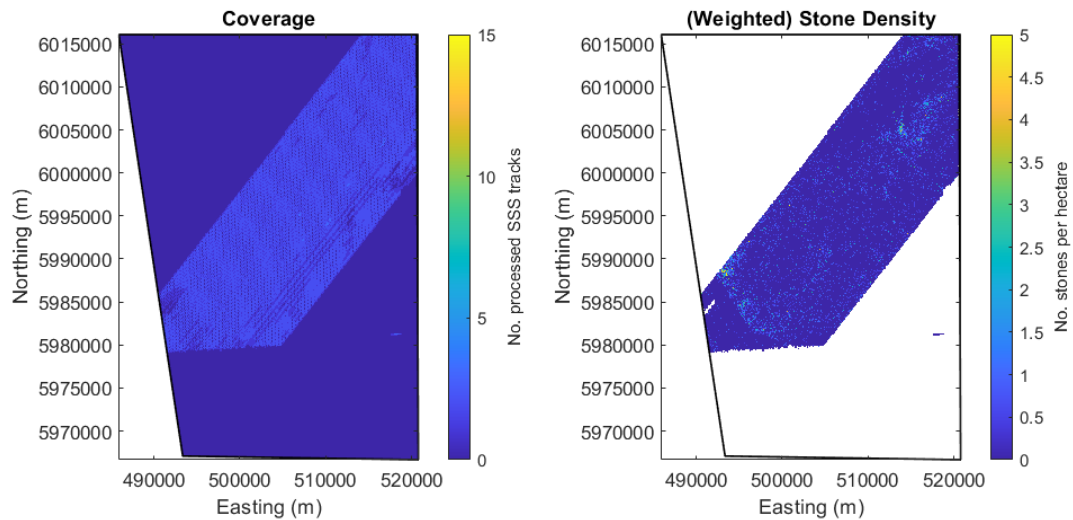


Figure 3.4: Coverage (left) and weighted stone density (right) maps for the Klaverbank area. Maps are displayed in ETRS89 UTM Zone 31N, with coordinates in metres.

3.2.2 Factors influencing detectability

When interpreting the stone density maps, it is important to recognise that seabed characteristics vary considerably between areas. This has a direct impact on stone detectability. In the Borkumse Stenen area, stones generally occur on a relatively homogeneous sediment background, resulting in clear acoustic signatures that are easy to detect. In contrast, the Texelse Stenen and Klaverbank areas are characterised by stones embedded within a more heterogeneous seabed, where sediment patterns, ripples, and textural transitions add complexity to the SSS imagery. These additional structures can obscure or resemble stone-like features, thereby increasing uncertainty in the detections. Furthermore, it appears that the Texelse Stenen area primarily contains clusters of smaller stones, while the stones in the Borkumse Stenen and Klaverbank area are somewhat larger and more scattered, making them more easy to detect.

In addition, the stone density map for the Texelse Stenen area exhibits an artefact that is associated with differences in survey line orientation and local data quality. Variations in acquisition geometry can introduce spatial patterns in the classifier output that are not solely controlled by geological conditions and should therefore be interpreted with caution.

Another source of uncertainty arises from the misclassification of biogenic structures, most notably Lanice/Loimia reefs. These organisms can produce strong acoustic reflections with pronounced shadows that closely resemble stones. This effect is particularly relevant in parts of the Borkumse Stenen area where such biogenic structures are known to be abundant. At present, these features have not been removed from the stone density maps and may locally lead to an overestimation of stone abundance. This overestimation is not necessarily a limitation of the Deep Learning approach, but also of the data itself, as even experts will have difficulty distinguishing stones from Lanice/Loimia.

By contrast, anthropogenic objects such as wrecks, cables, and pipelines, which are often also misclassified as stones, could be manually identified and excluded to prevent them from influencing the results. While effective, this manual removal is labour-intensive and introduces a degree of subjectivity.

3.2.3 Implications for large-scale mapping

Despite these limitations, the stone density maps represent a significant step towards objective and large-scale mapping of geogenic reef structures using SSS data. Compared to earlier approaches that relied heavily on manual hand-counting, the applied Deep Learning workflow enables stone detections to be generated considerably faster and more consistently over large areas. Once trained, the classifier can be applied efficiently to extensive SSS datasets, substantially reducing the time required to produce spatially complete stone maps.

Furthermore, the strong agreement with earlier manually derived maps, particularly in the Borkumse Stenen area, indicates that the workflow is capable of delivering robust and geologically meaningful spatial patterns of stone abundance. At the same time, the current results also show that the process is not yet fully automatic. Manual intervention remains necessary to address misclassification of biogenic structures such as Lanice/Loimia reefs, to remove anthropogenic objects, and to assess artefacts related to survey geometry and data quality. These steps, while smaller in scope compared to full manual mapping, still require expert judgement.

Future work should therefore besides the completion of areas that are currently only partially processed, such as Texelse Stenen and Klaverbank, also focus on further reducing the remaining manual effort. Improvements in class separation between stones and biologically induced acoustic features could be achieved by introducing additional classes or incorporating spatial and contextual information. Greater automation in the identification and exclusion of anthropogenic objects would improve reproducibility and scalability.

3.3 Wreck distribution maps

By combining an existing database of known seabed objects (SONARREG) with side-scan sonar imagery, an overview of the distribution of wrecks and other habitat-relevant objects could be created. The analysis focuses on identifying those objects that are clearly visible in the SSS data that have sufficient spatial extent to provide hard substrate suitable for habitat development, e.g. wrecks. For each database entry, a patch of 250 m × 250 m centered on the reported object was extracted. Each extracted patch was then inspected for the presence or absence of a visible object. An example of such a patch showing a wreck is provided in Figure 3.5, illustrating the acoustic appearance of such objects.

Not all database entries had a clearly detectable sonar signature. For objects that were visible in the SSS imagery, the spatial extent of it was determined manually. Where multiple overlapping SSS tracks were available, all tracks were considered to ensure that the maximum observable extent of the object was captured.

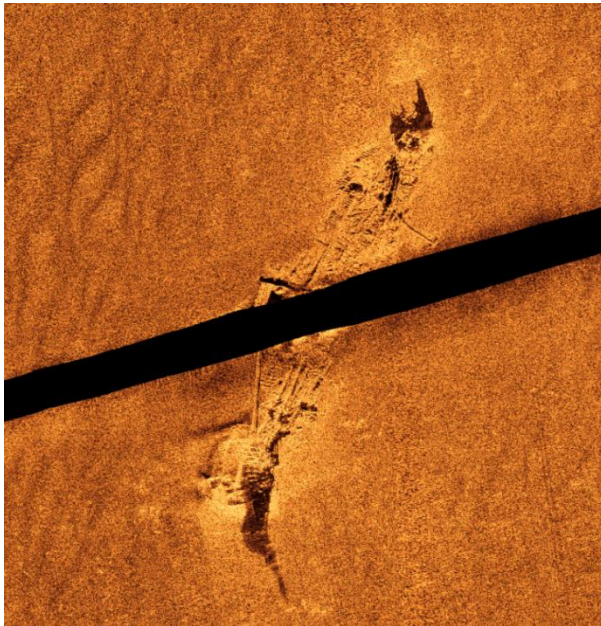


Figure 3.5: Example of a processed and georeferenced side-scan sonar patch showing a wreck located directly beneath the tow fish, with the nadir clearly visible. The wreck is visible as strong acoustic reflections with pronounced acoustic shadows.

3.3.1 Distribution of wrecks and other habitat-relevant objects

The results of the wreck analysis are summarised using two map products. The first shows the spatial distribution of all objects listed in the SONARREG database within the survey areas, irrespective of whether a corresponding sonar signature was detected. The second focuses on those objects for which a clear sonar expression was observed in the SSS data and whose estimated footprint exceeds 100 m². This threshold was chosen to ensure that only objects large enough to provide substantial hard substrate, and therefore potentially suitable as habitat for marine organisms, are included. A summary of the total number of acoustically visible objects (for the processed areas) and their combined footprint is provided in Table 3.1. The survey periods on which the corresponding SONARREG detections are based are also included. The resulting wreck maps are presented for the Borkumse Stenen, Texelse Stenen, Doggersbank, and Klaverbank regions (Figure 3.6 - Figure 3.9). In these figures, the green background indicates areas covered by and validated with at least one SSS track, while the plotted points show the locations of database objects. The filtered maps highlight only those wrecks that are both visible in the SSS data and exceed the selected footprint threshold, providing a spatial overview of hard-substrate features of potential ecological relevance.

Table 3.1: Total number of acoustically visible objects and combined footprint (m²) per processed area.

Area name	Number of visible objects	Combined footprint (m ²)	Survey period
Borkumse Stenen	54	33.396	1988 - 2025
Texelse Stenen	52	13.683	1887 - 2025
Doggersbank	22	11.624	1971 - 2019
Klaverbank	42	1.365	1969 - 2018

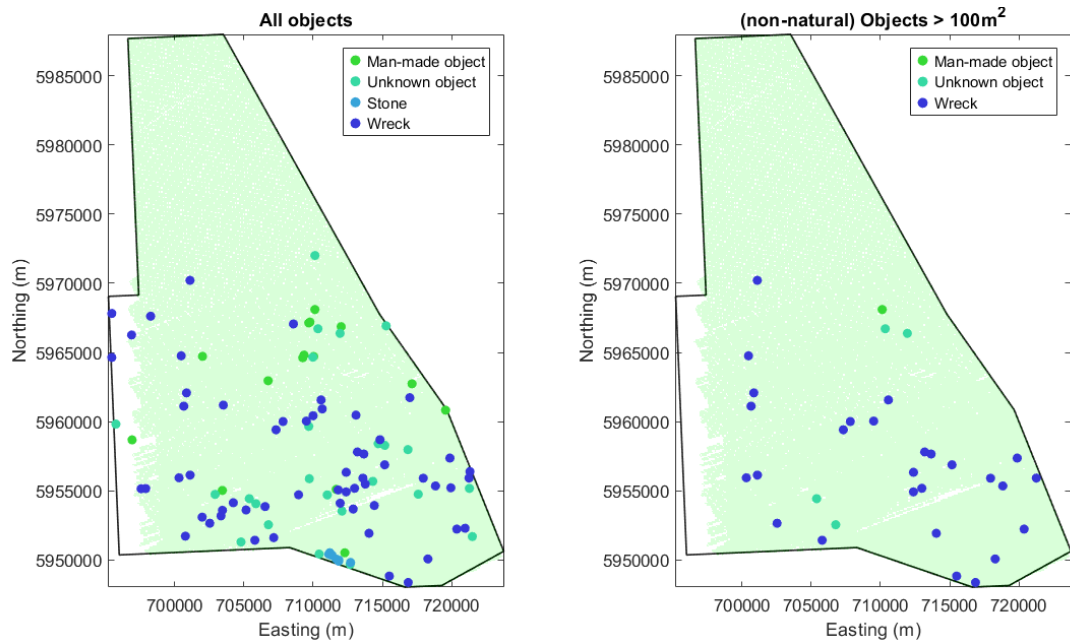


Figure 3.6: Distribution of SONARREG objects in the Borkumse Stenen area. The green background indicates areas covered by and validated with at least one SSS track. Maps are displayed in ETRS89 UTM Zone 31N, with coordinates in metres.

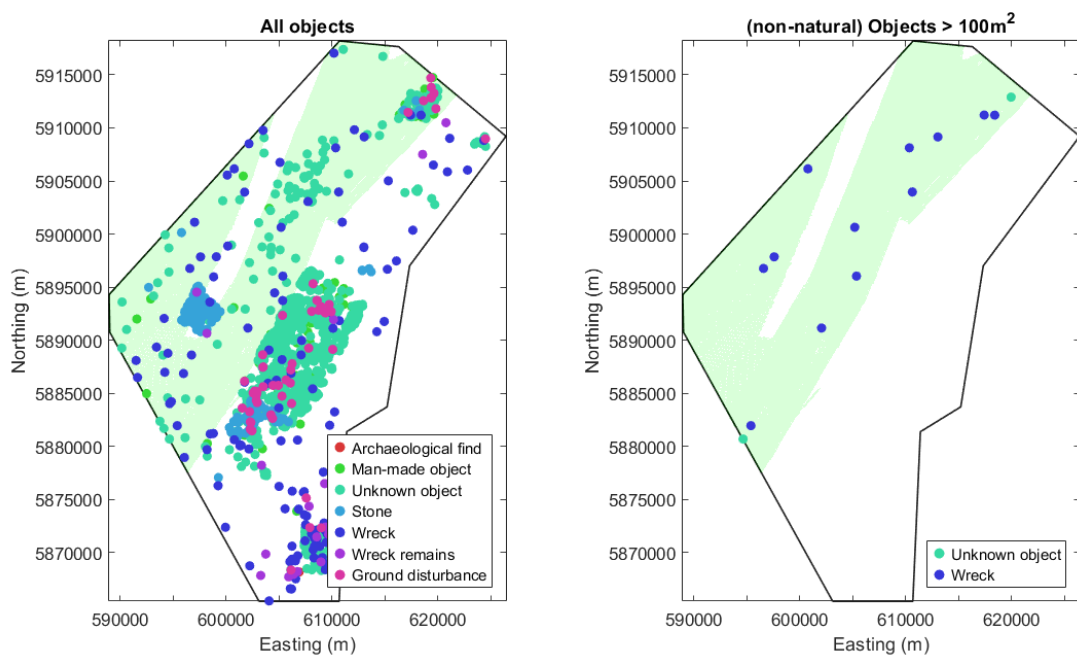


Figure 3.7: Distribution of SONARREG objects in the Texelse Stenen area. The green background indicates areas covered by and validated with at least one SSS track. Maps are displayed in ETRS89 UTM Zone 31N, with coordinates in metres.

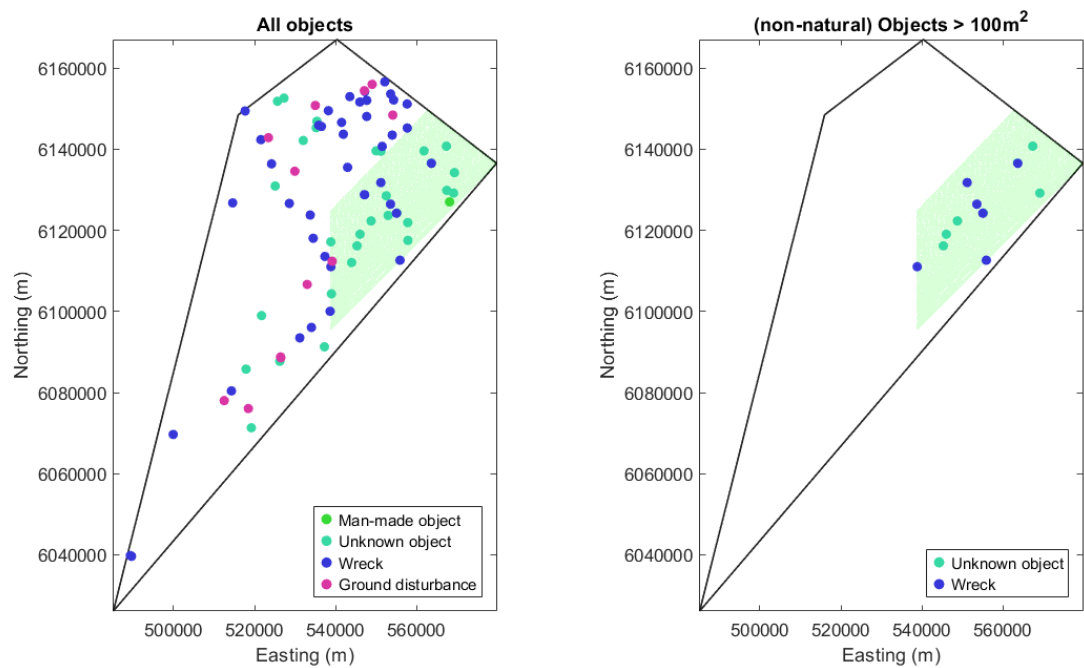


Figure 3.8: Distribution of SONARREG objects in the Doggersbank area. The green background indicates areas covered by and validated with at least one SSS track. Maps are displayed in ETRS89 UTM Zone 31N, with coordinates in metres.

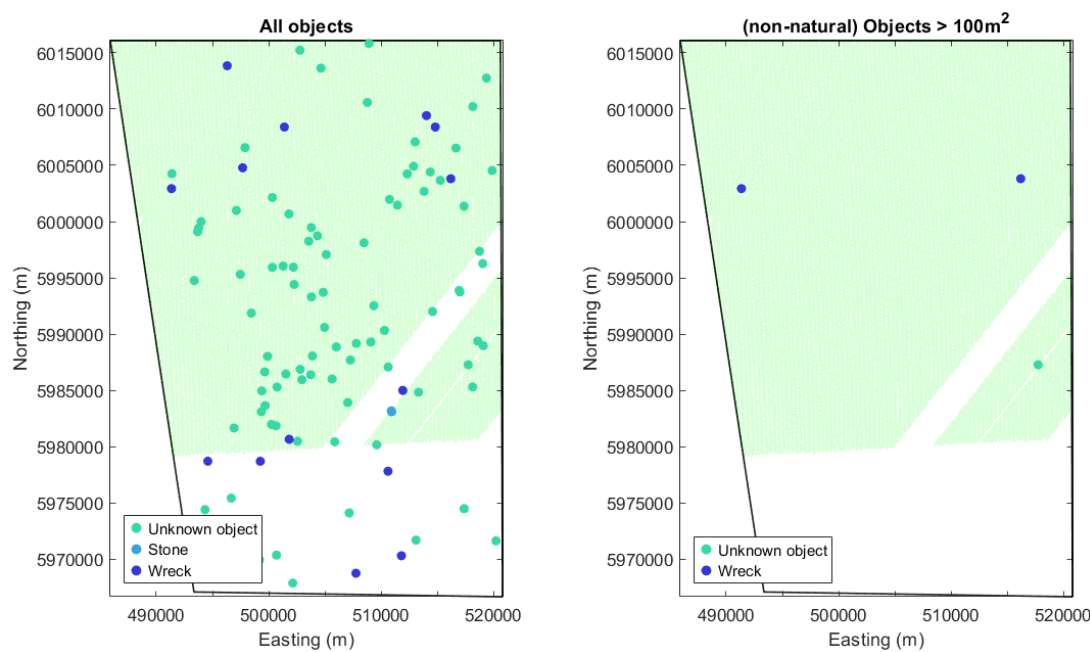


Figure 3.9: Distribution of SONARREG objects in the Klaverbank area. The green background indicates areas covered by and validated with at least one SSS track. Maps are displayed in ETRS89 UTM Zone 31N, with coordinates in metres.

3.3.2 Data and interpretation constraints

Interpretation of the wreck maps requires acknowledgment of uncertainty at several stages of the workflow. Although the SONARREG database provides a valuable and structured starting point, it is derived from historical reporting and compilation efforts and therefore incorporates positional uncertainty and variability in object descriptions. Consequently, not all entries can be unequivocally linked to identifiable targets in the available SSS data.

Most SONARREG records originate from surveys conducted within the last decade, yet some date back to 1887. Over such timescales, seabed conditions may have changed substantially. Sediment transport, erosion, and burial can modify the exposure of wrecks, leading to differences between the SONARREG data and the SSS surveys. Objects that were previously exposed may now be obscured, while others may have become more prominent.

Wreck detectability in SSS imagery is further influenced by object dimensions, orientation with respect to survey lines, and local data quality. As a result, wreck identification and footprint delineation rely on manual sonar interpretation. While this process is guided by established acoustic criteria, it inevitably introduces subjectivity, particularly where sonar signatures are fragmentary or ambiguous. The availability of overlapping SSS tracks helps to constrain this uncertainty but does not fully resolve it.

Finally, applying a minimum footprint threshold of 100 m² simplifies what is in reality a continuum of object sizes and characteristics. Smaller features may still constitute ecologically relevant hard substrate, while larger wrecks can vary considerably in morphology, relief, and ecological role. The resulting wreck maps should therefore be regarded as an indicative representation of larger, readily detectable hard-substrate structures rather than a comprehensive or definitive inventory of seabed wrecks.

3.3.3 Implications for habitat assessment

Despite these limitations, the wreck maps provide a clear and transparent overview of the distribution of large, hard-substrate objects across the survey areas. By combining an existing object database with targeted inspection of SSS imagery, the approach efficiently distinguishes between known objects that are acoustically visible and those that are not, and highlights wrecks that are most likely to contribute to benthic habitat complexity.

Compared to fully manual mapping approaches, this workflow allows results to be generated relatively quickly over large areas, while still retaining expert oversight where interpretation is required. The maps therefore form a practical basis for assessing the potential ecological role of wrecks and other man-made structures in the context of habitat mapping.

Future work could further reduce subjectivity by developing more formalised criteria or semi-automated routines for object detection and footprint estimation. Extending the analysis to newly acquired SSS data would allow the wreck maps to be expanded to additional areas or refined where coverage is currently limited. Together, these steps would strengthen the use of wreck maps as an operational component in regional-scale assessments of hard-substrate habitats.

4 Conclusion

4.1 Summary of key results

This study provides a multi-scale characterisation of abiotic seabed properties in the Dutch North Sea that are directly relevant to the implementation of the Nature Restoration Regulation (NRR). By combining North Sea-wide sediment mapping with targeted, high-resolution side-scan sonar (SSS) analyses, the project delivers both a consistent large-scale baseline and detailed local-scale insight into seabed heterogeneity, hard-substrate availability and geogenic reef occurrence.

At North Sea-wide scale, updated seabed-sediment maps based on the Folk classification system and an associated mud-percentage map were produced for the full Dutch North Sea. These products extend existing national datasets, include uncertainty information, and provide a transparent and reproducible reference for large-scale assessment and reporting under the NRR. The results highlight strong spatial variability in sediment composition and identify seabed properties relevant for habitat interpretation and restoration planning.

At local scale, SSS-based analyses for selected priority areas reveal pronounced fine-scale variability in sediment properties, seabed texture and hard-substrate occurrence that is not resolved in North Sea-wide products. These analyses demonstrate the added value of SSS for site-specific interpretation, while explicitly accounting for limitations related to spatial variability in data quality.

Semi-automated mapping approaches were applied to SSS data to generate stone density maps for three key geogenic reef areas: the Borkumse stenen, Texelse stenen and Klaverbank. The resulting maps show spatially heterogeneous stone distributions. In addition, an overview of wrecks and other anthropogenic hard-substrate objects was produced, providing an indicative assessment of their potential to support habitat restoration.

Overall, the results demonstrate that a combined use of North Sea-wide sediment maps and targeted SSS analyses provides a better basis for characterising the abiotic seabed context relevant to the NRR. The delivered maps and data (see Appendix G) support restoration planning, monitoring realized designs and choosing future habitat suitability assessments. Data limitations and uncertainties have been addressed.

4.2 Way forward

While the results of this study provide an abiotic characterisation of the seabed, some limitations should be considered when interpreting the outputs. A primary limitation is the limited spatial representativeness of validation data for mapping and classification results. Much of the interpretation, particularly for SSS-derived products and automated classifications, relies on acoustic response patterns supported by expert judgement. Targeted acquisition of validation data (e.g. video observations or physical sampling across representative substrate types) would allow improved quantification of classification accuracy, uncertainty, and class separability, and would support calibration and transferability of automated workflows.

In addition, empirical understanding of how specific seabed characteristics (e.g. stone densities, sediment heterogeneity and morphological patterns) translate into ecological value or biodiversity support remains context dependent. Although these features are widely recognised as important abiotic drivers of benthic communities, their functional relevance for particular species assemblages is not yet consistently quantified across spatial and temporal scales relevant for management. Further integration of biological observations with the delivered abiotic maps would help identify which seabed characteristics most strongly influence habitat suitability, persistence and restoration success.

A further limitation is that not all NRR-relevant areas could be analysed within the scope of this project. Expanding spatial coverage through prioritised processing of additional acoustic datasets, combined with a systematic assessment of data gaps, would improve comparability between regions and support more consistent prioritisation of restoration measures.

Further methodological development could focus on strengthening the integration of acoustic SSS backscatter within sediment-mapping workflows. Incorporating SSS-derived features as complementary predictors can improve spatial detail and thematic resolution, provided that differences in acquisition parameters, processing routines and quality control procedures are appropriately harmonised.

Finally, the delivered products can be considered as input for subsequent habitat suitability assessment rather than the end product. Future work may prioritise linking abiotic maps to biological observations, refining habitat-specific thresholds and strengthening the quantitative basis for evaluating restoration potential under the NRR.

References

- Bos, O. G., Bittner, O., van der Weide, B., Cuperus, J., Wijnhoven, S., Gaida, T. C., & Binnerts, B. (2025). *Borkum Reef Grounds: inventory of biodiversity and habitats. MONS ID49 Effectivity of Marine Protected Areas ID. Wageningen Marine Research. Waardenburg Ecology. Ecoauthor. TNO. Wageningen Marine Research report.*
- Evans, D., Aish, A., Boon, A., Condé, S., Connor, D., Royo Gelabert, E., Tunesi, L. (2016). *European Topic Centre on Biological Diversity Revising the marine section of EUNIS Habitat classification - Report of a workshop held at the European Topic Centre on Biological Diversity.*
- Gaida, T. C., Binnerts, B., & Bos, O. (2025, January). Semi-Automated Classification of Side-Scan Sonar Data for Mapping Sabellaria spinulosa Reefs in the Brown Bank, Dutch Continental Shelf. *Journal of Marine Science and Engineering*, 13, 74. doi:10.3390/jmse13010074
- Gaida, T. C., Binnerts, B., Cuperus, J., Bos, O., & van der Jagt, H. (2024). *Presence of Sabellaria spinulosa reefs in the northern Brown Bank, Dutch Continental Shelf, North Sea (MONS ID56: monitoring reef-building species).* Den Haag, Netherlands: TNO.
- Heinrich, C., Feldens, P., & Schwarzer, K. (2016, October). Highly dynamic biological seabed alterations revealed by side scan sonar tracking of Lanice conchilega beds offshore the island of Sylt (German Bight). *Geo-Marine Letters*, 37, 289–303. doi:10.1007/s00367-016-0477-z
- Powers, J., Brewer, S. K., Long, J. M., & Campbell, T. (2014, September). Evaluating the use of side-scan sonar for detecting freshwater mussel beds in turbid river environments. *Hydrobiologia*, 743, 127–137. doi:10.1007/s10750-014-2017-z
- Qin, X., Luo, X., Wu, Z., & Shang, J. (2021). Optimizing the Sediment Classification of Small Side-Scan Sonar Images Based on Deep Learning. *IEEE Access*, 9, 29416–29428. doi:10.1109/access.2021.3052206
- TNO-GDN. (2023). *Seabed-sediment map*. Opgehaald van www.dinoloket.nl/en/subsurface-models
- van Overmeeren, R., Craeymeersch, J., van Dalen, J., Fey, F., van Heteren, S., & Meesters, E. (2009, November). Acoustic habitat and shellfish mapping and monitoring in shallow coastal water – Sidescan sonar experiences in The Netherlands. *Estuarine, Coastal and Shelf Science*, 85, 437–448. doi:10.1016/j.ecss.2009.07.016
- Westphal, G. G., & Ostrensky, A. (2016, March). Use of side-scan sonar for estimations of Crassostrea brasiliana (Lamarck, 1819) stocks in subtidal banks on the south coast of Brazil. *Brazilian Journal of Oceanography*, 64, 49–56. doi:10.1590/s1679-87592016104506401
- Zhamoida, V., Ryabchuk, D., Kropatchev, Y. P., Kurennoy, D., Boldyrev, V. L., & Sivkov, V. (2009). Recent sedimentation processes in the coastal zone of the Curonian Spit (Kaliningrad region, Baltic Sea). *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, 160(2), 143–157.

Appendix A

North Sea wide maps

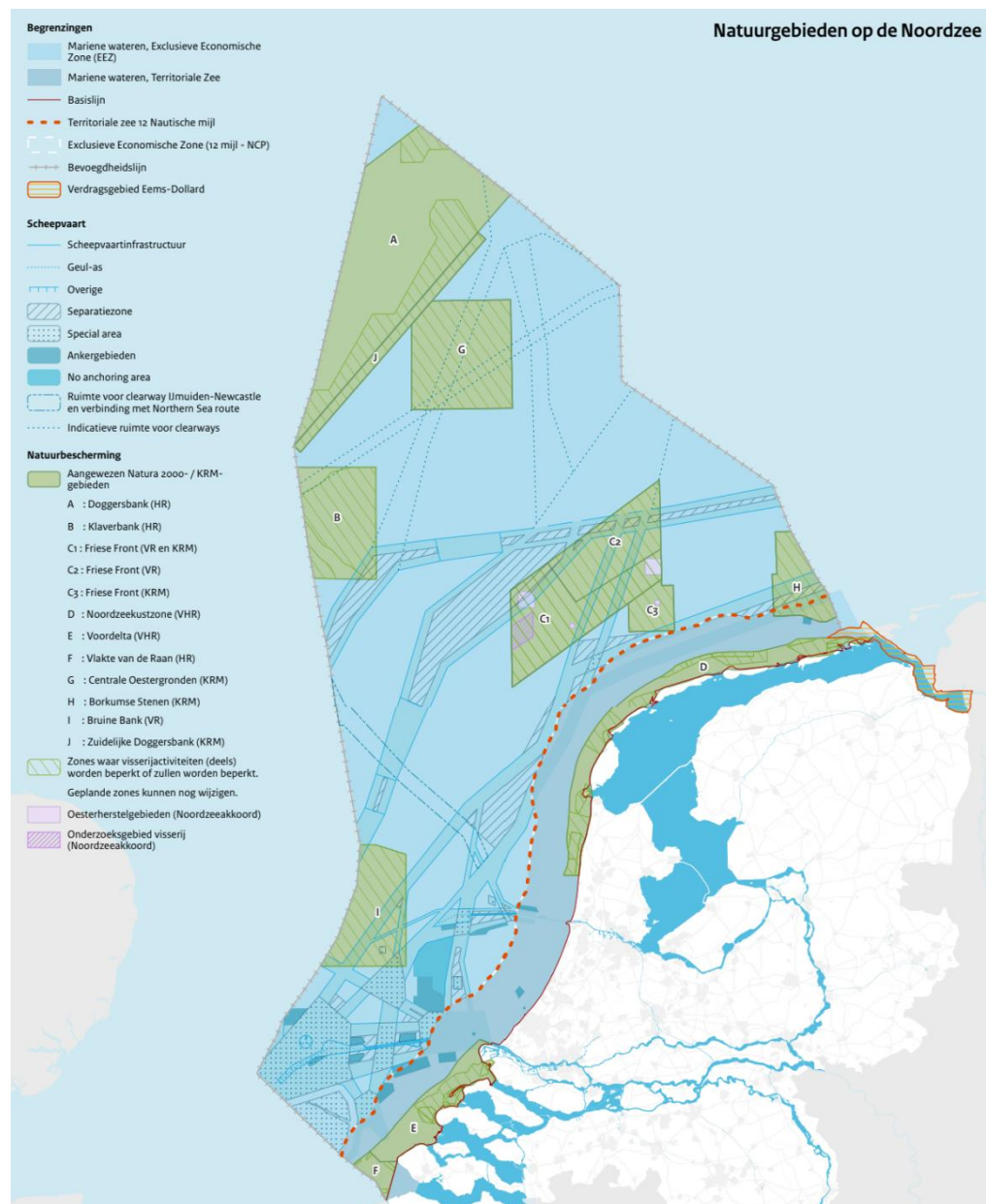


Figure A.1: Natura 2000 and KRM areas within the Dutch EEZ.

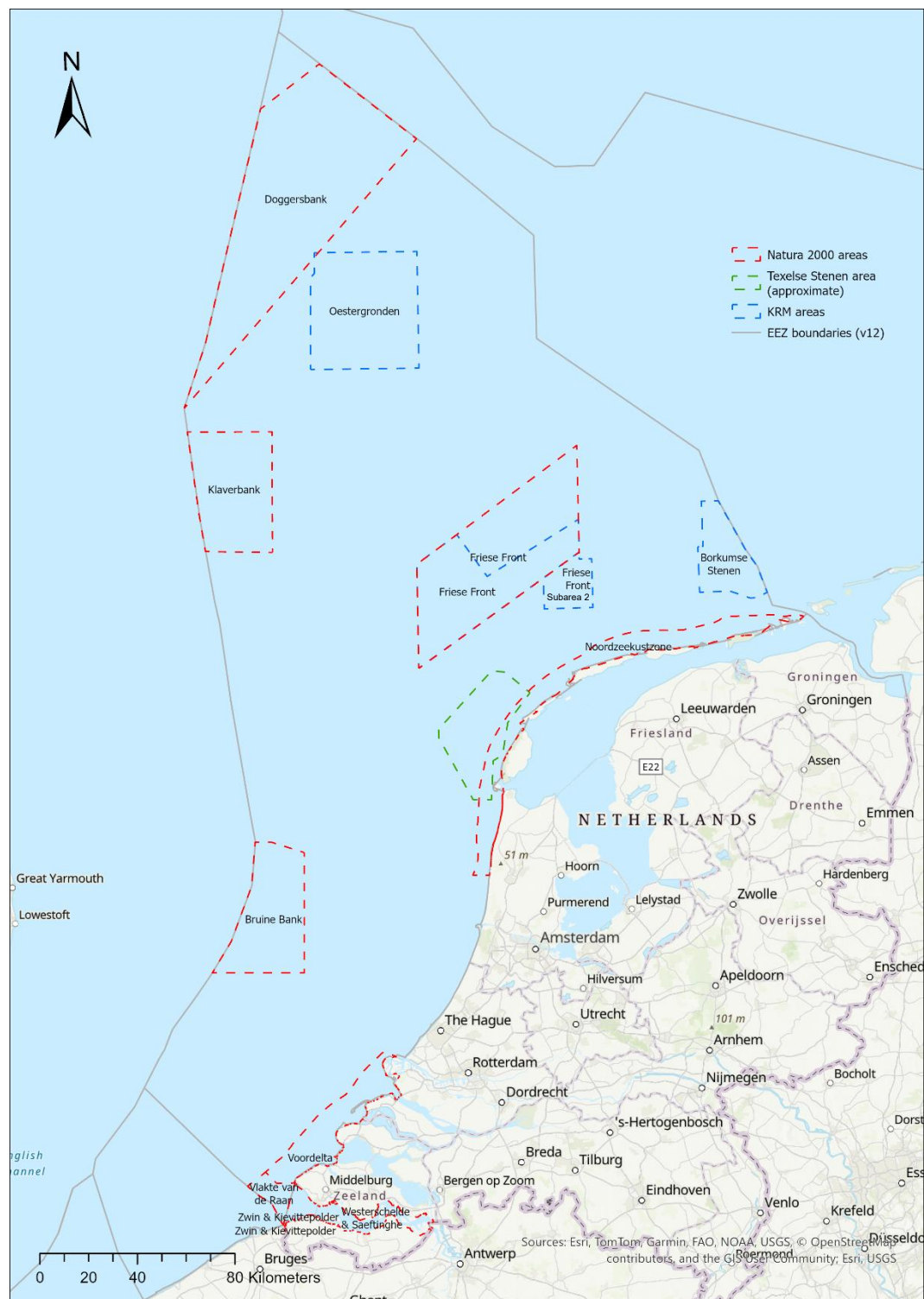


Figure A.2: Natura 2000 and KRM areas within the Dutch EEZ as well as the approximate Texelse stenen region. Note that the KRM area Zuidelijke Doggersbank is not shown here on the map. The outline of the Texelse Stenen area was defined by TNO-GDN on the basis of the presence of coarse sediments derived from the Folk maps and high concentrations of gravel in seabed-samples. The southern KRM Doggersbank is not shown.

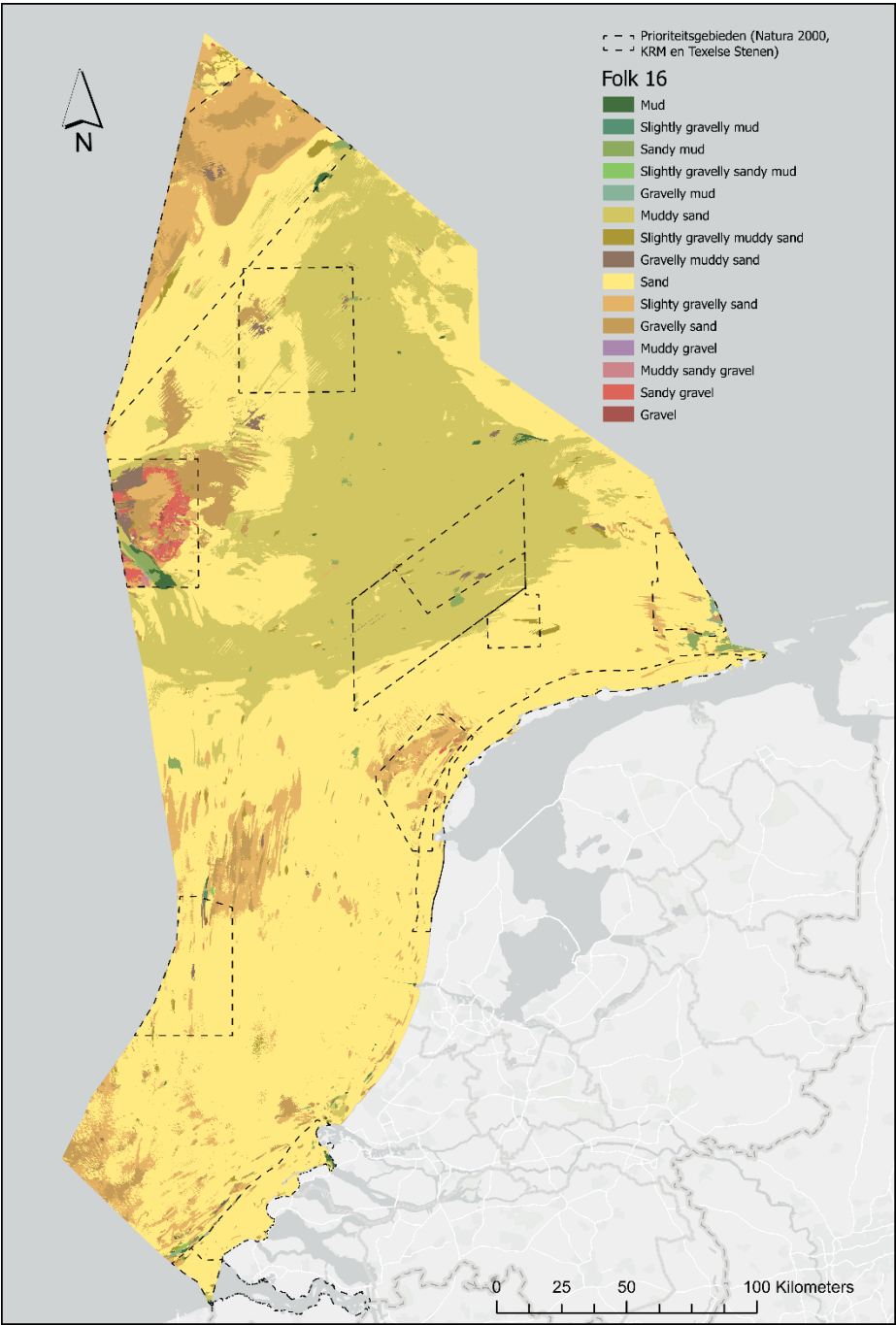


Figure A.3: Seabed-sediment map – Folk 16 classification system. Grid resolution is 100 m x 100 m.

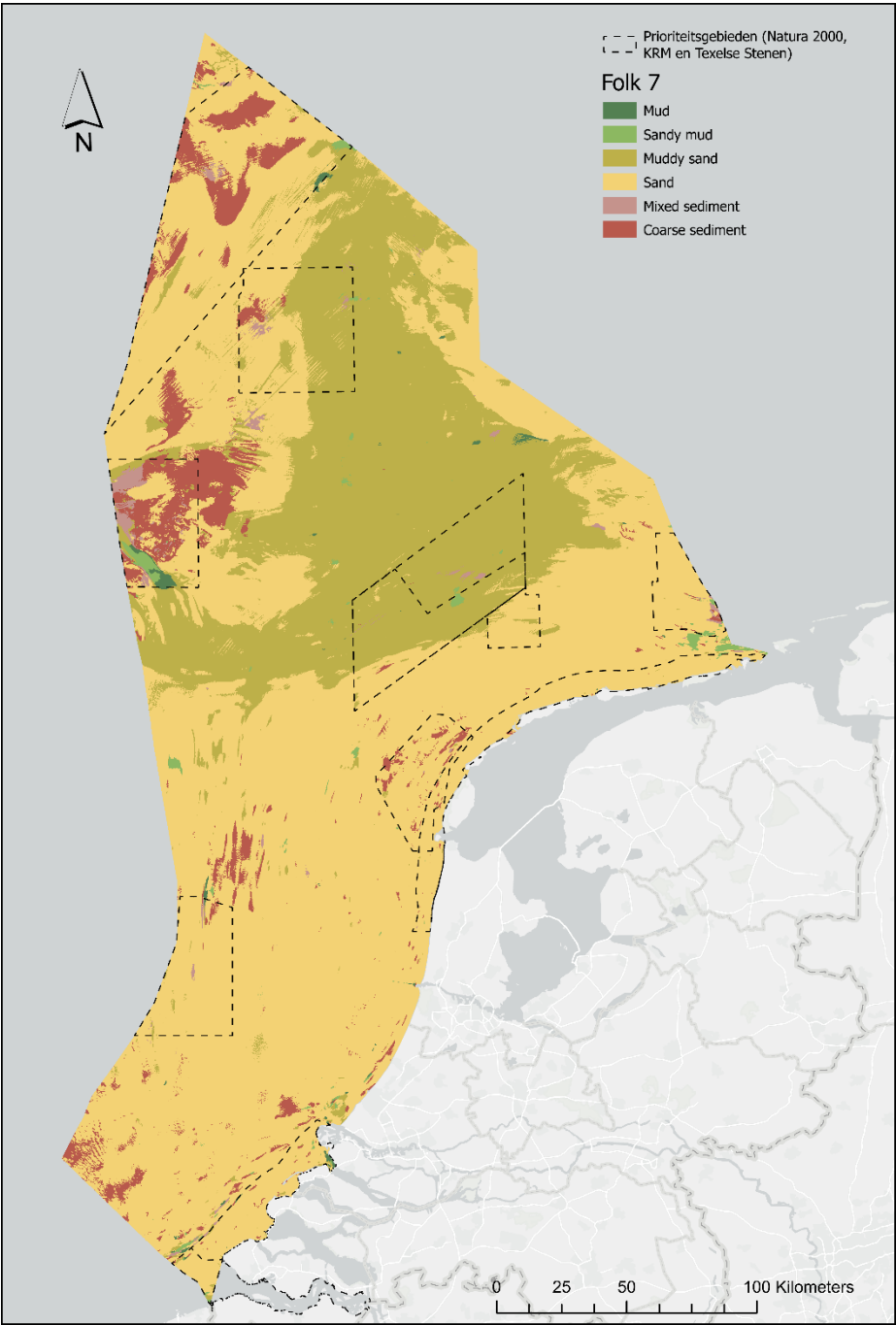


Figure A.4: Seabed-sediment map – Folk 7 classification system. Grid resolution is 100 m x 100 m.

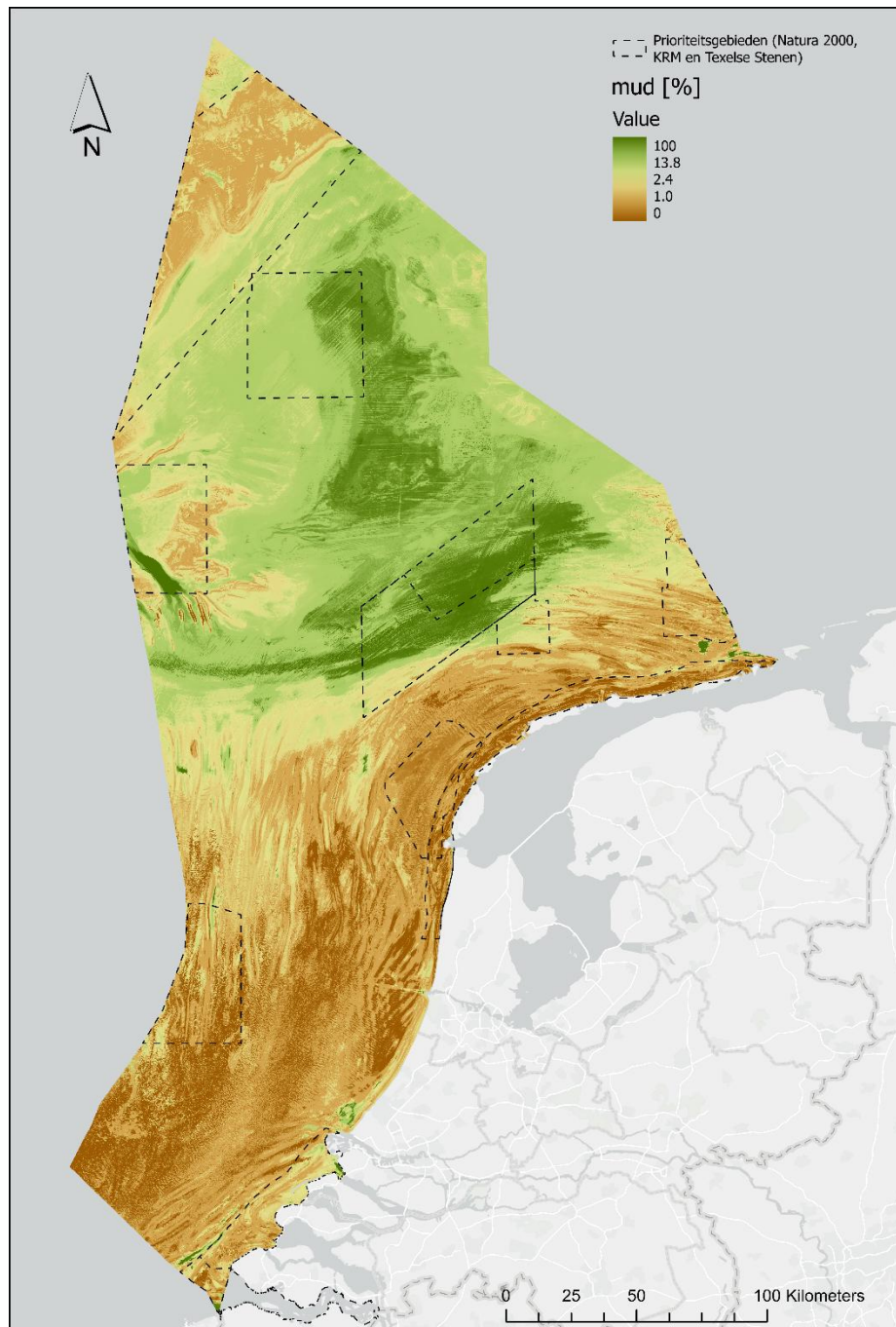


Figure A.5: Seabed-sediment map - mud percentage. The non-linear colour scale improves the visibility of transitions in mud percentage, but as a result, specific values cannot be read directly from this figure. Grid resolution is 100 m x 100 m.

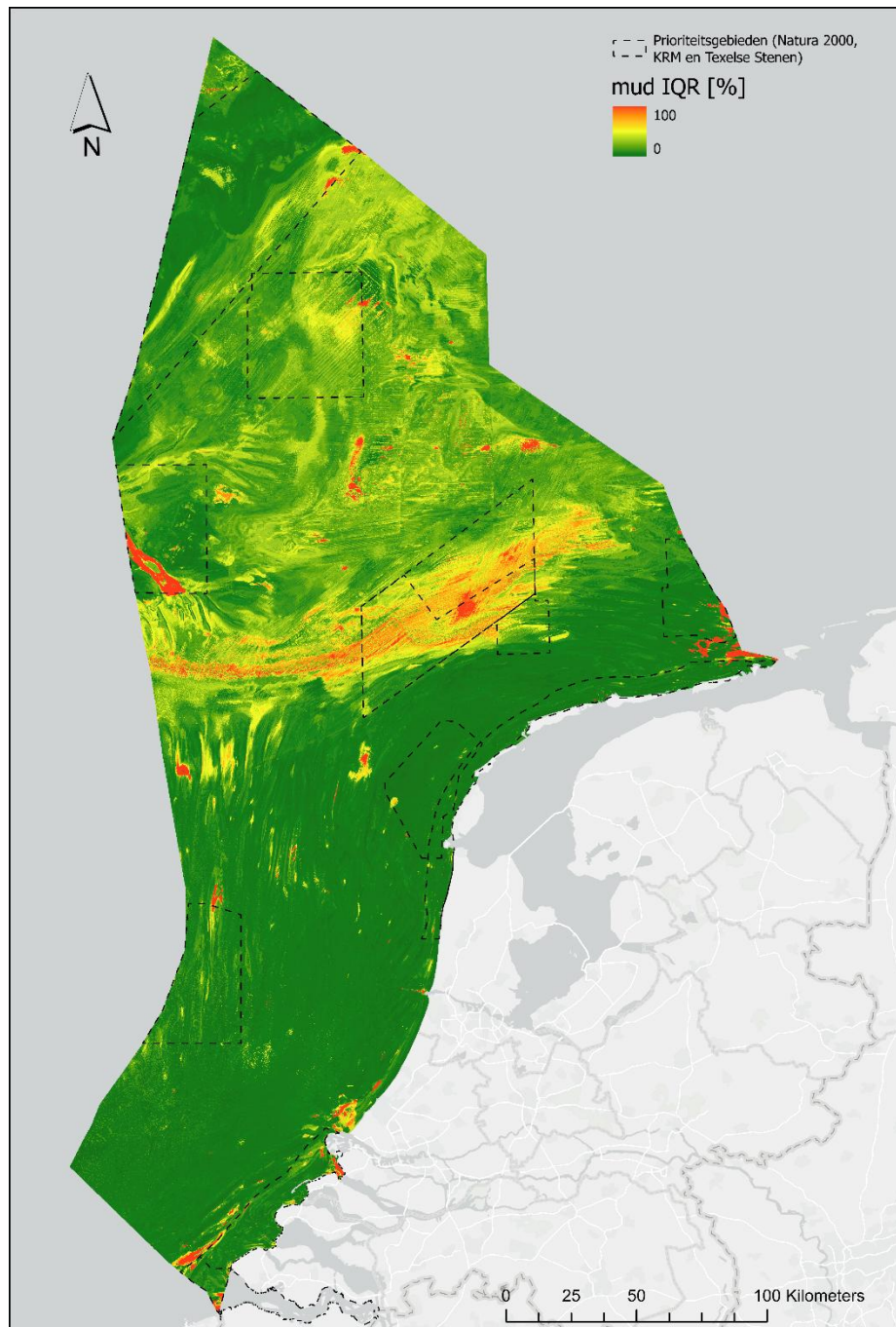


Figure A.6: Uncertainty of the mud-percentage map, expressed as interquartile range. Grid resolution is 100 m x 100 m.

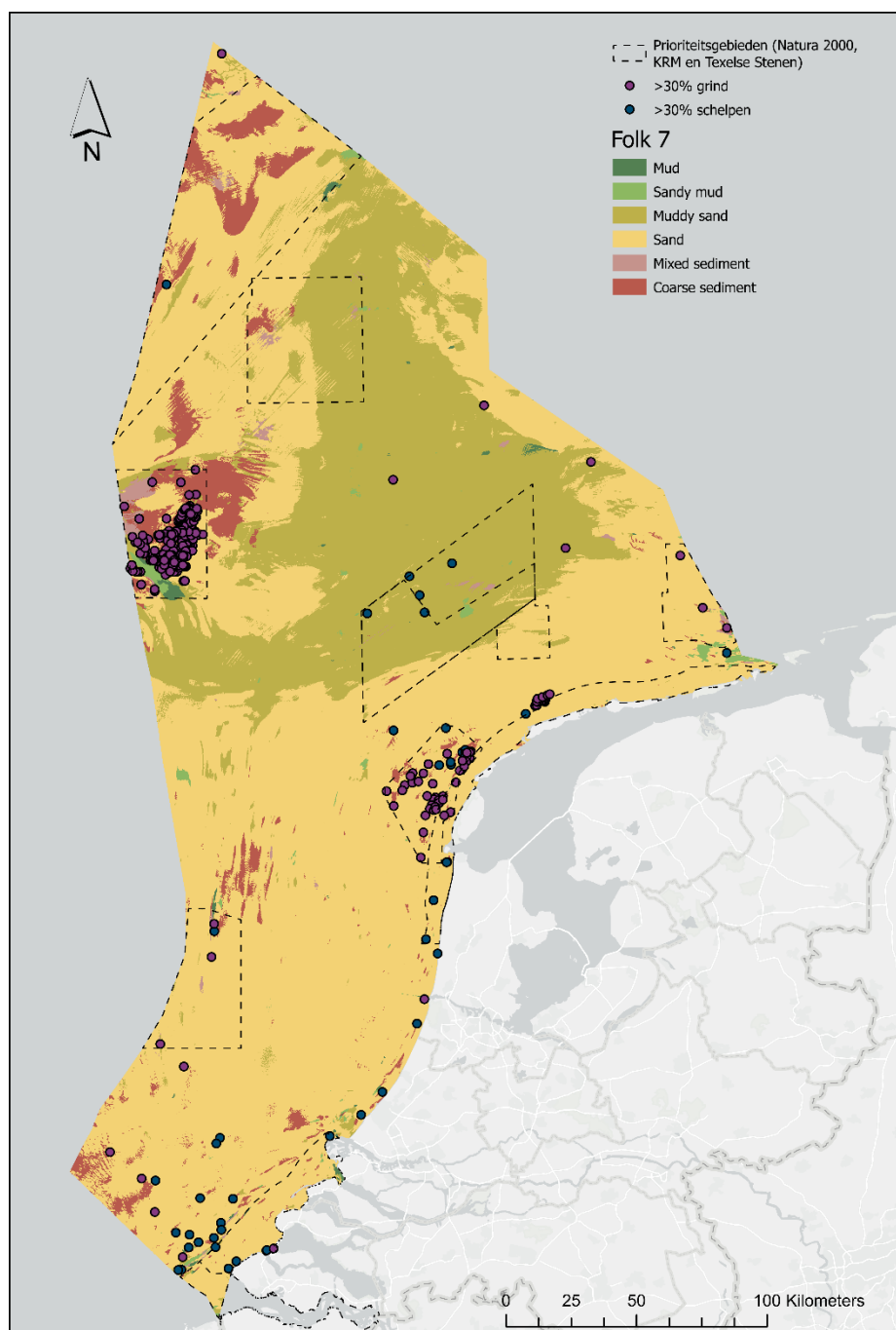


Figure A.7: Locations of hard-substrate data points with >30% gravel and >30% shells; Folk 7 map shown for reference. Grid resolution is 100 m x 100 m.

Appendix B

Sediment folk classification method

Technical details of the percentile-weighting procedure

For each Folk class, percentile values of mud percentage are determined separately from a series of randomly selected trees from the random forest. The contributions of these trees are weighted according to the predicted probability that the location belongs to the relevant Folk class:

$$\hat{m}_i^\alpha = q_\alpha \left(\sum_{c \in \mathcal{C}} \{ \hat{m}_i^{t,c} \}_{t=1}^{n_c} \right)$$

where $\hat{m}_i^\alpha$ is the predicted mud percentage at location i for percentile α , q_α is the percentile function for $\alpha \in [0,1]$ (for example, $\alpha = 0.1$ for the 10th percentile), $\hat{m}_i^{t,c}$ is the predicted mud percentage of tree t under the assumption of class $c \in \mathcal{C}$ (Folk 16 classes), T is the total number of trees in the random forest, and $n_c = T * \hat{p}_{i,c}$ is the number of draws for class c , proportional to the predicted probability of the Folk 16 class $\hat{p}_{i,c}$.

The most likely value of the mud percentage (Figure A.5) is equal to the median (50th percentile), and the uncertainty in the prediction of the mud percentage is then expressed by the interquartile range $IQR_i = \hat{m}_i^{0.75} - \hat{m}_i^{0.25}$ (Figure A.6).

Appendix C

Sonar aided sediment and reef classification methods

In this project, side-scan sonar (SSS) data provided by the Hydrographic Service were used to assist in the characterisation of the seabed. Three distinct mapping approaches were applied: one approach for mapping sediment type distributions (covering soft and hard substrates) and two approaches for identifying biogenic and geogenic reefs or other morphological features, which required a finer scale analysis of the sonar data (Figure C.1). While sediment mapping relies primarily on large-scale variation in the seabed reflectivity (10th of meters to kilometres), the mapping of reefs and morphological features is based on pattern recognition of fine scale structures (decimetre to meters). When only considering the seabed reflectivity (i.e. backscatter amplitudes) in the mapping approach, a specific detrending approach is necessary, which differs from the method used for pattern recognition. Both the detrending method and the desired spatial resolution are defined before the first step of the workflow, where SSS data were processed and georeferenced onto the seabed (Figure C.1). Consequently, for reef- and sediment mapping different georeferenced sonar images are generated.

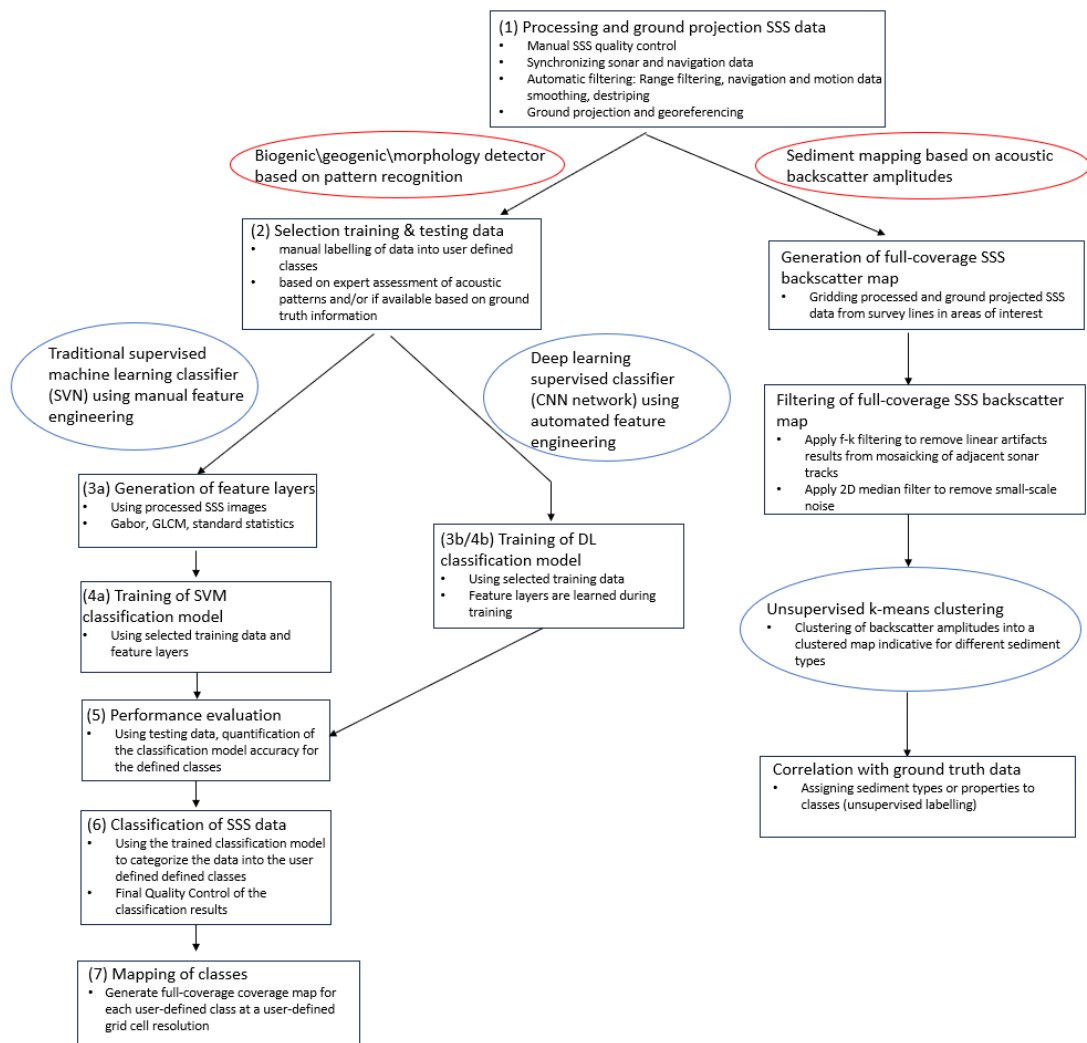


Figure C.1: Classification workflows for biogenic and geogenic reef mapping, morphology detection and sediment type mapping. Workflow is displayed for traditional supervised machine learning classifier based on manual selected features, a Deep Learning approach with a supervised CNN network classifier based on automated feature engineering and sediment mapping based on unsupervised k-means clustering.

C.1 Manual search for acoustic indicators for biogenic and reefs of other relevant seabed characteristics

An initial step in the SSS-based classification workflow involves the generation of high-resolution georeferenced sonar images (20 cm × 20 cm), enabling a detailed manual search for acoustic indicators of relevant seabed classes (Gaida, Binnerts, & Bos, 2025), Figure C.1. These images were produced for several Natura 2000 areas, including Borkumse Stenen, Texelse Stenen, Klaverbank, Doggersbank and the Frieze Front. Although this process is time-consuming and not all available survey lines could be processed, substantial spatial coverage was achieved for the selected areas (Figure 2.4). In total, around 41693 SSS images were computed, with each image covering an area of around 1000 m x 220 m. The total area of all SSS images is around 8340 km², however, as the SSS tracks were scanned with some overlap, the actual area covered on the seabed is smaller.

The identified acoustic indicators (also referred to as acoustic signatures or patterns) form the basis for training supervised classification algorithms. While characteristic acoustic patterns associated with specific reef types have been described in scientific literature and previous projects, these examples are used only as references. Due to variations in sonar instrumentation, acquisition settings, survey parameters and environmental conditions, acoustic signatures derived from external datasets cannot be directly transferred. Consequently, classifier training relies on indicators derived from the current dataset.

Processed and georeferenced sonar images were systematically reviewed to identify acoustic evidence of biogenic reefs (including oyster and mussel beds, as well as reefs formed by Sabellaria, Lanice or Loimia), geogenic reefs (e.g. stones and rock outcrops), and other seabed features such as glacial outcrops that may provide suitable substrate for reef-building species. For instance, if an acoustic pattern that indicates a particular type of biogenic reef, geogenic reef or morphological feature is absent, the classifier cannot be trained on those features. The quality of georeferenced sonar imagery varies both within and between survey areas, depending on factors such as noise levels, image sharpness and acquisition geometry. Different seabed classes place different demands on data quality and are affected to varying degrees by specific types of noise. If the data and images are excessively noisy for a specific mapping task, the algorithm is omitted. A description of the noise categories considered in this study is provided in Appendix E.1. For example, reduced image sharpness may hinder the identification of small-scale reef features, while still allowing reliable interpretation of larger-scale sediment patterns.

For each Natura 2000 area, the presence or absence of acoustic indicators for specific seabed classes is evaluated in relation to the local data quality. Where insufficient indicators are available to reliably train a classifier for a given class, no automated classification is applied for that class in the corresponding area.

Borkumse Stenen

Overall, the SSS data quality in the Borkumse Stenen is well-suited for reef mapping, identification of seabed morphology and mapping sedimentary patterns. Only a limited number of track lines exhibiting significant high amplitude noise. Rocks are scattered throughout the southern and northern parts of Borkumse Stenen. While Lanice/Loimia reefs were identified and classified in a previous project, acoustic indicators for Mussel beds, Oysters or Sabellaria were not identified. Numerous trawl marks are visible in certain areas. Throughout the area variations in the sediment types are visible (see). The seabed is predominantly flat, though there are sections with notable small-scale ripples.

Texelse Stenen

Overall, the SSS data quality in the Texelse Stenen is well-suited for identification of seabed morphology, sedimentary patterns and rocks. However, an increased number of track lines exhibits significant high amplitude noise or amplitude variations due to flying height fluctuations. These noise sources could propagate into a sediment map based on SSS backscatter or hide biogenic or geogenic reef structures. Rocks are scattered throughout a large part of the Texelse Stenen. Acoustic indicators for any type of biogenic reefs were not identified. However, it should be noted that in a majority of the survey block the images lack sharpness, compared in particular with the Borkumse Stenen data, potentially hampering a clear identification of biogenic reefs such as Oysters or mussels. Nevertheless, acoustic indicators of outcrops were identified, in particular in the northern part in survey block HY09204. Extensive regions of the seabed are covered with megaripples, while only a minor portion remains flat. Variations in the sediment types are visible throughout the area and large regions are additionally marked by trawling activities.

Klaverbank

Overall, the SSS data quality in the Klaverbank is well-suited for reef mapping, identification of seabed morphology and mapping sedimentary patterns. While only a limited number of track lines exhibiting high amplitude noise, interference noise is very present in selective areas. The latter could hide biogenic or geogenic reef structures in these areas. A few traces of stripe noise are present without having a negative impact on the seabed characterization. Few rocks are scattered throughout area. The Klaverbank is marked by strong variations in sedimentary patterns forming remarkable structures on the seabed indicated by the variation in SSS backscatter. No acoustic indicators of biogenic reefs (Mussel beds, Oysters, Sabellaria or Lanice/Loimia) were identified. However, the sediment variations and presence of small-ripples hampered the manual scan for biogenic reef indicators. Trawl marks are scattered throughout certain areas but are not very extensively distributed. The seabed is predominantly flat, though there are sections with notable small-scale ripples.

Doggersbank

The SSS data quality on the Doggersbank is generally low due to high amplitude, interference, and stripe noise, especially at long range, making it difficult to identify biogenic reefs or morphological features. This noise could significantly affect a full-coverage SSS backscatter map. However, in some areas, such as block HY17425, and at short ranges, data quality would allow for the identification of reefs, sedimentary variations and morphological features. However, in areas with sufficient quality, no biogenic reefs, rocks, or notable sediment variations were found. Most of the region is flat with occasional small ripples, and large sections are marked by trawling activity.

Friese Front

Overall, the SSS data quality in the Friese Front is well-suited for reef mapping, identification of seabed morphology and mapping sedimentary patterns. Only a limited number of track lines exhibiting significant high amplitude noise and flying height related amplitude variations. Rocks could not been identified in the processed sonar data. Acoustic indicators for Mussel beds, Oysters, Lanice/Loimia or Sabellaria were not identified. Some indicators of glacial features are visible but could not clearly be assigned for example to outcrops or bedrocks. Numerous trawl marks are visible in certain areas. Throughout the area variations in the sediment types are visible. The seabed is predominantly flat, though there are sections with notable small-scale ripples and larger mega-ripples.

Table C.1: provides an overview of seabed classes identified in the georeferenced sonar images for each Natura 2000 area. Green indicates adequate data quality for detection; yellow indicates that data quality may hinder successful detection; and orange denotes significant challenges for detection due to data quality. The colour coding reflects observations made across the majority of each area, however, individual track lines or survey blocks may deviate from this overall assessment.

	Borkumse Stenen	Texelse Stenen	Klaverbank	Doggers-bank	Friese Front
Mussels	No	No	No	No	No
Oysters	No	No	No	No	No
Sabellaria	No	No	No	No	No
Lanice/Loimia	Yes	No	No	No	No
Rocks	Yes	Yes	Yes	No	No
Sedimentary variation	Yes	Yes	Yes	No	Yes
Outcrops	No	Yes	No	No	Possibly
Flat seabed	Yes	Yes	Yes	Yes	Yes

	Borkumse Stenen	Texelse Stenen	Klaverbank	Doggers-bank	Friese Front
Megaripples	No	Yes	No	No	Yes
Ripples	Yes	No	Yes	Yes	Yes
Trawl marks	Yes	Yes	Yes	Yes	Yes

C.2 SSS based sediment mapping

The methodology for generating full-coverage SSS backscatter (reflectivity) and clustered maps indicative for the seabed sediment properties is outlined. Both MBES or SSS backscatter, which can be seen as a measure of the acoustic reflectivity of the seabed, can be used to map the distribution of sediments across the seabed. The acoustic backscatter strength depends on how coarse and hard the seabed is (Lurton, 2010). Factors such as grain size, the presence of shells or shell fragments, bioturbation, trapped gas, or biogenic material all influence seabed coarseness and hardness. For instance, muddy sediments or those with biogenic content may have gas inclusions, leading to increased backscatter. Sometimes, a mix of fine and coarse sediments can have backscatter values similar to a uniform medium-grained sediment. As a result, the relationship between backscatter and sediment type is not always straightforward, so ideally, these maps should be validated using video surveys and grab samples. Generally, however, backscatter increases with increasing coarseness and hardness, progressing from mud through fine sand, medium sand, and coarse sand, up to gravel, shells, and stones (APL-UW, 1994). Therefore, these maps provide spatial insights into variations in sedimentary patterns at local to regional scales.

The backscatter data of a MBES is primarily used for mapping sediment distribution, while the SSS backscatter is better suited for identifying fine-scale features such as reefs, rocks, or mines. The aim of sonar data processing is, besides the removal of noise, to ensure backscatter values reflect only seabed properties, unaffected by environmental or system factors. This is essential for mapping sediment distributions, where MBES offers advantages due to its technical setup and the fact that it is mounted on the vessel's hull. For instance, it can measure bathymetry, which allows for removing the effect of the seabed morphology on the backscatter amplitudes, and it maintains a constant altitude, both enabling physical based radiometric corrections (i.e. geometric spreading and sound absorption correction). However, the biggest challenge in using sonar data for sediment mapping is dealing with changes in survey settings, including variations in source level, frequency, pulse type, and signal gains. The use of different sonar types or models, as well as changes in environmental conditions, further complicates the use of sonar data for sediment mapping. This is especially concerning when data is collected during multiple surveys or over several years, as has been the case with Hydrographic Service surveys in certain Natura 2000 areas. To overcome some of these challenges, a dedicated processing strategy was developed for the Hydrographic Service data in step 1.

In step 1 of the workflow, a trend removal is used to empirically eliminate range dependent amplitude variations, ensuring backscatter values mainly reflect seabed properties. This project uses local detrending for pattern recognition and global detrending for sediment mapping. Global detrending calculates range-dependent trends across the entire dataset, while local detrending focuses on a small window of sonar pings. Global detrending preserves comparability of backscatter amplitude across variations in sediment types covered by the dataset but is less effective than local detrending when gains or source levels vary, or when targeting small-scale features like reefs. To remove the effect of sonar altitude variations, global trends are calculated as a function of altitude, and curves are computed per survey

block to minimize effects from changing settings, environmental factors, or sonar models within a Natura 200 area.

An additional processing step for generating the large-scale SSS backscatter maps was introduced. This step removes linear artifacts that appear when mosaicking multiple adjacent sonar track lines. The processing steps involves the transformation of the spatial x-y map into the frequency-wavenumber (f-k) domain via a 2D FFT (Fast-Fourier-transformation). In this domain the linear sonar artifacts are mapped on straight lines. These lines are masked in the f-k domain before transforming back via a 2D iFFT (inverse FFT) to the spatial domain. To further remove small scale artifacts a 2D median filter is applied. The individual steps are visualized for the Borkumse Stenen in Figure C.2.

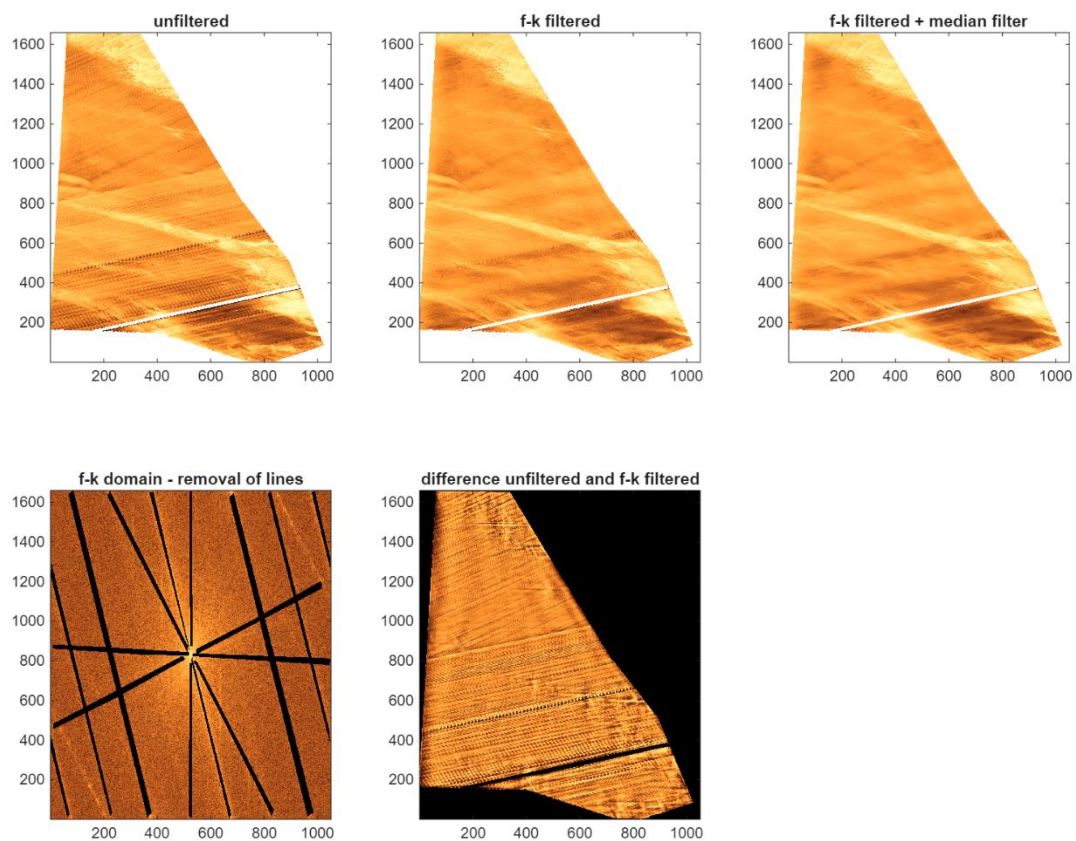


Figure C.2: F-K filtering applied to Borkumse Stenen SSS backscatter map to remove linear artefacts resulting from mosaicking multiple adjacent sonar tracks.

The primary focus is on broad sediment type variation, rather than centimetre-level scale differences. Accordingly, sonar images are produced using a 25 m x 25 m grid resolution, which offers two advantages: it enhances computational efficiency and helps to average out small-scale noise. However, sonar and survey settings enable a resolution of 20 cm x 20 cm, which theoretically allows for further enhancement of small-scale details (see e.g. Figure E.5).

Figure C.3 compares MBES and SSS backscatter maps from the same survey with those taken 11-16 years ago. Ignoring possible seabed changes, both sonar images and classified maps show similar sediment variation, confirming SSS's usefulness for sediment mapping. To further characterise spatial variability in acoustic seabed properties, k-means clustering can be applied to the SSS backscatter data, resulting in classes representing distinct

reflectivity patterns. Comparing locally the clustered results with video footage confirms that increased shells and gravel on the seabed correlate with the defined classes (Figure C.4). The SSS maps used local detrending with large ping windows, which works well for such a small area, but larger regions like the entire Borkumse Stenen require the described global detrending.

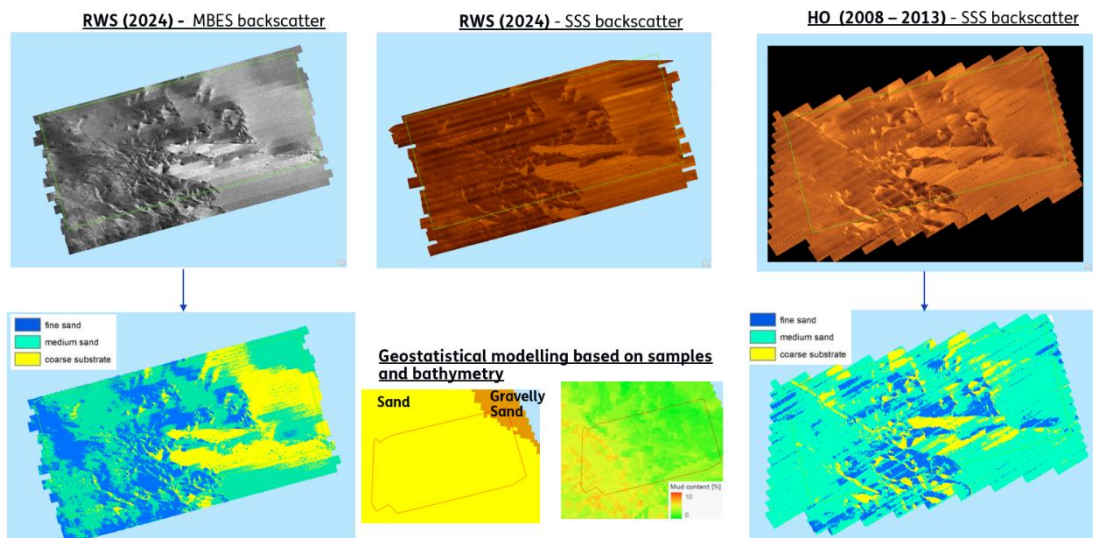


Figure C.3: presents sonar-based sediment mapping within a region of approximately 4 km by 2 km, highlighting sedimentological variations across the Borkumse stenen. The left column displays processed MBES backscatter data acquired in 2023 (top) and the corresponding k-means clustered sediment map derived from MBES backscatter input (bottom). In the right column, the top image provides SSS backscatter data collected in 2008 by the Hydrographic Service, with the bottom image showing the k-means clustered sediment map based on SSS backscatter. The central column includes processed SSS backscatter obtained during the 2023 survey together with the MBES data (top), while the bottom images facilitate comparison via Folk 16 and mud content maps for the same area (red polygon), generated through geostatistical mapping of grab samples and bathymetry data.

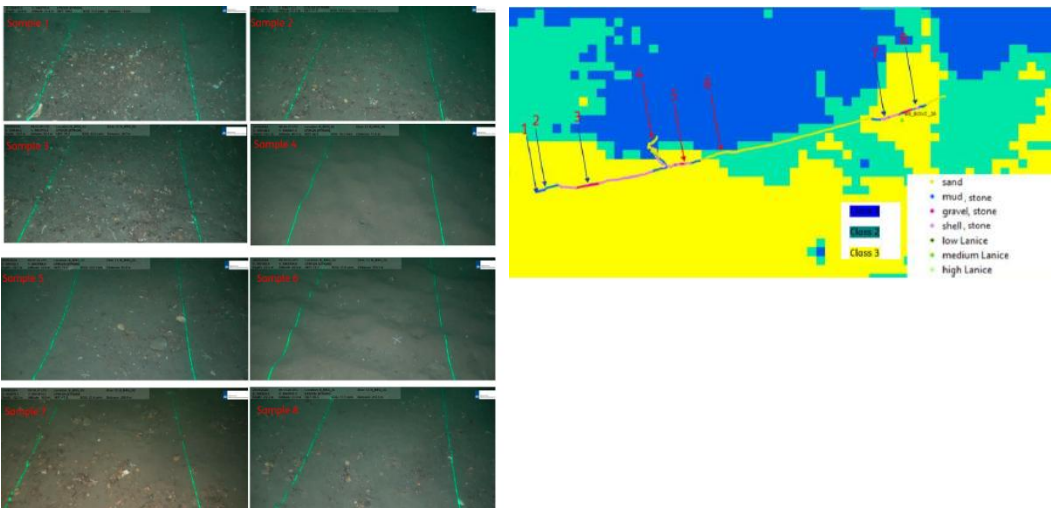


Figure C.4: Validation of sediment map based on SSS backscatter using video images acquired in the Borkumse Stenen.

C.3 Traditional machine learning classifier based on manual feature engineering

Seven key steps are used to map a reef type or a morphological feature, such as glacial outcrop, from Side-scan Sonar (SSS) data using the traditional machine learning approach (Figure C.1). A detailed description of the methodology is given in (Gaida T. C., Binnerts, Cuperus, Bos, & van der Jagt, 2024) and here the main steps are only roughly outlined. First, raw SSS data is loaded, filtered (e.g. destriping, removal of low SNR at long ranges and nadir region, smoothing of navigational data), detrended, and projected onto a regular georeferenced grid. Second, training and testing data are manually selected in areas with indicative acoustic patterns for the classes of interest (e.g. glacial outcrops) and the classes representing the remaining seabed (e.g. no outcrops). Third, feature layers are generated from pre-processed SSS lines, including basic statistics, texture metrics (GLCM), and directional spatial information (Gabor filters). This step is called manual feature engineering and differs from the other classification approach used in this project. Fourth, a supervised machine learning classifier (SVM) is trained using the selected training samples and the generated features. In a fifth step, the performance of the classifier is evaluated using the selected testing samples. In a sixth step, the trained classifier is applied to the georeferenced sonar images for classification, assigning each pixel to a class. Seventh, classified SSS lines are aggregated onto a larger grid to create a presence map of the class of interest (e.g. glacial outcrops).

C.3.1 Mapping Hard Substrates

As part of the **first step** of the data processing workflow, the raw SSS data in part of the Texelse Stenen was processed and projected on a regular 20 cm x 20 cm georeferenced grid in the ETRS89 UTM 31N coordinate reference system. Quality control of the SSS data showed that the data quality was sufficient at all ranges up to 120 m was sufficient for the reliable detection of locations of *reworked glacial deposits*.

As part of the **second step**, it was decided to define two labels for which training and testing data were created:

1. **Reworked glacial deposits:** This class includes glacially derived lag deposits that are visible on the surface of the seabed. They are outcropping glaciogenic soils which are reworked and fine-grained sediments are winnowed out, leaving behind coarse-grained sediments, i.e. a 'hard' substrate. They are often accompanied by possible bedrocks. It is characterized by distinct acoustic patterns shown in SSS images, with high amplitudes and clear morphological shapes that set it apart from the surrounding seabed (see Figure C.5). An acoustic shadow before the feature suggests either a depression preceding the outcrop or that the outcrop itself lies within a depression. Occasionally, small ripples appear atop the glacial formation. It's important to note that these patterns have not been verified by ground truth data; the definition relies on expert acoustic and geological assessment, supported by examples from existing literature (Zhamoida, et al., 2009).
2. **Absence of glacial deposits:** The "no glacial deposits" category describes areas of the seabed without presence of reworked glaciogenic soils at the seabed. This includes areas in the Texelse Stenen, characterized by flat, homogeneous seabed or megaripples. Acoustic patterns typical of a flat, uniform seabed or megaripples were selected to train and test the classifier for this class.

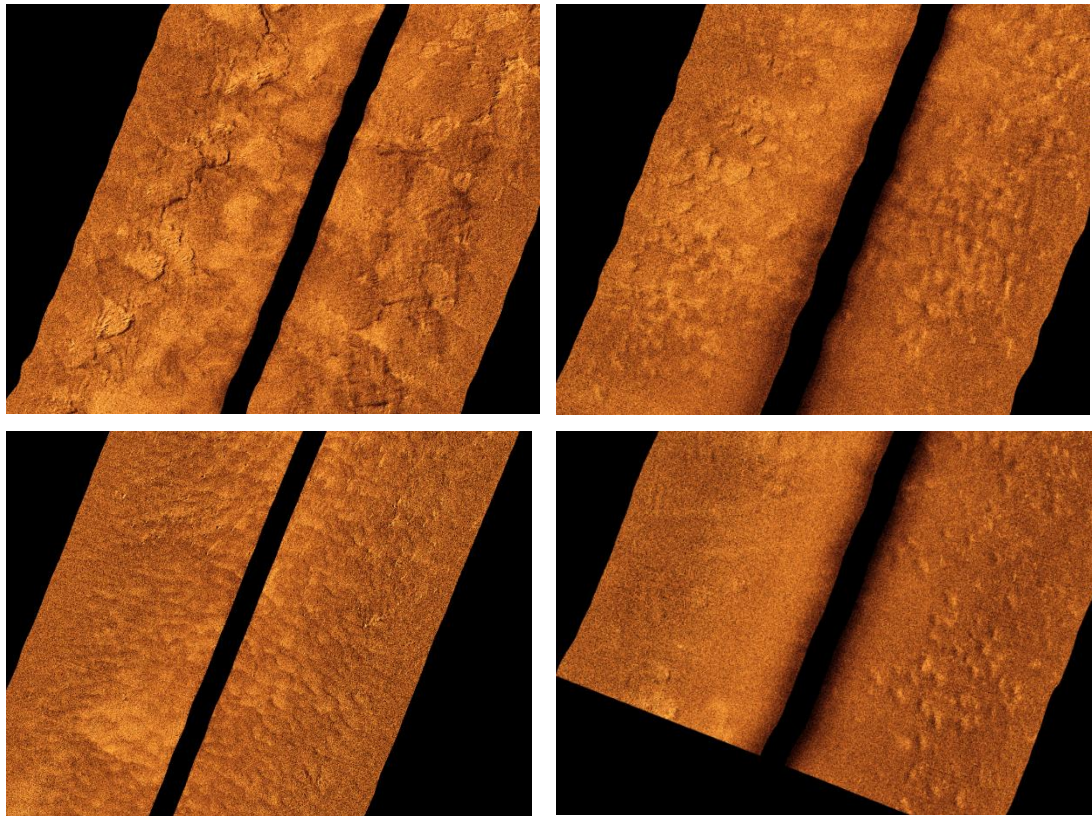


Figure C.5: Examples of acoustic patterns indicative for (top) outcrops of reworked glacial deposits, (bottom, left) megaripples and individual rocks, (bottom, right) left part: flat and homogeneous seabed, right part: outcrops. The SVM classifier was trained and tested on these patterns in the Texel Stenen in survey block HY09204.

Next, the feature layers are generated (step 3) and fed into the Support Vector Machine (SVM) machine learning algorithm (step 4) for training. The GLCM metric, Gabor filter and basic statistics were used to create a variety of feature combinations aiming to highlight different sizes of the outcrops. Up to 62 different feature layers were formed. It was shown that using a combination of 20 feature layers consisting only of layers generated with the Gabor filter performed equally well as using all 62 feature layers in the training process of the SVM classifier. Since the computation time was significantly less using only 20 feature layers, this combination was chosen.

A Gabor filter² was applied to obtain directional spatial wavelength information. This filter investigates a specific spatial frequency (i.e. wavelength) content in the image in specific directions in a localized region around the point or region of analysis. Wavelength of 5, 10, 24 m towards the direction of 45 (SW-NE), 60 (WSW-ENE) 90 (W-E) and 135 (NW-SE) degrees were analyzed. The wavelength were adapted to the expected sizes of the outcrops.

In step 5 of the classifier, the trained SVM classifier achieved good performance on the selected testing data with an overall accuracy of 93.7% (Figure C.6). In particular, the precision is very high with 98.2%, describing how well the outcrop prediction of the trained classifier corresponds the true class. Here, it should be noted that the testing dataset was selected on expert judgment of the acoustic patterns and not on ground truth data.

² <https://nl.mathworks.com/help/images/ref/gabor.html>

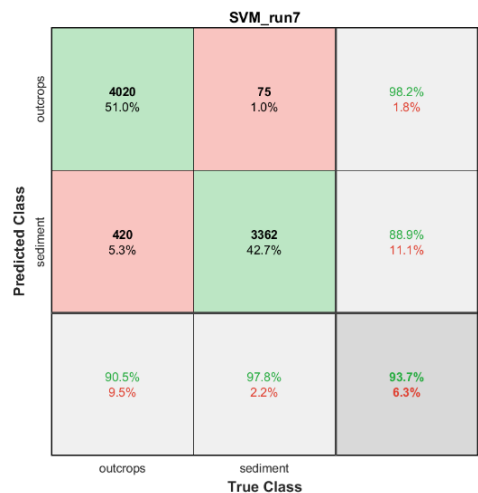


Figure C.6: Confusion matrix obtained from the application of the trained SVM classifier to the testing dataset (expedition data). Green values in the right column show the precision per class and the green values in the bottom row show the sensitivity per class.

The trained SVM classifier was applied to each georeferenced SSS image of the dataset (step 6,). The classified SSS images were merged into a full-coverage map (Figure 2.9) displaying the percentage outcrop coverage on the seabed (step 7, Figure C.1).

C.4 Stone Classification using Deep Learning

Transfer learning, which involves leveraging a pre-trained model to enhance performance on a related task, has been shown to improve sediment classification performance in sonar imagery (Qin, Luo, Wu, & Shang, 2021). Building on this idea, a compact neural network (ResNet-4-2) was first pretrained on the grayscale CIFAR10 dataset (see Figure C.7) to help the model learn general visual patterns. This network is subsequently refined on the labelled SSS data, containing two classes *Stone* and *Background*. This approach requires less training samples, as only the classification layers of the network require extensively training. Unlike Qin et al. (2021), no generative data augmentation with GANs was used here: The approach focused purely on supervised transfer learning.

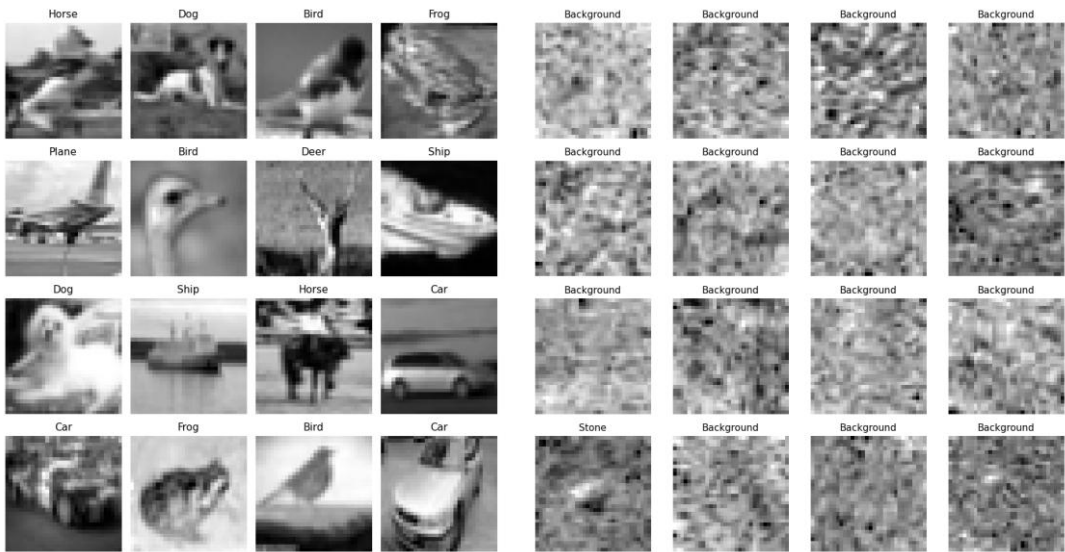


Figure C.7: Example images of grayscale CIFAR10 (left), and our SSS data (right).

Processed and ground projected sonar patches with a size of 24 pixels x 24 pixels ($\approx 4.8\text{ m} \times 4.8\text{ m}$), from the Texelse Stenen, Borkumse Stenen, and Klaverbank were used to train and validate the classifier. The data preparation for the class *Background* followed the procedures described by previous work (Gaida, Binnerts, & Bos, 2025). Labelled polygons in the SSS tracks, shown in Figure E.7, were transformed into internal sample points using a Python reimplementa-tion of their original MATLAB extraction workflow. A 24 pixels x 24 pixels ($\approx 4.8 \times 4.8\text{ m}$) patch was extracted for each point, following the patch size of Qin et al. (2021), as shown in Figure C.7. For the class *Stone*, the stone locations were manually identified, and corresponding 24 pixels x 24 pixels patches were collected around each stone. Both classes were randomly divided into an 80%–20% training–validation split. After an initial iteration, it became clear that the classifier often classified sediment transitions and (mega) ripples as stones. Therefore, an additional number of polygons of this sediment type were selected and included in the training dataset. The resulting number of samples is summarized in Table C.2.

Table C.2: Number of training and validation samples for each class.

	Training	Validation
Background	207 068	53 370
Stone	475	120

The neural network was initially trained on the CIFAR10 dataset for 30 epochs. Although Qin et al. (2021) reports training for 100 epochs, no further performance gains were observed beyond epoch 30 in our experiments, so training was halted early to prevent overfitting. An accuracy of 88.12% was reached on the validation set of CIFAR10. The convolutional backbone of this pretrained model was then transferred into a new network designed for our labelled SSS dataset. Due to the disbalance in datasets (see Table C.2) a weighted loss function was used during training. This second training stage took 45 epochs and reached a validation accuracy (i.e. Precision and Sensitivity) of 90.83% of the stone class on the validation data of the 80%–20% training–validation split (see Figure C.8).

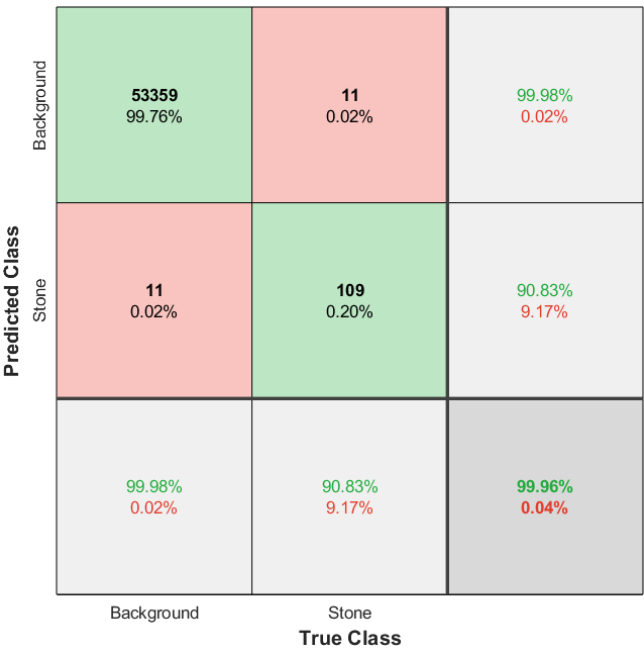


Figure C.8: Confusion matrix obtained from the application of the trained Deep Learning classifier to the testing dataset. Green values in the right column show the precision per class and the green values in the bottom row show the sensitivity per class.

After pretraining and transfer learning, the resulting neural network can be applied to classify the SSS images from all track lines. The classifier operates at the pixel level: for every pixel in the SSS track, a 24 pixels × 24 pixels patch centred on that pixel is extracted and fed through the network. The output of the network is a probability for the class *Stone* at each pixel location. To obtain discrete stone detections, connected components of at least 30 pixels with a predicted probability greater than 0.8 are retained. The centroid of all such patches is then used as a detected stone location. Applying the model to an entire SSS track (Figure E.8) demonstrates that the network correctly distinguishes between stones and background, in agreement with the manually labelled reference data shown in Figure E.7.

The detected stone locations are subsequently converted into a stone density map. The study area is first divided into hectare-sized grid cells (100 m × 100 m), and the number of detected stones within each cell is counted. Some locations are covered by multiple overlapping SSS tracks. To avoid artificially inflating densities in these areas, a weighting procedure is applied: for each hectare cell, the total number of detected stones is divided by the number of SSS tracks covering that same cell. The resulting Weighted Stone Density maps thereby represent an estimate of stone abundance that is comparable across the entire survey area.

C.5 Comparison between traditional supervised machine learning and a Deep Learning

The developed Deep Learning approach used for the stone classifier (see Appendix C.4) was also trained on the Lanice/Lomia pattern detected in the Borkumse Stenen (Bos, et al., 2025). As the traditional machine learning approach, used for the classification of glacial deposits (see Appendix C.3) was already trained and applied to the HS data in the Borkumse Stenen in the previous project (Bos, et al., 2025), it facilitated a comparison between both method for

the specific task of mapping Lanice/Lomia. Both classifiers use the same training samples (i.e. the coordinate of the sonar image pixels) but differ in how they are trained. Each classifier maps the primary patterns of Lanice/Lomia at the same locations with comparable coverage rates (Figure C.9). In certain areas, the Deep Learning approach identifies a slightly higher percentage of Lanice/Lomia. This may be because the this classifier attributes similar acoustic patterns to Lanice/Lomia, which the traditional machine learning method does not. The comparison of the two maps provides an assessment of the performance of the newly developed Deep Learning method for reef mapping applications. Since the traditional machine learning method was well validated in the previous project, it is well suited for benchmarking the new Deep Learning method.

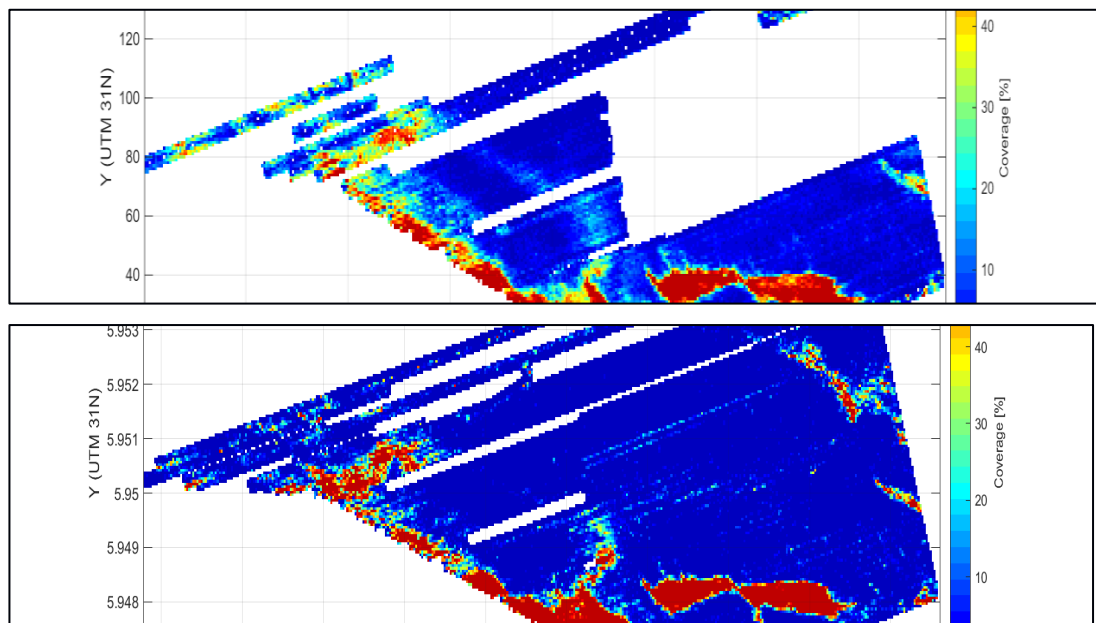


Figure C.9: Comparison of classified Lanice/Lomia reefs in the southern Borkumse Stones using (top) Deep Learning approach via Convolutional Neural Network using automated feature engineering and (bottom) traditional machine learning approach via Support Vector machine using manual feature engineering. The primary input for both classifiers are processed and georeferenced sonar image with a resolution of 20 cm x 20 cm.

Appendix D

Literature study oysters and mussels

The SSS data and classification approaches applied in this study can in principle also be used to detect other hard and rough seabed features, including mussels, oysters and other shellfish aggregations. Similar to stones or outcrops, shellfish beds introduce small-scale seabed roughness and hard reflective elements that lead to characteristic acoustic responses in SSS imagery, primarily through increased backscatter intensity and textural contrast with respect to surrounding sediments (van Overmeeren, et al., 2009).

Previous studies demonstrated that both mussel and oyster beds can be detected in SSS data when their acoustic appearance differs sufficiently from the background seabed. Van Overmeeren et al. (2009) provide detailed examples of shellfish mapping using high-frequency SSS in Dutch coastal waters, including the Wadden Sea and the Eastern Scheldt. Mussel beds (*Mytilus edulis*) are described as relatively broad zones of increased backscatter with a distinct texture compared to sandy or muddy sediments, while oyster beds (*Crassostrea gigas*) appear as clusters of small but very strong reflectors associated with individual shells or shell groups. Their figures (see Figure D.1) clearly illustrate these contrasting acoustic expressions in Dutch conditions, supported by field observations and aerial imagery.

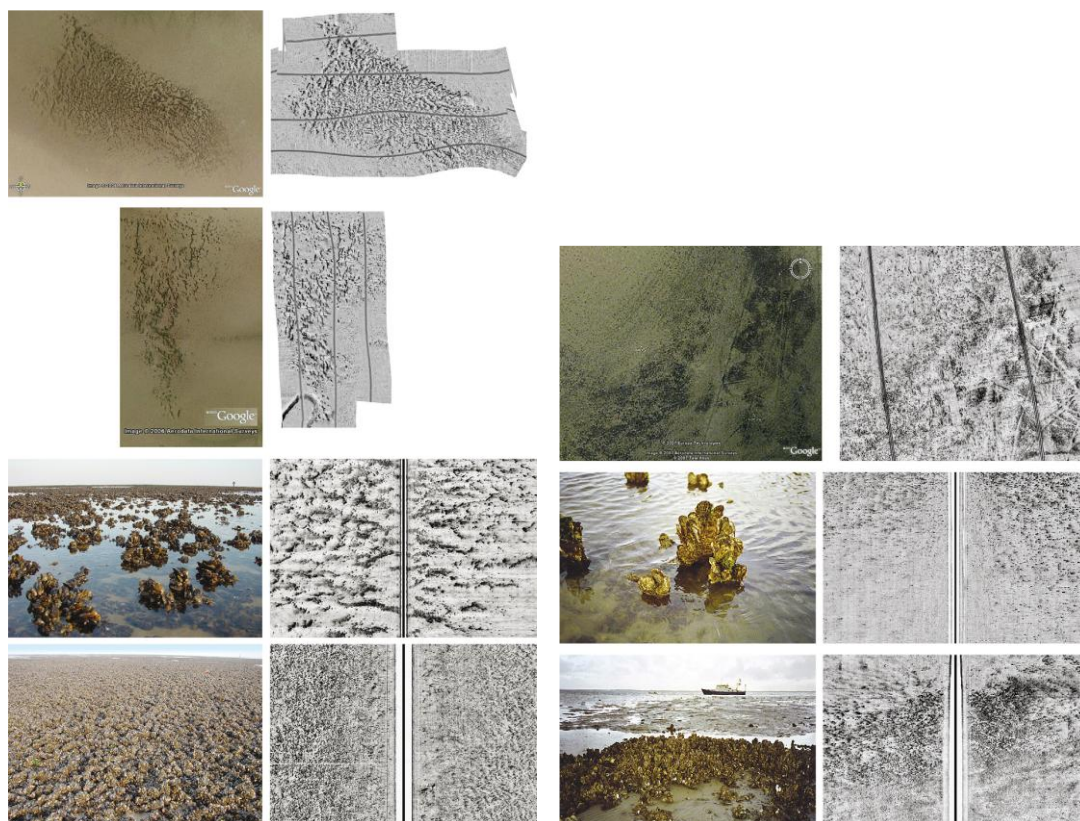


Figure D.1: Images of mussel beds (left) and oyster beds (right), with corresponding SSS images, taken from Van Overmeeren et al. (2009).

Comparable results are reported by Westphal et al. (2016), which mapped subtidal oyster reefs using SSS and confirmed the acoustic detections through diver observations. Although conducted in a different environmental setting, this study supports the general applicability of SSS for detecting dense shellfish aggregations. Powers et al. (2014) further showed that mussel beds are typically composed of groups of smaller reflectors (ranging from 64.39 to 194.89 mm) rather than single dominant objects, and that detectability strongly depends on seabed type, with smoother, fine-grained sediments providing the highest contrast.

Moving beyond visual interpretation alone, Heinrich et al. (2016) and Gaida et al. (2025) also demonstrate that texture-based analysis of SSS data can be used to identify biologically altered seabeds. While their focus is on tube-worm beds, the underlying principle is equally relevant for shellfish beds, which also modify seabed roughness at small spatial scales. Their results indicate that quantitative texture measures can help distinguish biological structures from sedimentary patterns and reduce subjectivity in interpretation.

Taken together, this body of literature shows that SSS is well suited for detecting mussel and oyster beds in shallow coastal environments, including Dutch waters. Given the similarity in acoustic characteristics between stones and shellfish beds (both being hard, rough seabed features) the Deep Learning-based stone detection workflow described in Appendix C.5 provides a promising starting point for future extension towards automated detection of mussels, oysters and other shellfish. Such an extension would require dedicated training data and potentially additional classes, but the methodological framework applied in this study is almost directly transferable.

Appendix E

Sonar data and classification examples

E.1 Categories of noise

Figure E.1 through Figure E.4 show examples of typical sonar noise present in the HS dataset. The terms “altitude/flying height noise”, “interference noise”, “high amplitude noise” and “stripe noise” are not common terms used in literature. The terms are used to describe the type of noise related to its appearance or origin. For example, the “interference noise” is not necessarily originated from interference with other acoustic sources. However, its appearance is similar to interference patterns described in literature. These categories of noise are observed to varying degrees within the Natura 2000 area, and the figures serve as illustrative examples only.

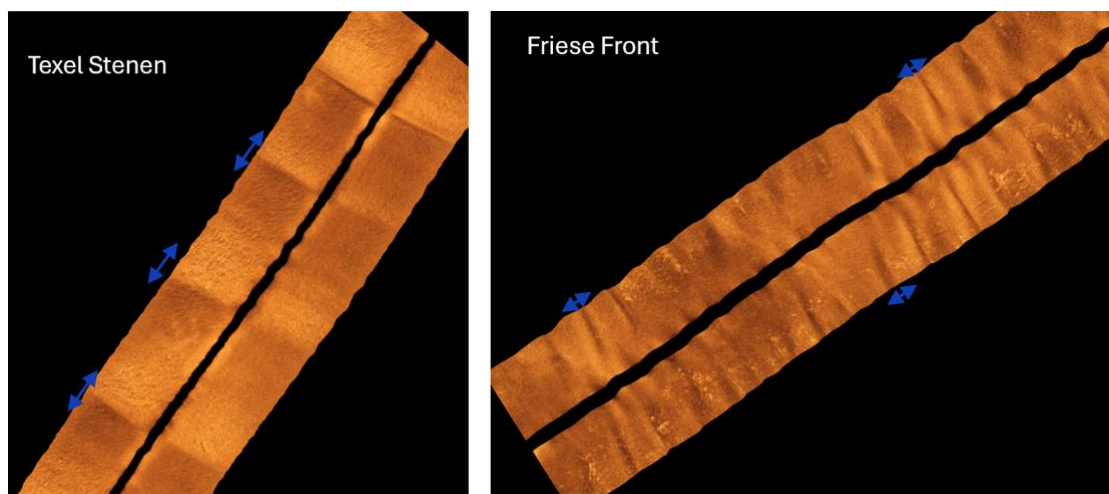


Figure E.1: Examples for sonar noise related to fish altitude variations shown as variation of low and high amplitude in sailing direction across the full range (see blue arrows for some examples).

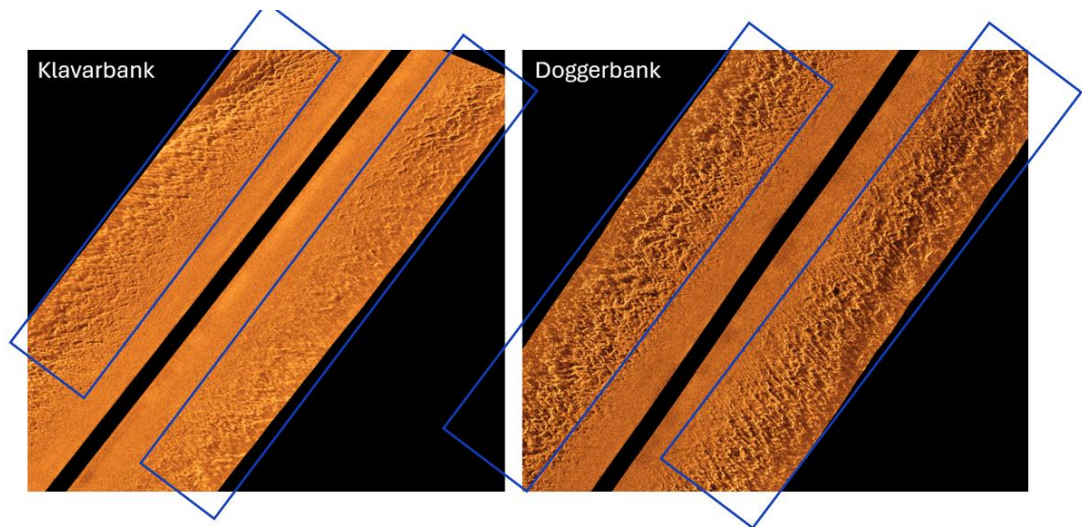


Figure E.2: Examples for interference noise shown as wiggly lines of high and low amplitudes at long ranges (see blue rectangles). This noise can be distinguished from real seabed features due its consistent presence only at long ranges. A real seabed features would also be present at shorter ranges.

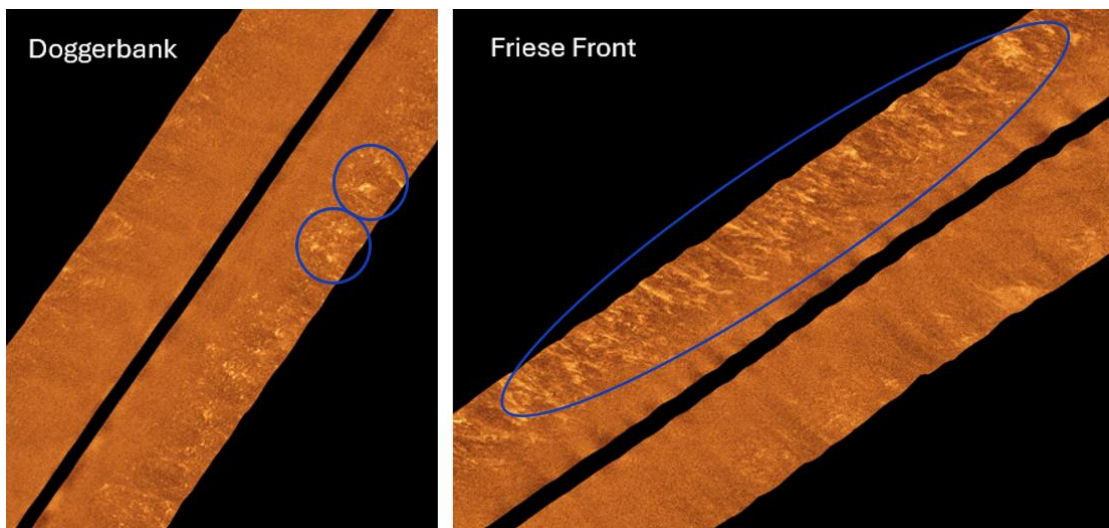


Figure E.3: Examples for high amplitude noise visible as isolated spots of high amplitudes (see blue circles), in particular at longer ranges. This noise can be distinguished from real seabed features due its presence primarily at long ranges, sometimes only occurring at one side or in general very unnatural shape.

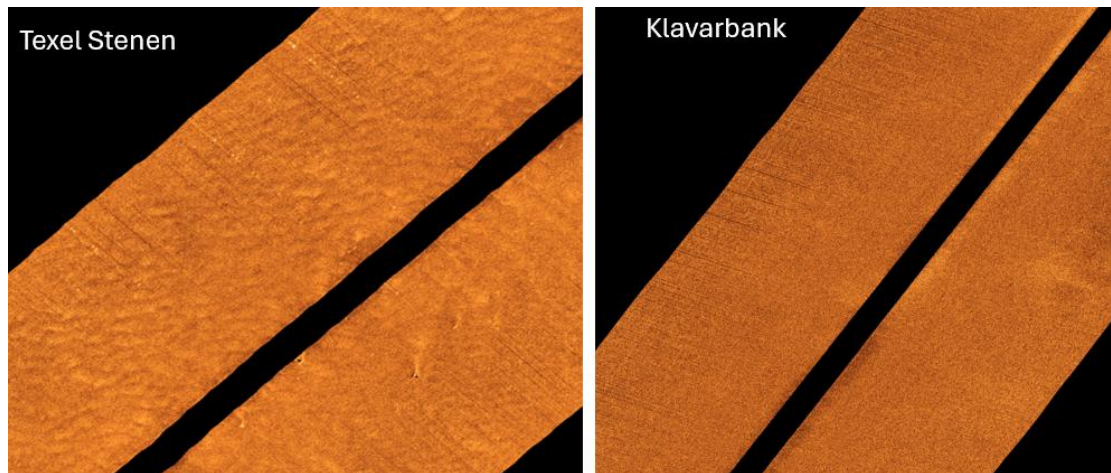


Figure E.4: Examples for stripe noise shown visible as stripes perpendicular to sailing direction. This noise can be removed with a destriping filter. However, this filter is only applied if this type of noise is present in a larger part of the dataset.

E.2 Sedimentary patterns

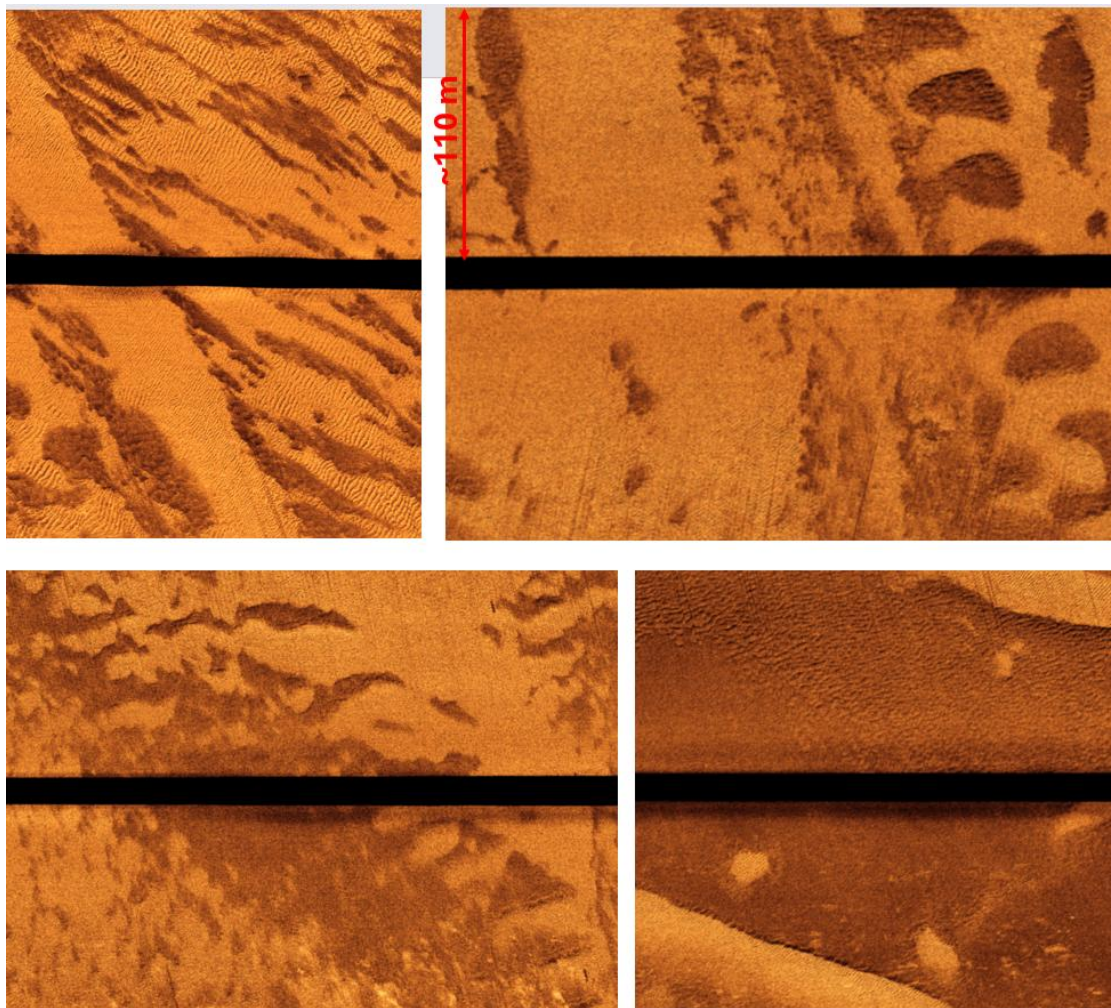


Figure E.5: Sediment heterogeneity in the Klaverbank indicated by variation in SSS backscatter amplitudes.

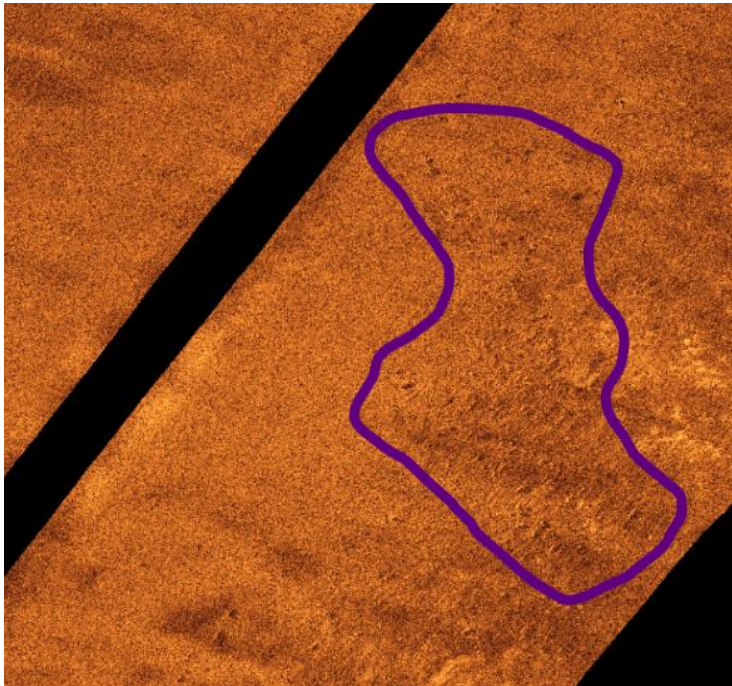


Figure E.6: Example SSS image of likely presence of geological debris in the Klaverbank.

E.3 Geogenic reef classification

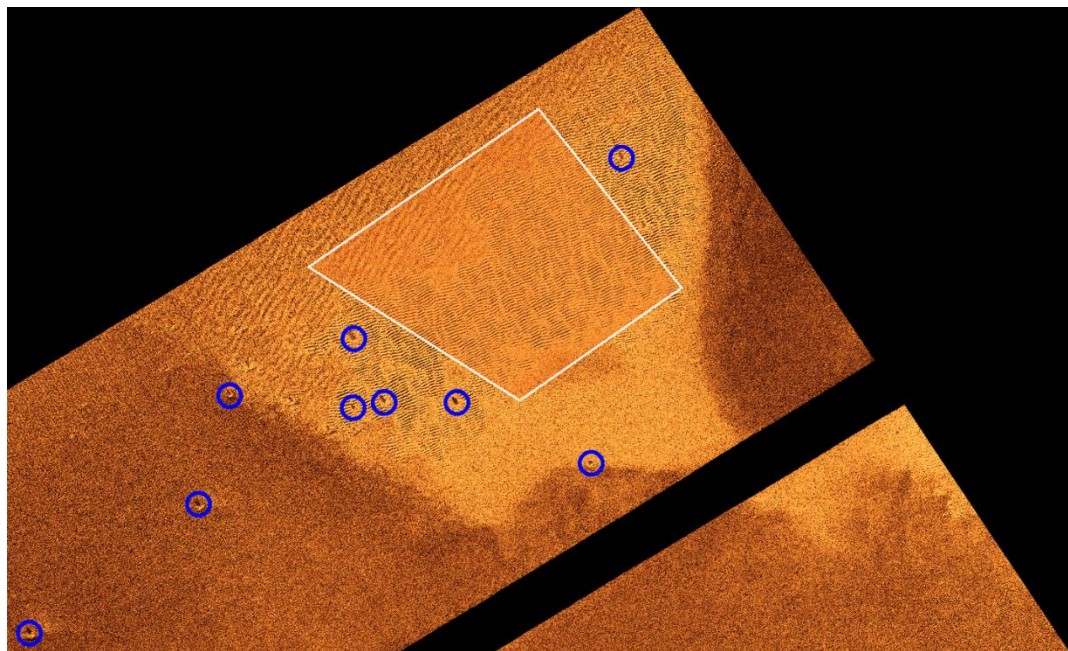


Figure E.7: Example SSS track, with labelled stones and background polygons.

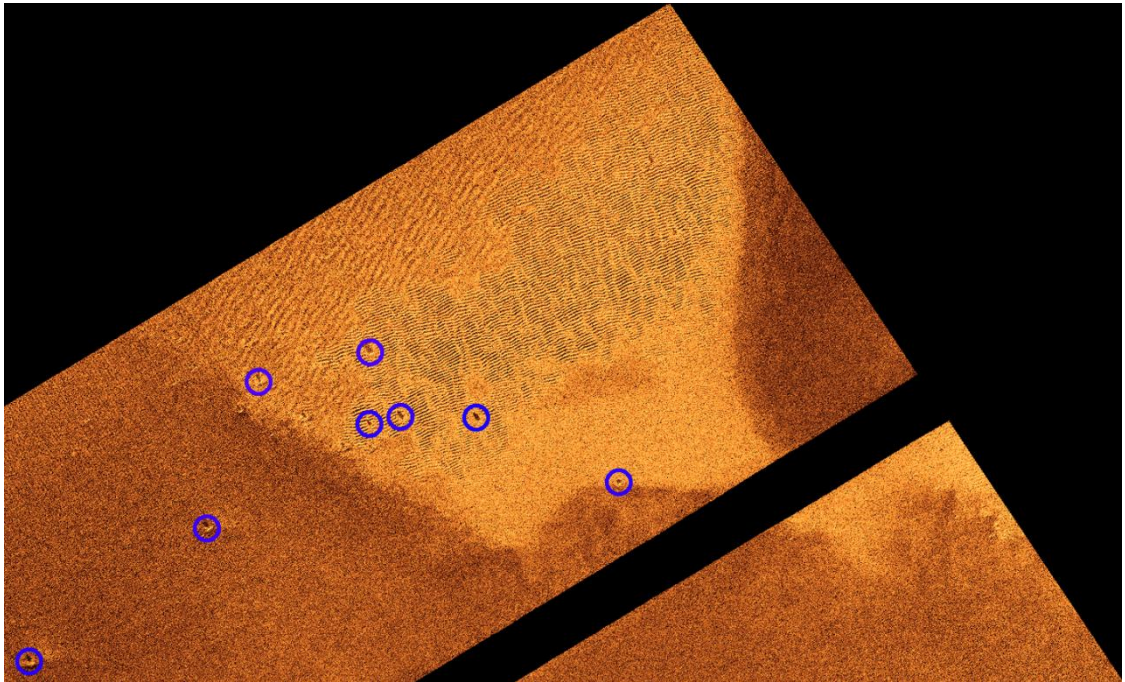


Figure E.8: Classified SSS track. When compared to Figure E.7, it can be seen that most stones and background are correctly classified.

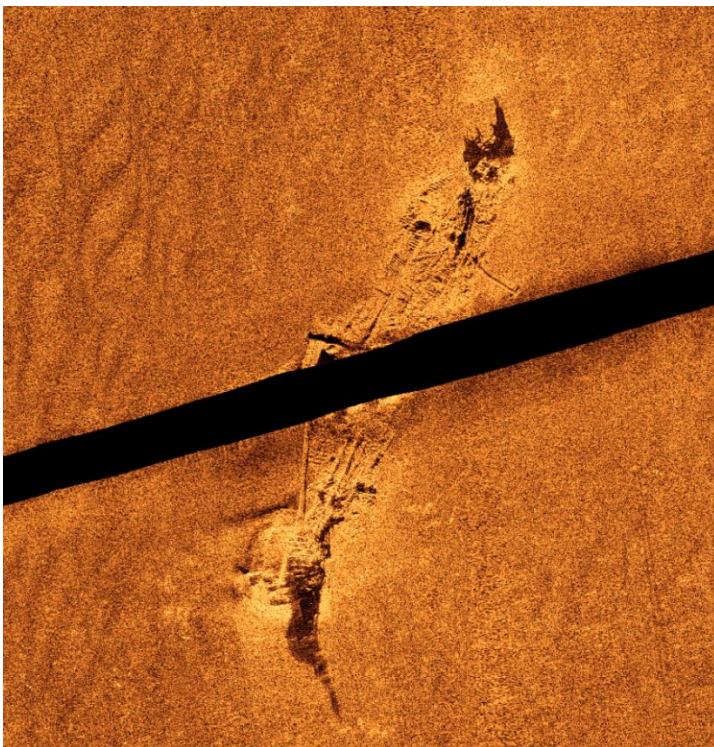


Figure E.9: Example SSS image of a wreck located directly beneath the tow fish, with the nadir clearly visible.

Appendix F

Overview of available data

F.1 Introduction

For this project a number of types of data regarding the seabed were used, some datasets are publicly available, other are confidential or are available under limitations of use. These seabed data are available at TNO-GDN and other organisations. These include:

- › SSS data (confidential);
- › MBES backscatter data (confidential);
- › MBES and SBES derived bathymetry (public);
- › Seabed sample data (public);
- › Objects on the seabed (confidential).

These data types are addressed in more detail in the following sections with respect to their availability, quality and limitations of use.

For this project various (governmental) organisations and institutes were approached for seabed data and information, including HS, Rijkswaterstaat, and Vlaamse Hydrografie. These organisations and institutions acquire seabed data for a specific purpose or task. However not all the acquired data are being stored in a public database such as EMODnet or BROloket, either they are confidential or cannot be easily stored in a standardised or harmonised database.

For example, the digital SSS data that was shared by HS to TNO-GDN till 2017 is currently stored on tapes because these data types are voluminous. However, that makes access and retrieving certain SSS datasets time consuming. The SSS and MBES data that was shared since 2018 is stored on the TNO network and are therefore easier accessible. The navigation lines and meta-data of the SSS survey datasets are included in the DINO database. Within TNO, these SSS meta-data can be searched through in GIS and any required SSS lines can be selected and the associated SSS files can be requested.

TNO-GDN is in the process of setting up a large file datastore for the SSS and MBES datasets which makes both access to the datasets and archiving new datasets easier for users within TNO.

F.2 Overview maps SSS and MBES coverage

Figure F.2 to Figure F.4 present overview maps with the SSS coverage in the Dutch North Sea and Figure F.5 to Figure F.12 are maps with a more detailed view of the SSS coverage within the selected Natura 2000 and KRM priority areas and the Texelse Stenen area. Figure F.13 illustrates the coverage of MBES backscatter data in the Dutch North Sea.

SSS and MBES data, that are currently available at TNO-GDN, are from several sources, namely the HS, RVO, TenneT and TNO-GDN, which are indicated in the figures. The coverage, quality and limitations of data usage differ per source.

TNO-GDN 'vintage' data

TNO-GDN has acquired SSS survey data in specific areas for projects in the past, such as the Waddenzee, Zeeuwse estuaries or gas seepage locations in the North Sea. These 'vintage' SSS data are available at TNO-GDN and are available upon request. The coverage of 'vintage' SSS data of TNO-GDN in the North Sea is very small and limited to a few lines or areas (e.g. Klaverbank, gas seepage locations). The quality of the SSS data is highly variable. A few lines overlap with the Klaverbank area and the Noordzee Kustzone, but for the purpose of this project these lines were not considered.

RVO data

RVO is in the lead for offshore windfarm development in the Dutch North Sea. Several areas in the North Sea are designated for windfarm development. Some areas have already developed, such as Borssele and Hollandse Kust Noord. Other areas are still in the investigation or construction phase. For the development of the windfarms, extensive and detailed geophysical surveys of the seabed have been conducted, including SSS and MBES. These data are open to the public and available at the RVO website ([Offshorewind RVO](#)). Copies of the offshore windfarm datasets are also stored at TNO-GDN. The coverage of the RVO windfarm data is relatively large, but is focussed on the windfarm areas. The quality of these survey data are generally good. The RVO offshore windfarm datasets do not overlap with any of the priority areas and were for that reason not considered in this project.

TenneT data

TenneT has acquired survey data for various cable routes from the offshore windfarm areas to shore, including SSS and MBES. These cable route survey data have been shared with TNO-GDN, but they are not open to the public. The data are confidential and can be shared and used only within TNO. The coverage of TenneT is relatively small, and is focused only along a narrow zone of the cable routes from windfarm areas to shore. The quality of these survey data are generally good. The TenneT cable route survey datasets do not overlap with any of the priority areas and were for that reason not considered in this project.

HS data

The HS monitors the seabed within the Dutch North Sea on a yearly basis. Figure F.4 shows the area in the Dutch North Sea which is monitored and surveyed by the HS. Every year specific areas in the North Sea are visited and surveyed by means of MBES and SSS. The SSS data of these surveys are shared with TNO-GDN. Initially, these data comprised analog data (print-outs), but since 2002 as digital data which are stored in the digital archives of TNO-GDN (on tape and in the DINO database). Since 2025, also MBES backscatter data, i.e. the reflectivity of the seabed, are shared with TNO-GDN (Figure F.13). TNO-GDN has an agreement with the HS regarding usage and sharing of the SSS data. These data are confidential and can be shared and used within TNO. Publication of the data or sharing with other institutes or parties can only be done after approval of HS and when certain conditions are met.

The digital SSS dataset of HS covers the majority (~82%) of the Dutch EEZ and comprises survey data from 2002 to recent and is by far the largest SSS dataset. HS surveyed the seabed along more than 32,000 survey lines since 2002 with a total length of more than 506,000 km of SSS data.

The quality of the data varies per survey and also within the survey dataset due to fluctuating meteocean conditions. For example, the SSS fish stability (i.e. position, roll, pitch, heading, crabbing) may vary between surveys or even per line within the survey (Figure F.1). The settings of the SSS survey of HS are for the detection of objects at the seafloor and set at

maximum range (i.e. 150 m) to cover a large ground surface, which are not optimal for the detection of biogenic and geogenic reefs (a more preferred range of 75 m).

Typical characteristic of the HS SSS survey dataset:

- › Sensor used: from 2002 to 2018 Klein 5000 sonar, since 2018 Klein 5900 sonar type;
- › Target flying height (altitude): aimed for ~15 m (10% of the range) with variations between 11 and 19 m;
- › Ground range: ~150 m;
- › Frequency: 450 kHz (Klein 5000), 600 kHz (Klein 5900);
- › Range (across-track) resolution: ~3.75 cm for both Klein 5000 and Klein 5900;
- › Along-track resolution (Klein 5000): 10 cm (at 38 m range), 20 cm (at 75 m) and 36 cm (at 150 m);
- › Along-track resolution (Klein 5900): 6.2 cm (at 50 m range), 9.3 cm (at 75 m) and 15.5 cm (at 125 m);
- › Along-track ping spacing: 15 to 25 cm (varies with speed);
- › Track line spacing: between 10 and 400 m, with the majority around 120 m;
- › Sonar seabed coverage (max useful range up to 120 m): around 200% (relates to track line spacing and sonar range).

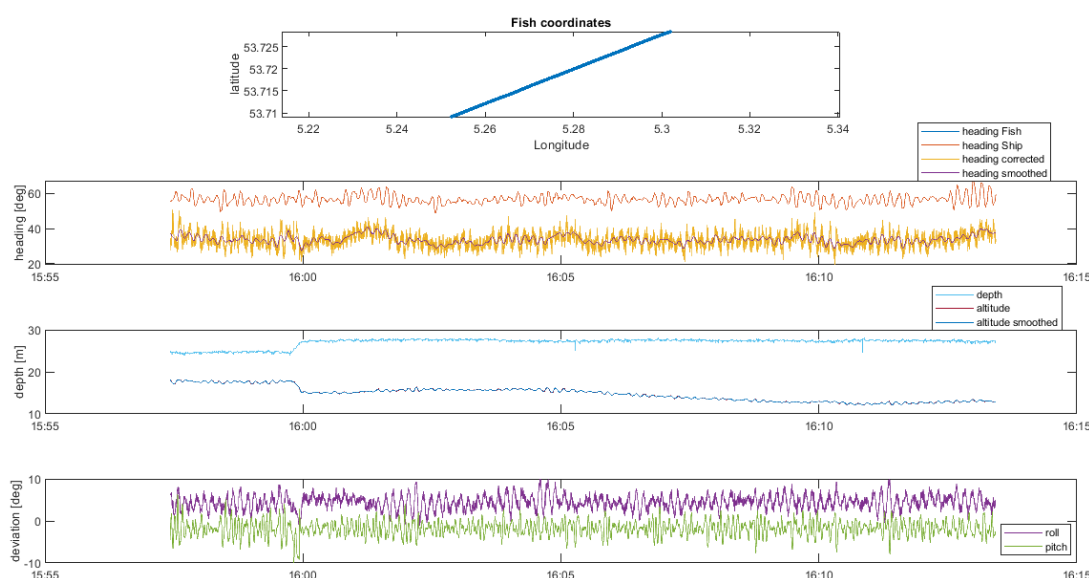


Figure F.1: Navigation and motion data of the sonar fish and ship for an example track line acquired in the Friesian Front. Figure gives an example for relative strong motion with roll and pitch values up to 10 deg, high fluctuating fish heading of up to 20 deg and large crabbing (indicated by difference between ship and fish heading).

The Figure F.5 to Figure F.12 show the coverage of the SSS data in the Natura 2000 / KRM priority areas and the Texelse Stenen area. Note that SSS data coverage is presented as lines (i.e. the individual SSS lines of the survey dataset) or as polygons (i.e. the outline / full extent of the SSS survey dataset). For the latter the individual SSS lines could not be produced and plotted in time for this report since the data were recently provided by HS during this project. It should be noted that the HS does not survey the full Dutch North Sea. Certain areas are surveyed and monitored by Rijkswaterstaat and the Vlaamse Hydrografie. These areas include the coastal zones, the Voordelta, the Vlakte van Raan and the Zeeuwse estuaries. Unfortunately, Rijkswaterstaat and the Vlaamse Hydrografie do not use SSS for monitoring of the seabed, but single- and multi-beam echosounder systems, i.e. for these areas there is no coverage with SSS.

Summarised on the coverage in these areas:

- › Friese Front area: Large coverage with few data gaps. 15 out of 25 available survey datasets retrieved from TNO-GDN archive or shared by HS, which are in the order of 12,000 files with a combined volume of 9,000 gigabytes of data. In process of retrieving the remaining datasets.
- › Texelse Stenen area: Almost full coverage with overlapping surveys. 18 out of 28 available survey datasets retrieved from TNO-GDN archive or shared by HS, which are in the order of 28,000 files with a combined volume of 13,225 gigabytes of data. In the south eastern margin is no monitoring by HS and therefore no coverage with SSS data. In process of retrieving the remaining datasets.
- › Borkumse Stenen area: Complete coverage with multiple overlapping surveys. 7 out of 8 available survey datasets retrieved from TNO-GDN archive or shared by HS, which are in the order of 6,750 files with a combined volume of 6,742 gigabytes of data.
- › Doggersbank and Centrale Oestergronden areas: A large coverage of the Doggersbank area, but hardly any coverage in the Centrale Oestergronden area. The area of the Centrale Oestergronden was surveyed before 2002, and is due to be surveyed in the coming years. 4 out of 5 available survey datasets retrieved from TNO-GDN archive or shared by HS, which are in the order of 2100 files with a combined volume of 2,167 gigabytes of data. In process of retrieving the remaining dataset.
- › Bruine Bank area: Almost full coverage with multiple overlapping surveys. Few data gaps due to incomplete or missing survey lines. 15 out of 25 available survey datasets retrieved from TNO-GDN archive or shared by HS, which are in the order of 14,000 files with a combined volume of 9,300 gigabytes of data. Remaining datasets requested.
- › Klaverbank area: Full coverage of the area, with a few data gaps due to incomplete or missing survey lines. 4 out of 4 available survey datasets retrieved from TNO-GDN archive or shared by HS, which are in the order of 1,500 files with a combined volume of 1,800 gigabytes of data.
- › Noordzeekustzone area: Only coverage along the margin of the area. In process of retrieving the available datasets.
- › Vlake van de Raan and Voordelta: Only coverage along the margins of the areas. In process of retrieving the available datasets.
- › Gasfonteinen, Zeeuwse banken and Historische Oestergronden: For these areas the location and extent (outline) were not available. Therefore they were considered out of scope of this project.

Figure F.13 shows the coverage of MBES backscatter maps of the HS in the North Sea. Partial coverage of MBES backscatter data in the Friese Front, Noordzeekustzone, Borkumse Stenen and Texelse Stenen areas. For this project focus was on the SSS data due to the limited coverage of the MBES backscatter data, and as such a detailed analysis on the quality and usability was not performed.



Figure F.2: Regional map showing the coverage of the SSS data currently available at TNO-GDN in one colour (light orange), overlain by the outlines of the Natura 2000 and KRM priority areas and the Texelse Stenen area (dashed black lines). The SSS coverage in the North Sea is about 82%, including data from the HS and RVO (offshore windfarms). Note that several SSS survey lines in the Waddenzee and Zeeuwse estuaries acquired for TNO projects in the past are also available.

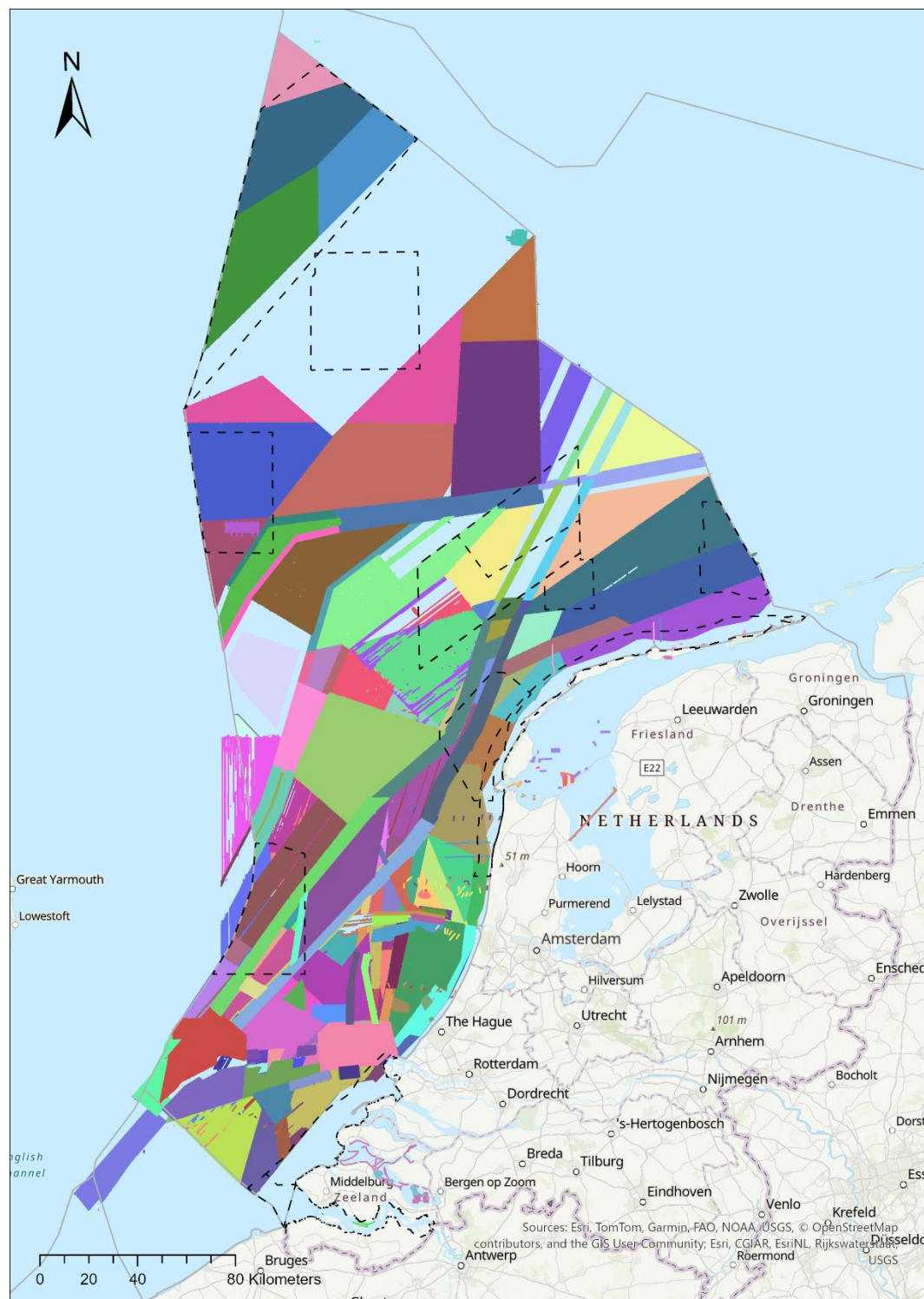


Figure F.3: Regional map showing the coverage of the SSS data currently available at TNO-GDN in multiple colours; a different colour for each survey dataset that is available at TNO, including datasets of HS, RVO, vintage data of TNO-GDN. Overlay of the Natura 2000 and KRM priority areas and the Texelse Stenen area (dashed black lines).

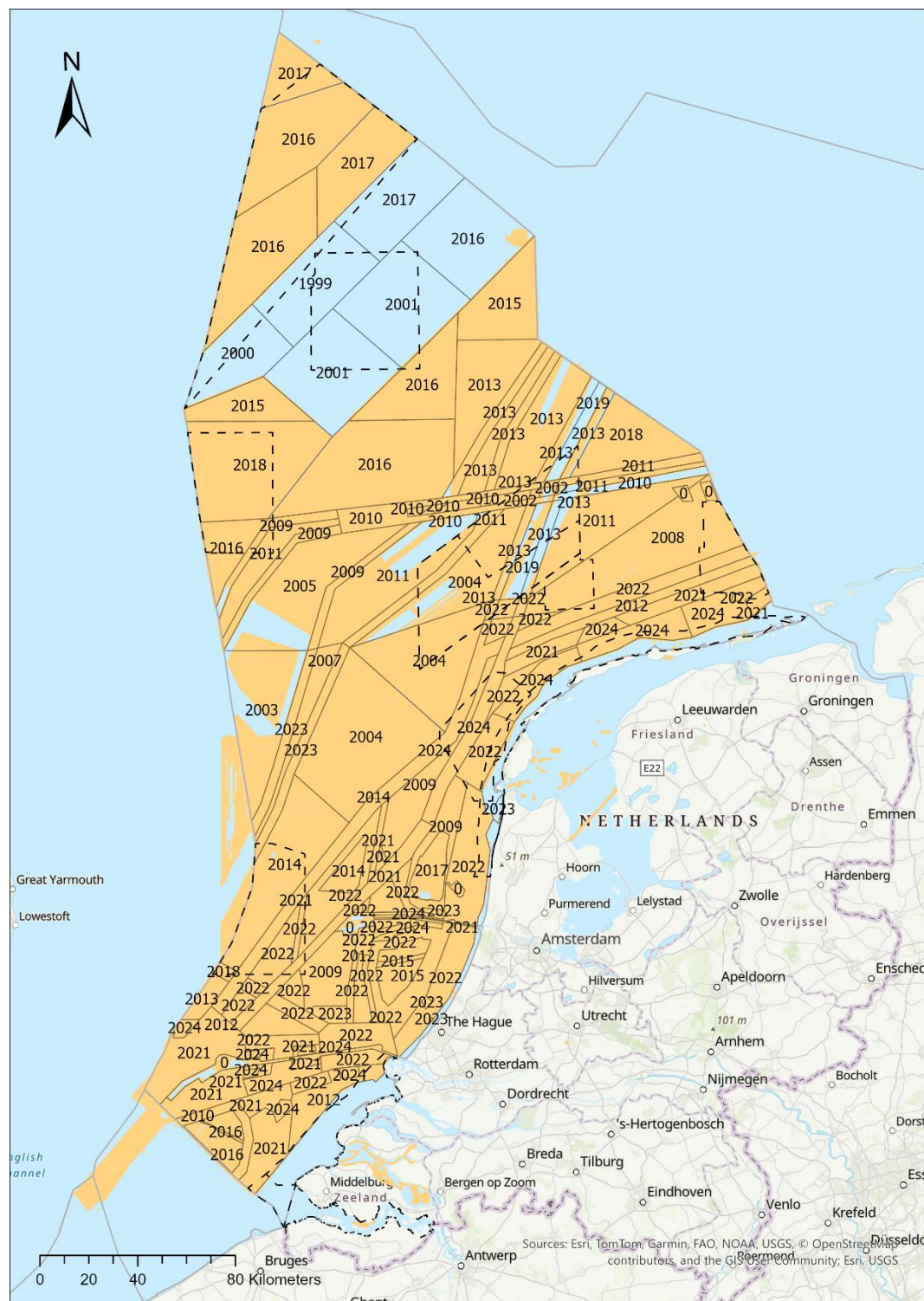


Figure F.4: Regional map showing the coverage of the SSS data currently available at TNO-GDN in one colour (light orange), overlain by the outlines of the Natura 2000 and KRM priority areas and the Texelse Stenen area (dashed black lines), and outlines of the HS survey areas (grey) with the year of the last survey of that area as label. The areas surveyed before 2002 (northern part of the Dutch North Sea) are not (digitally) available at HS, but are due to be surveyed again in the coming years. For a few areas, the missing digital SSS data are in the process of being retrieved.

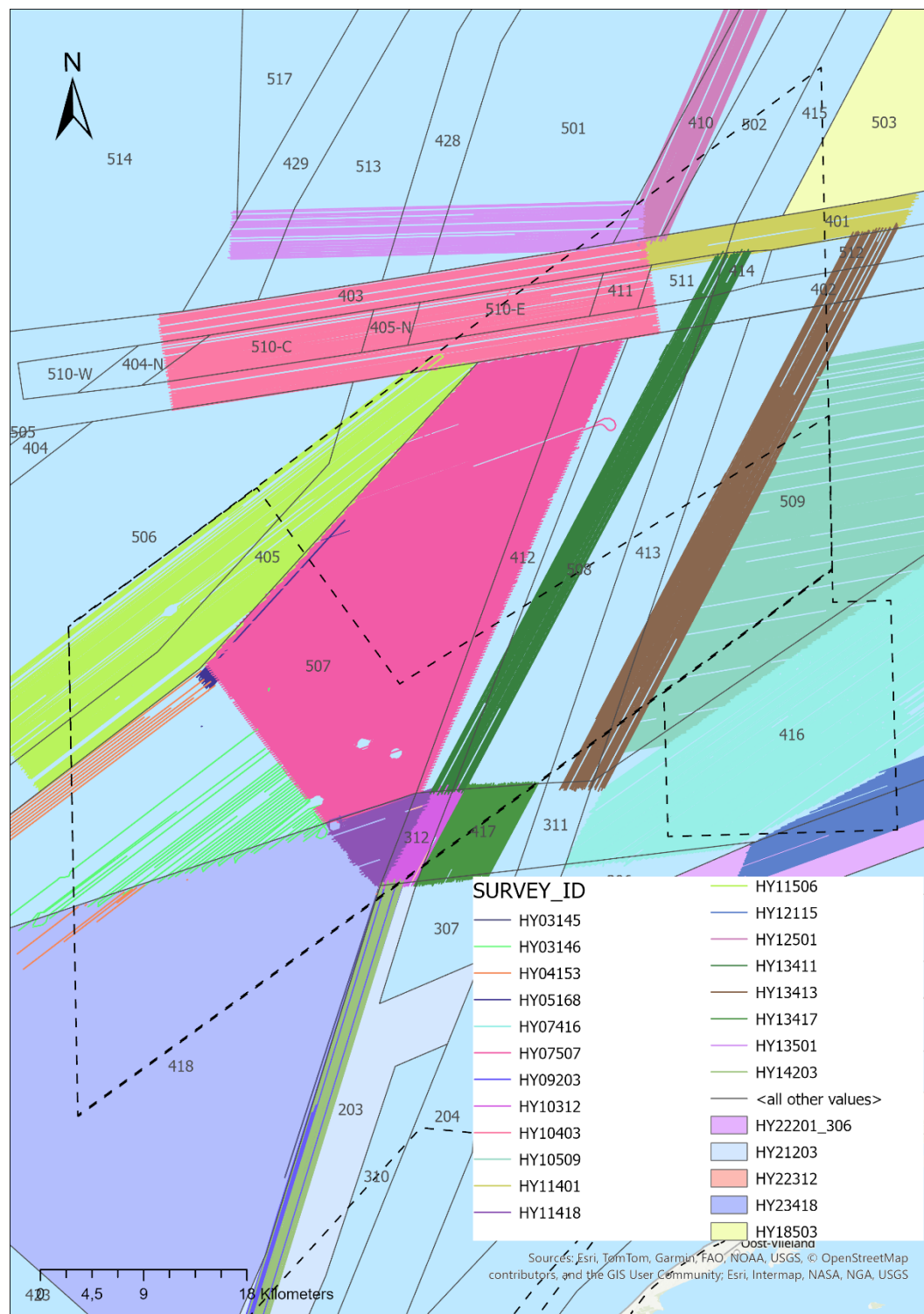


Figure F.5: Friese Front area (dashed line) showing the coverage of the available and used SSS survey data; a different colour for each survey (see legend). Overlay of the outlines of the HS survey areas (grey) with the 3-digit area number as label. Note that some survey areas have been split up in smaller survey areas in recent years. A few gaps in the data coverage of the area (e.g. line gaps due to missing survey line sections), but overlapping surveys in some other parts of the area.

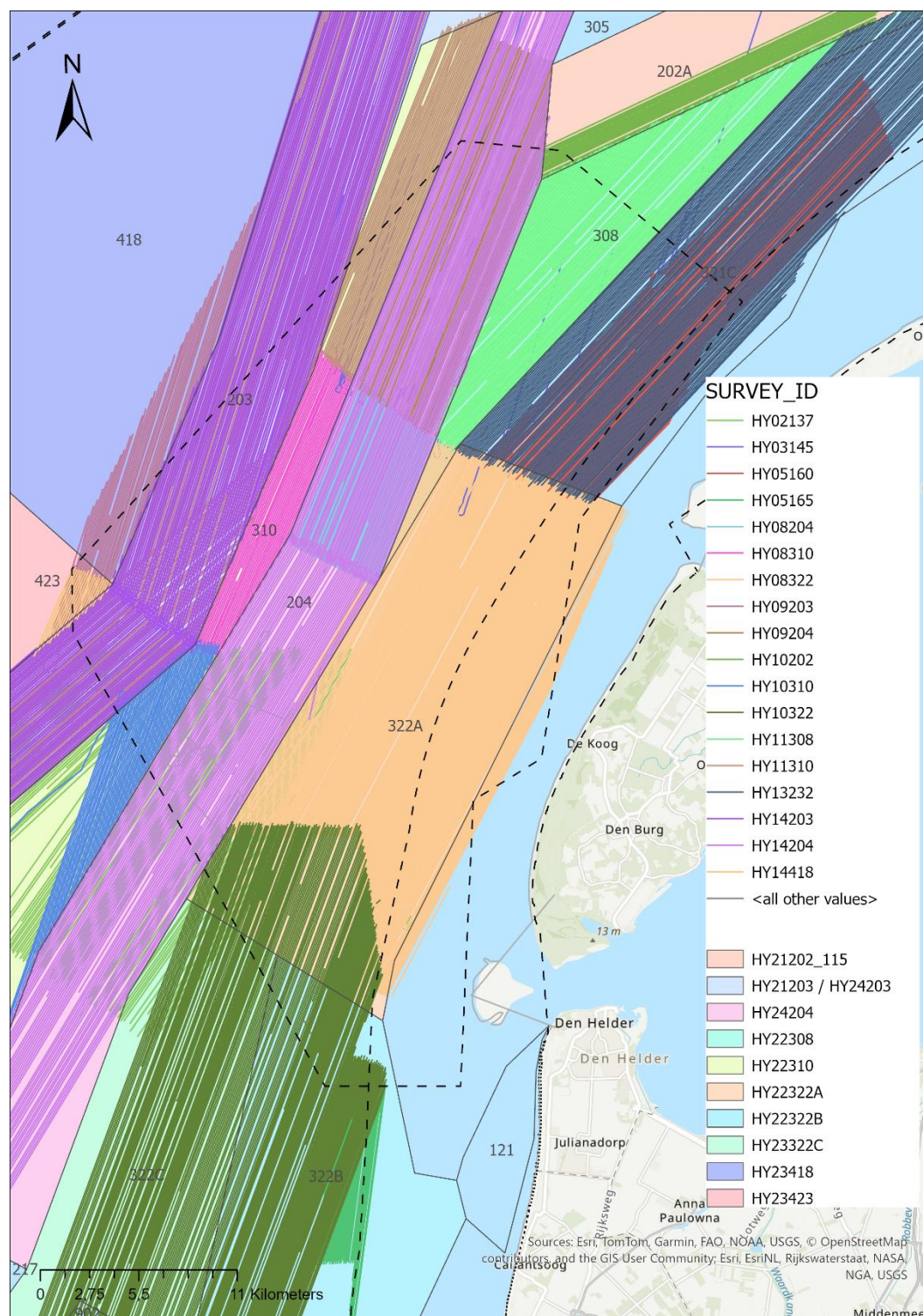


Figure F.6: Texelse Stenen area (dashed line) showing the coverage of the available and used SSS data; a different colour for each survey (see legend). Overlay of the outlines of the HS survey areas (grey) with the 3-digit area number as label. Note that some survey areas have been split up in smaller survey areas in recent years. No coverage at the southeastern tip, but multiple overlapping surveys in many parts of the area. In some places line gaps due to missing survey line sections.

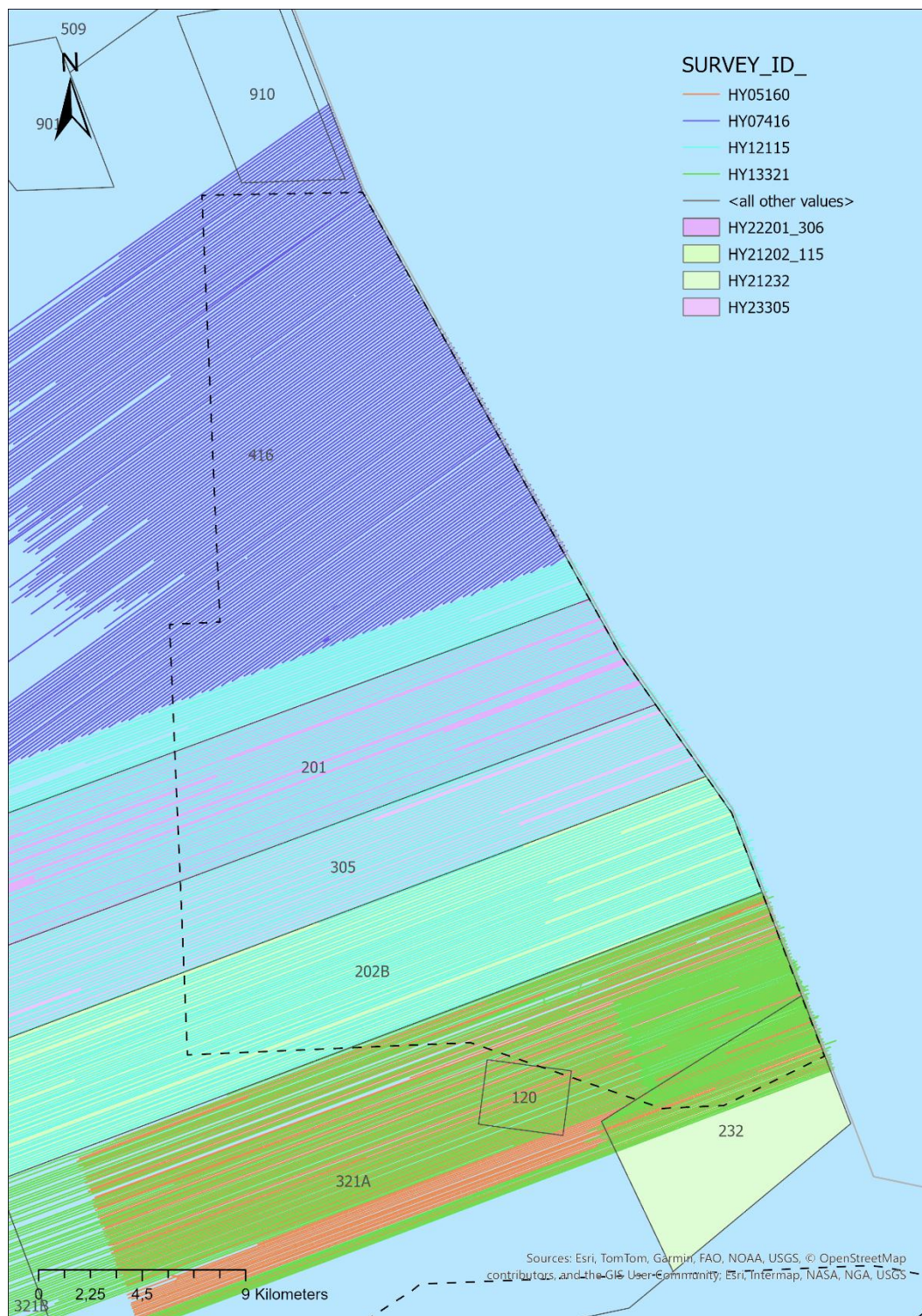


Figure F.7: Borkumse Stenen area (dashed line) showing the coverage of the available and used SSS survey data; a different colour for each survey (see legend). Overlay of the outlines of the HS survey areas (grey) with the 3-digit area number as label. Note that some survey areas have been split up in smaller survey areas in recent years. Full coverage of the area, with overlapping surveys in the centre and southern part of the area. In some places line gaps due to missing survey line sections.

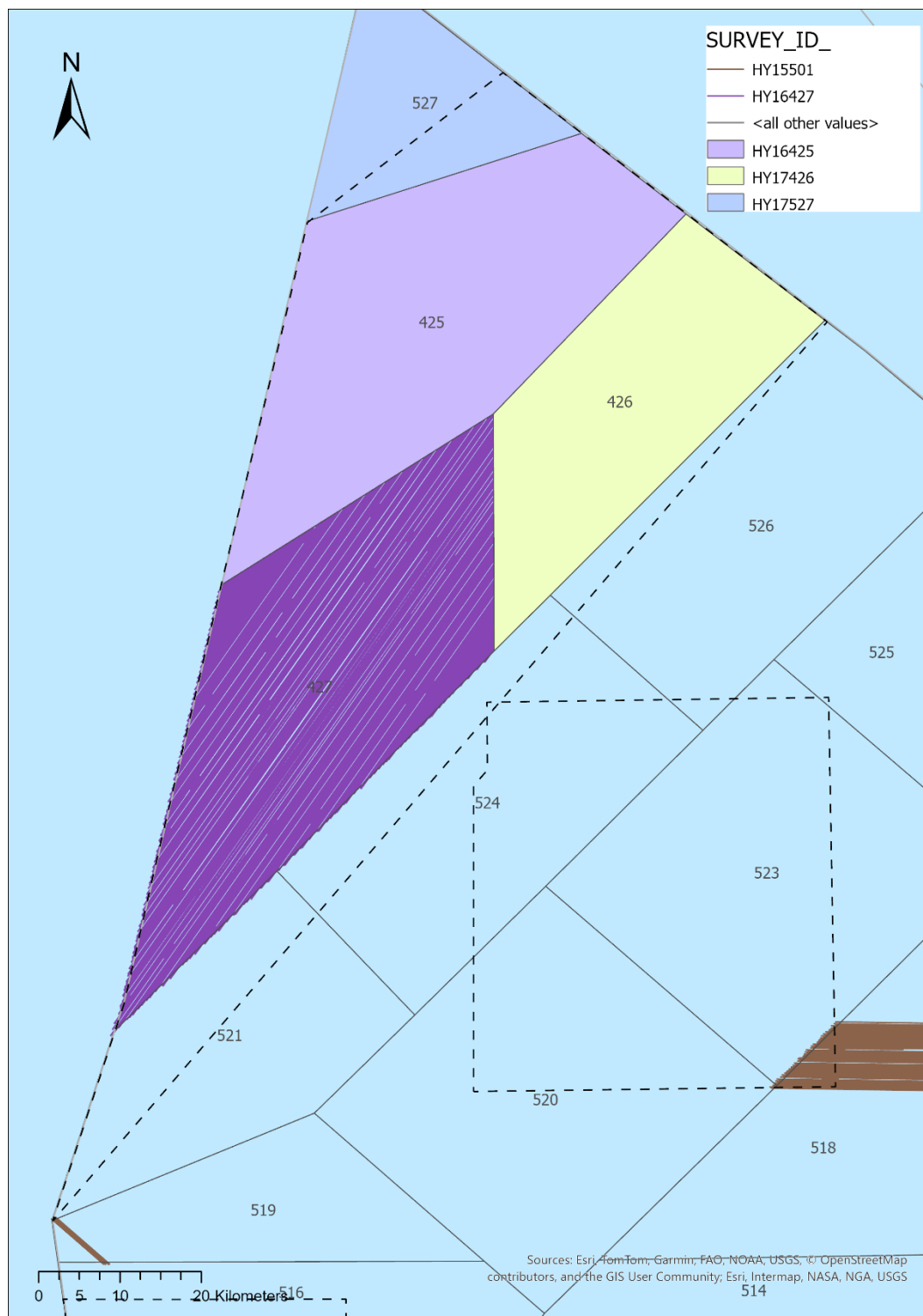


Figure F.8: Doggersbank and Centrale Oestergronden areas (dashed line) showing the coverage of the available and used SSS survey data; a different colour for each survey (see legend). Overlay of the outlines of the HS survey areas (grey) with the 3-digit area number as label. Note that some survey areas have been split up in smaller survey areas in recent years. Significant coverage of the Doggersbank area. Hardly any coverage of the Centrale Oestergronden area. In some places line gaps due to missing survey line sections.

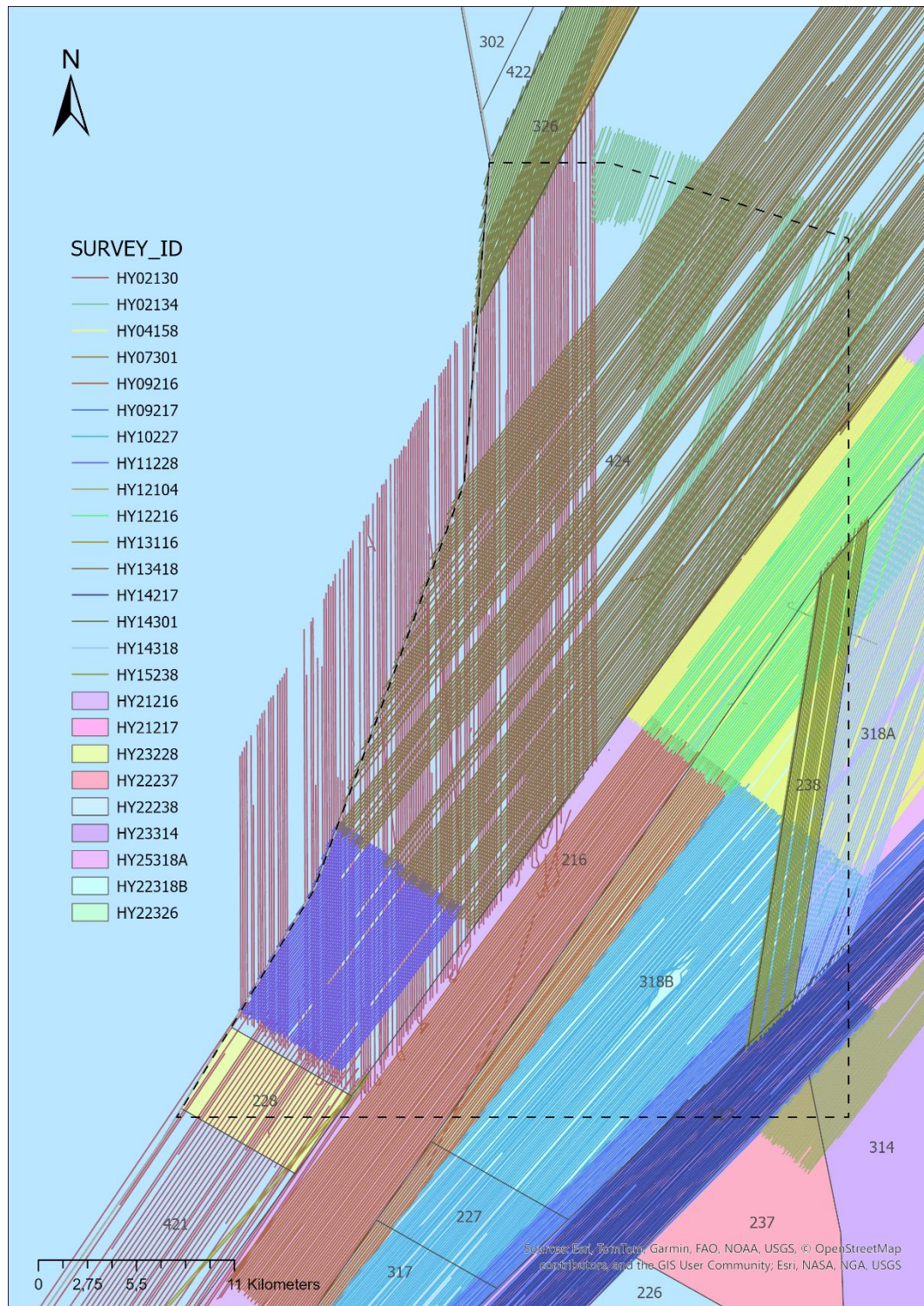


Figure F.9: Bruine Bank area (dashed line) showing the coverage of the available SSS survey data; a different colour for each survey (see legend). Overlay of the outlines of the HS survey areas (grey) with the 3-digit area number as label. Note that some survey areas have been split up in smaller survey areas in recent years. Almost full coverage of the area, with multiple overlapping surveys. In some places line gaps due to missing survey line sections.

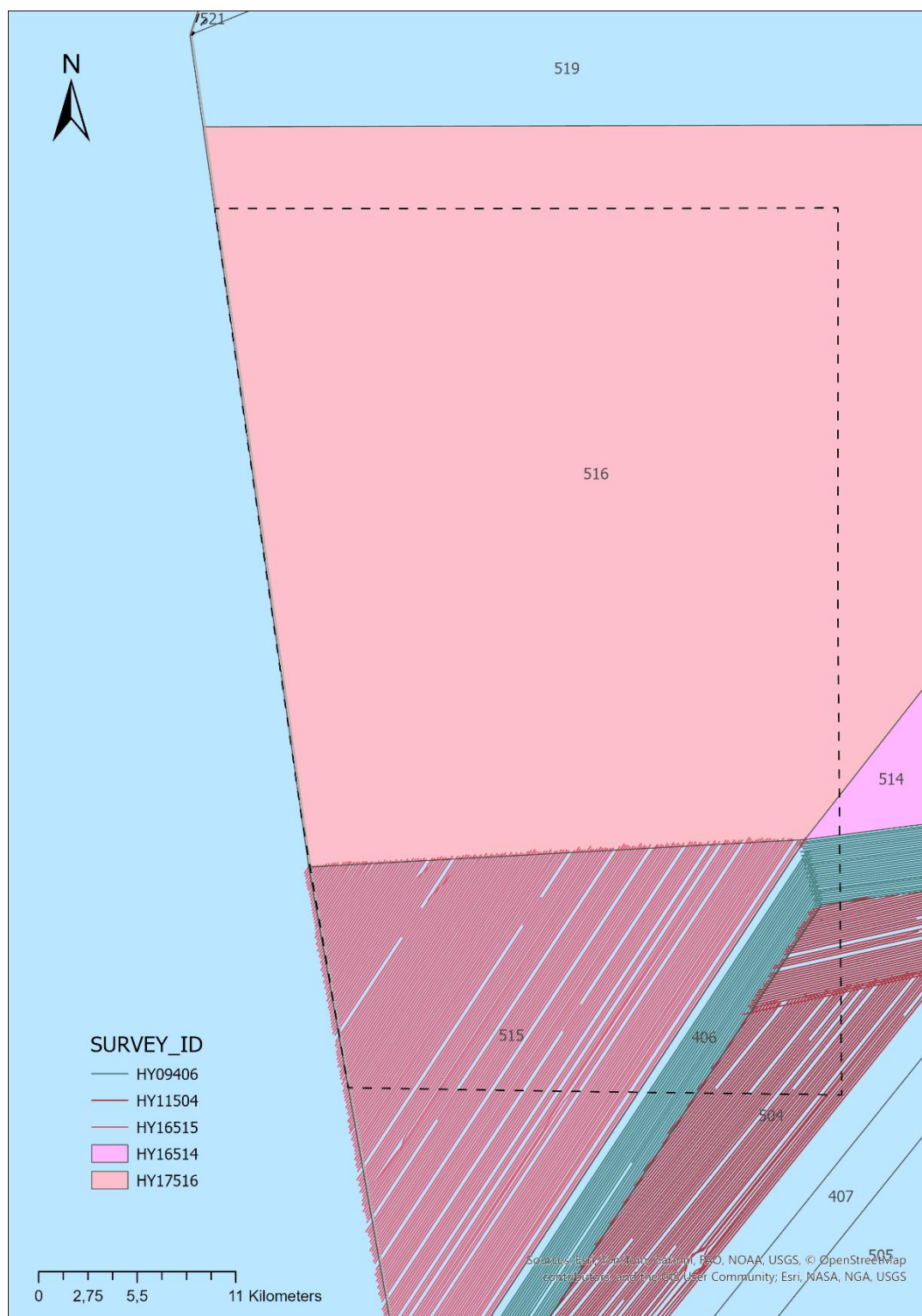


Figure F.10: Klaver Bank area (dashed line) showing the coverage of the available and used SSS survey data; a different colour for each survey (see legend). Overlay of the outlines of the HS survey areas (grey) with the 3-digit area number as label. Full coverage of the area except for a few line gaps due to missing survey lines.

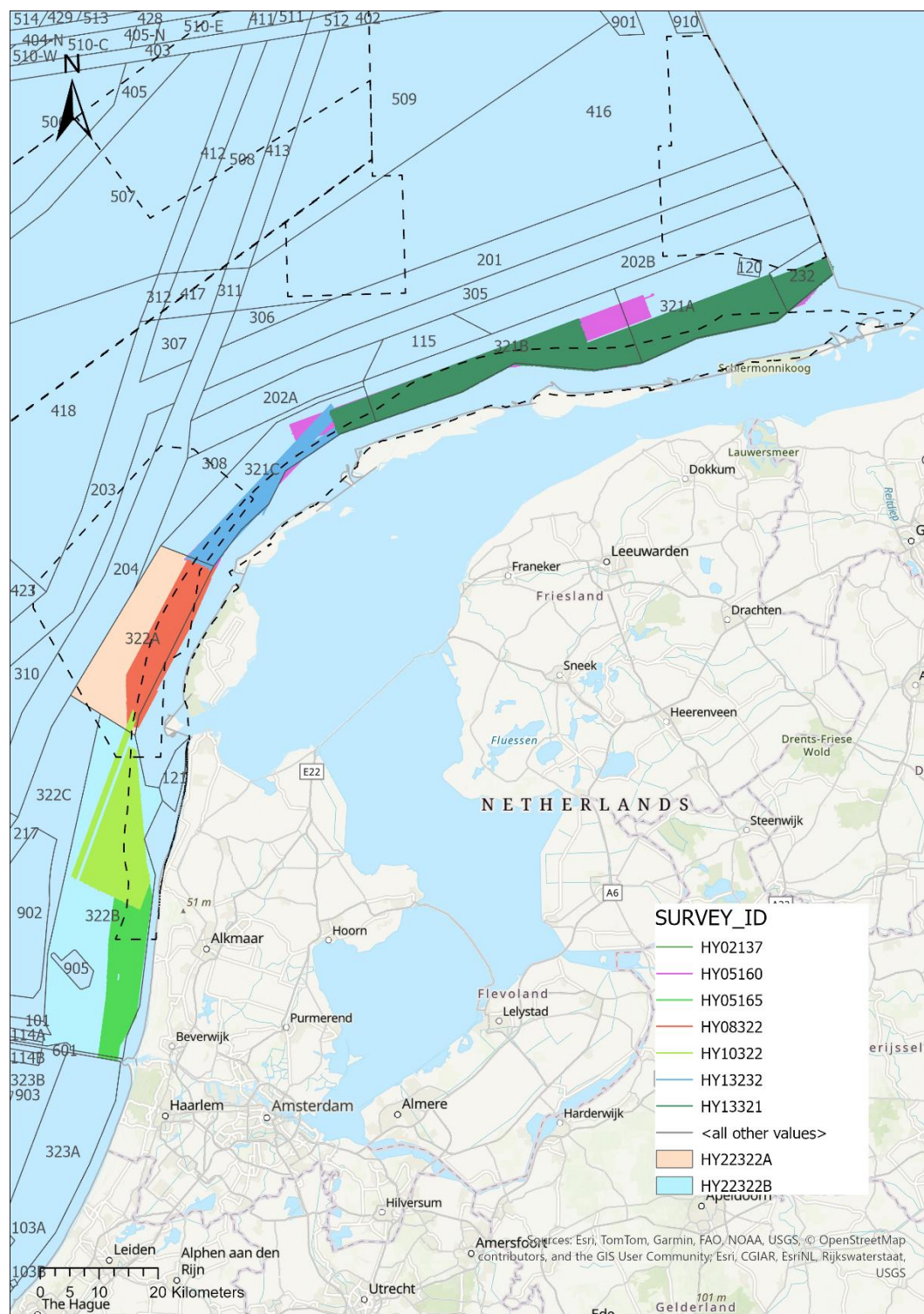


Figure F.11: Noordzeekustzone area (dashed line) showing the coverage of the available SSS survey data; a different colour for each survey (see legend). Overlay of the outlines of the HS survey areas (grey) with the 3-digit area number as label. Note that some survey areas have been split up in smaller survey areas in recent years. Only data coverage along the margins and a few overlapping surveys.

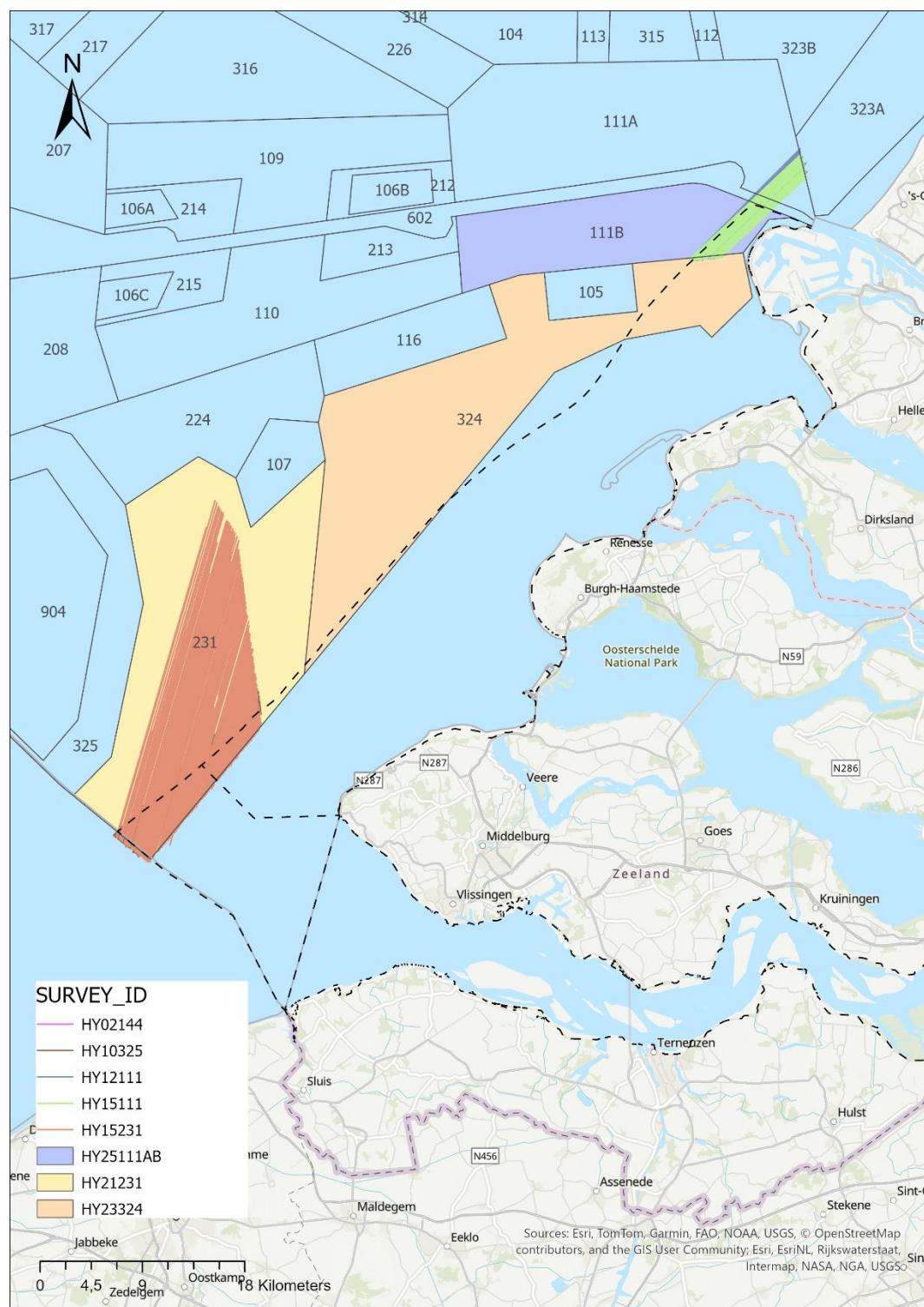


Figure F.12: Vlakte van de Raan and Voordelta areas (dashed lines) showing the coverage of the available SSS survey data; a different colour for each survey (see legend). Overlay of the outlines of the HS survey areas (grey) with the 3-digit area number as label. Note that some survey areas have been split up in smaller survey areas in recent years. Only coverage along the margins of the area. And a few overlapping surveys.

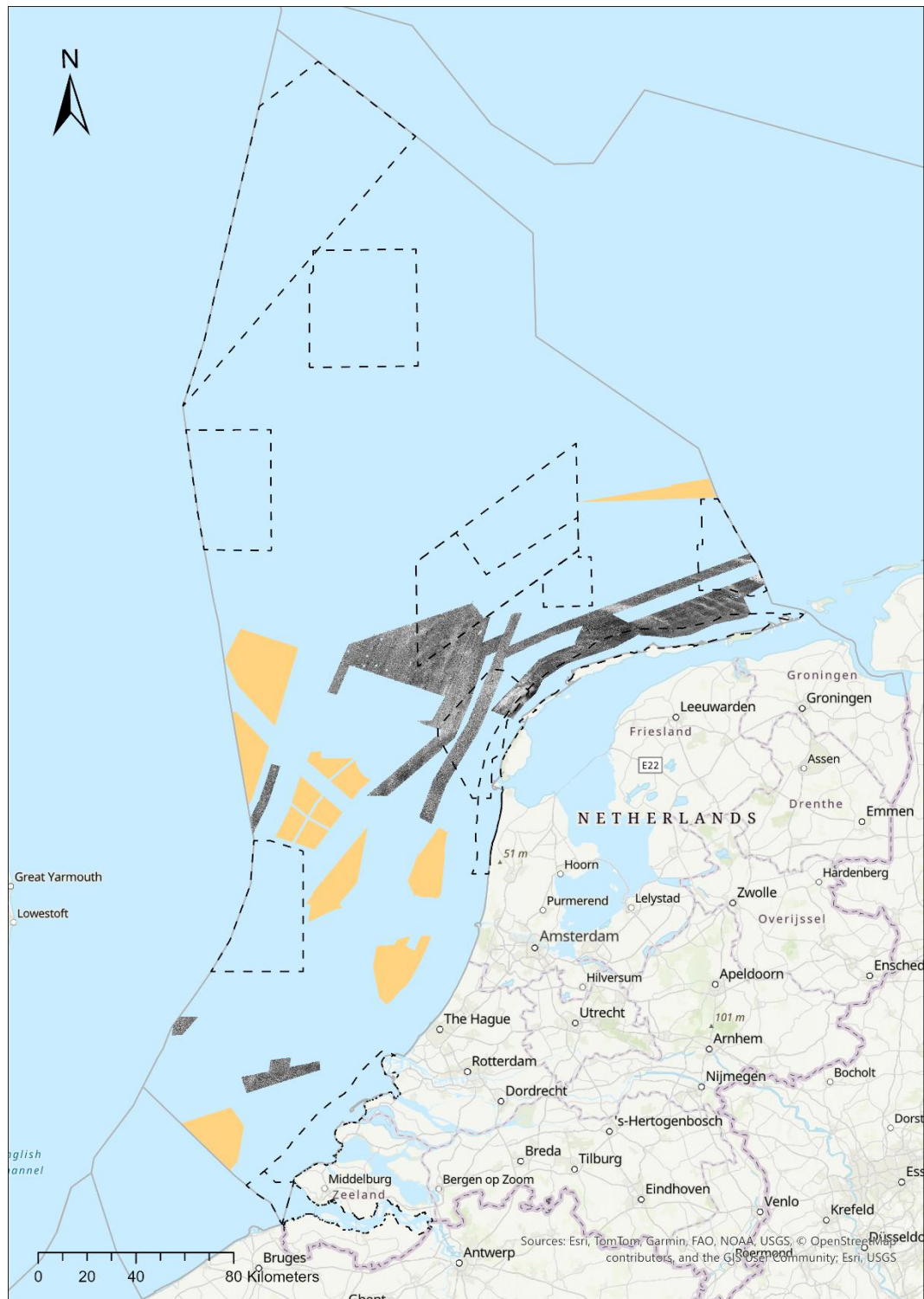


Figure F.13: Regional map showing the coverage of the MBES backscatter data in the Dutch North Sea which is currently available at TNO-GDN. In orange the datasets of the offshore windfarms (RVO) and in grey scale the datasets of HS, overlain by the outlines of the Natura 2000 and KRM priority areas and the Texelse Stenen area (dashed black lines). The coverage is currently limited to a few areas in the Dutch North Sea.

F.3 Sonar register

Rijkswaterstaat maintains the SONARreg database which holds information on objects that were found on the seabed during monitoring surveys in the Dutch North Sea by HS and Rijkswaterstaat or were provided by other institutes and organisations (e.g. RVO, Periplus) or survey companies. The information includes location, dimensions, description and identity (if known) and other parameters. The objects range from shipwrecks, anthropogenic debris to stones. Large parts of the information in this database is confidential and is therefore not open to the public. Upon request, parts of the information in this database was made available to TNO for the purpose of this project (Figure F.14). Details cannot be shared in this report.

It should be noted that HS is also maintaining an object database identified from sonar, the so-called AML database. The objects registered in this database are small objects found on the seabed. The data and information in this database is confidential and not open to the public.

F.4 Sediment sample data

Seabed sample data and information of the Dutch North Sea are available via DINOloket (www.dinoloket.nl) and BROloket (www.broloket.nl), which are both maintained by TNO-GDN. The data are publicly available. DINOloket publishes all available data at TNO-GDN, including vintage data or non-standard data. The BROloket is a new key register where data and information published uphold a certain standard and quality. New public data and information are being added to the BROloket by stakeholders (e.g. Deltares, Rijkswaterstaat, RVO, etc.). Currently few seabed data are available at the BROloket. In due time data will be harmonised and migrated from DINOloket to BROloket. Figure F.15 and Figure F.16 show the currently available seabed sample locations.

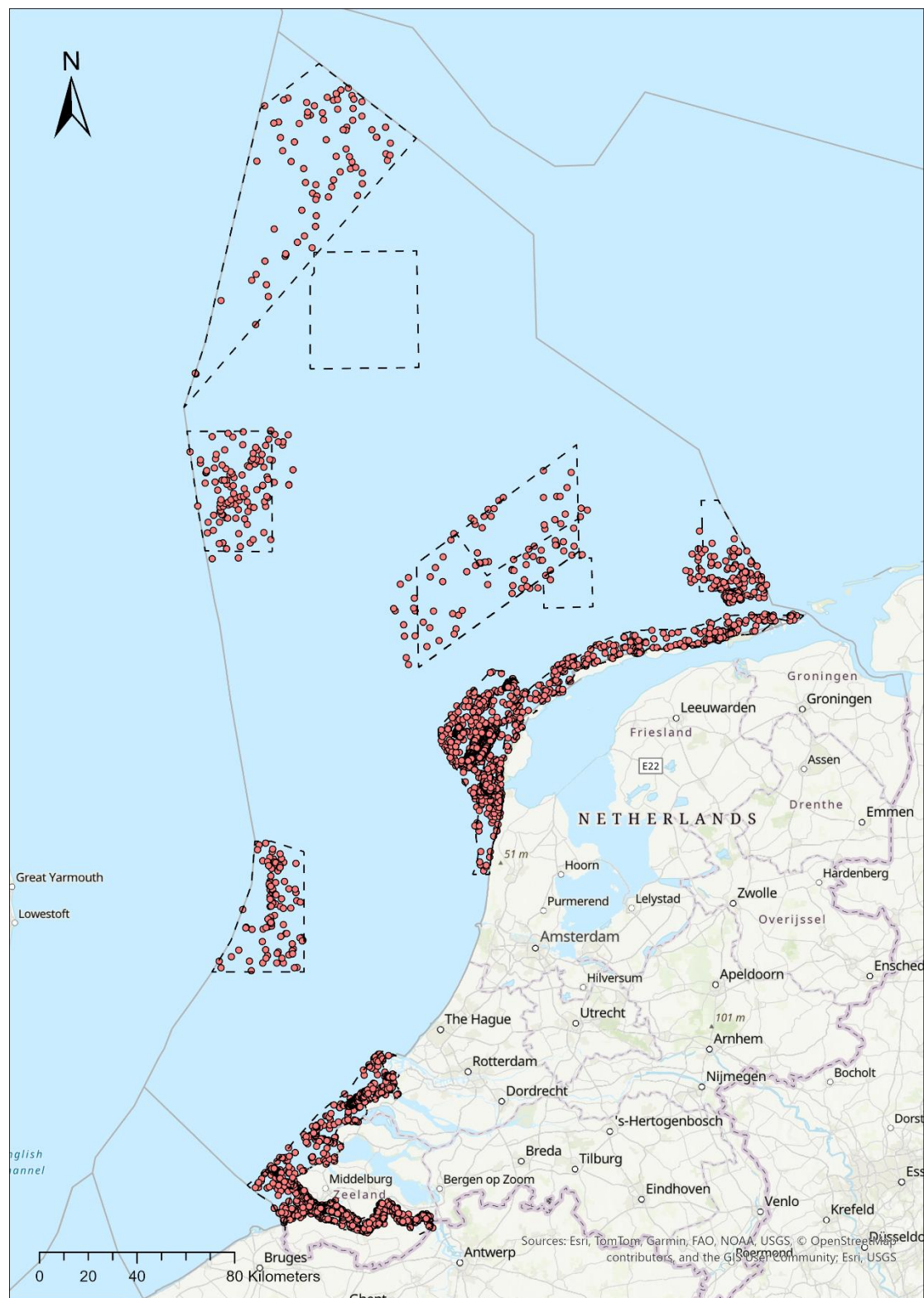


Figure F.14: Regional map showing the export of locations (and information) from the SONARreg database. Details cannot be shared in this report. Overlay of the outlines of the Natura 2000 and KRM priority areas and the Texelse Stenen area (dashed black lines).

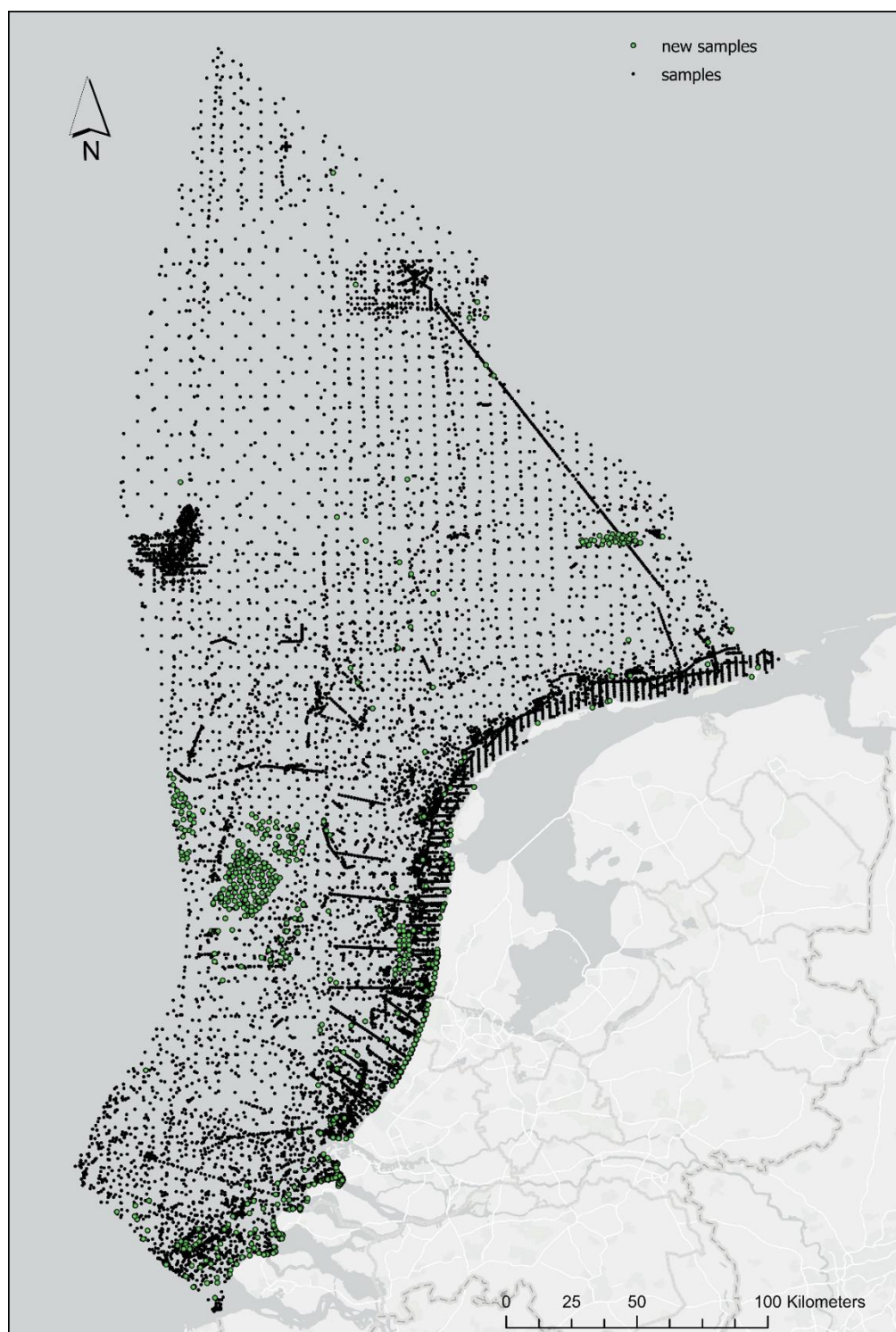


Figure F.15: Available sample locations in the Dutch North Sea. 'new samples' indicate sample locations that were not available for previous 2023 Folk seabed-sediment map.

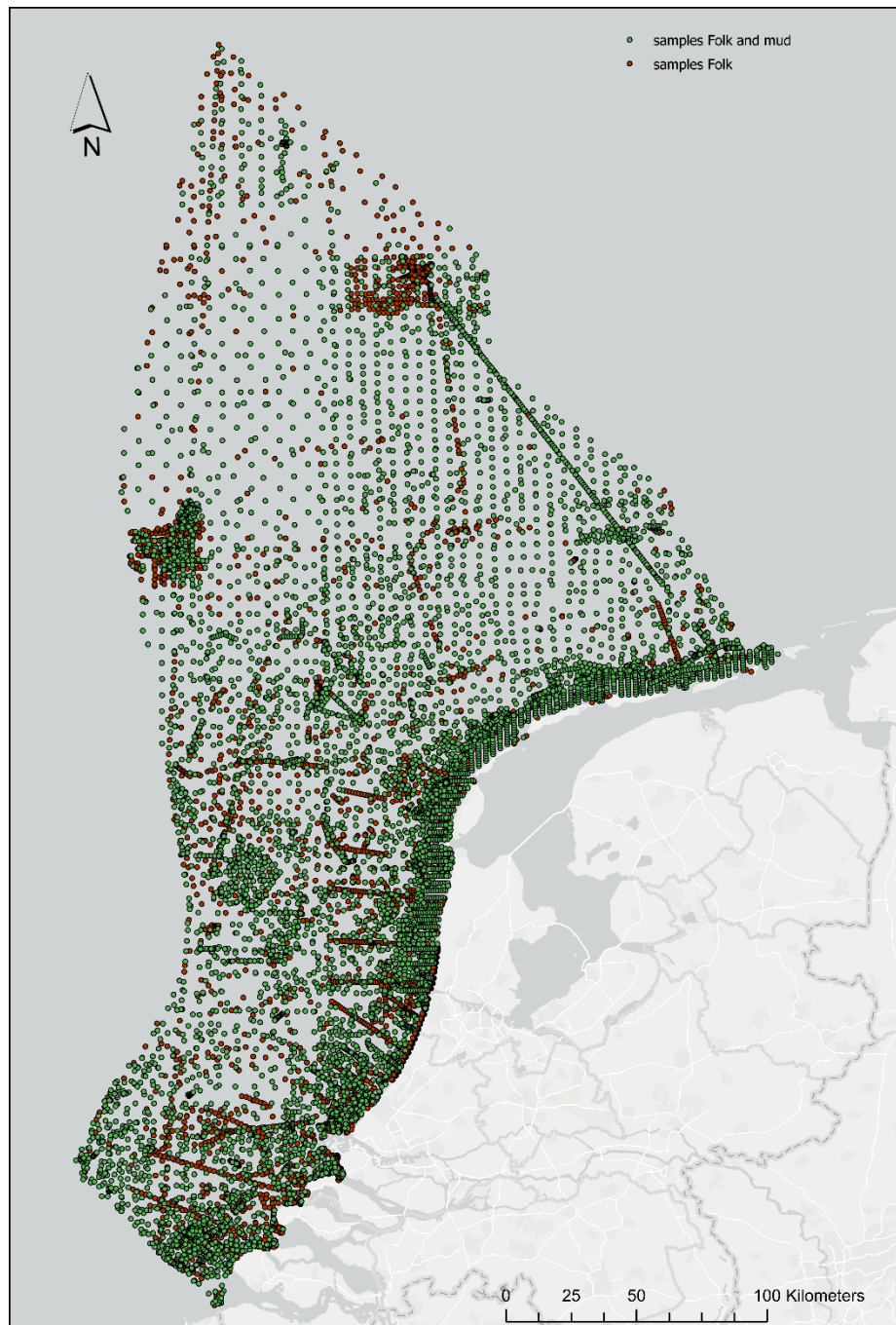


Figure F.16: Available sample locations in the Dutch North Sea which are publicly available on DINOLOket and BROLOket. The sample locations shown in this map contain information regarding Folk class and mud percentage (samples Folk and mud) and Folk class only (samples Folk).

F.5 Bathymetry

The primary source of bathymetric data of the Dutch North Sea is from the HS for the Dutch North Sea and from Rijkswaterstaat and Vlaamse Hydrografie for the coastal zone, Waddenzee and Zeeuwse estuaries and from RVO regarding the offshore windfarms.

- › The bathymetric data from HS is made publicly available via the open data viewer of Informatie Huis Marien ([IHM viewer](#)). The bathymetric grid (20m resolution) is compiled from all digital datasets of sounding surveys in the past two to three decades. Currently, this bathymetric grid contains gaps; in these areas is no coverage by MBES surveys and only single beam echo sounder (SBES) point measurements along the survey lines are available. Some of these areas with no MBES coverage overlap with parts of a few N2000/KRM areas (Doggersbank, Centrale Oestergronden, Friese Front) and the Texelse Stenen area. In the coming years, new surveys will be planned by HS in the areas with no MBES coverage to fill in the blanks.

Rijkswaterstaat and Vlaamse Hydrografie survey and monitor the state of the seabed in the coastal zones and Zeeuwse estuaries. The Vlaamse Hydrografie is responsible for monitoring the Wester Schelde and parts of the Vlakte van de Raan. On request, Vlaamse Hydrografie can make high resolution bathymetric data available, but limitations of use apply. Rijkswaterstaat is responsible for monitoring of the coastal zones and other Zeeuwse estuaries. In these coastal zones, typically SBES is used due to the operational limitations of MBES in shallow water depth. These data are published via the webservice of Rijkswaterstaat.

HS (in collaboration with Deltares) compiles all these bathymetric datasets into one dataset and make these available through EMODnet.

Via EMODnet a regional bathymetric dataset of the North Sea is publicly available ([Bathymetry | European Marine Observation and Data Network \(EMODnet\)](#)). This grid has a resolution of $1/16 * 1/16$ arc minutes (ca. 115 meter grid). This grid was developed from the HS compiled dataset of the Dutch North Sea, Wadden Sea and Zeeuwse estuaries, downsized and interpolated to a full coverage bathymetric grid. This dataset was used a source for the seabed-sediment maps.

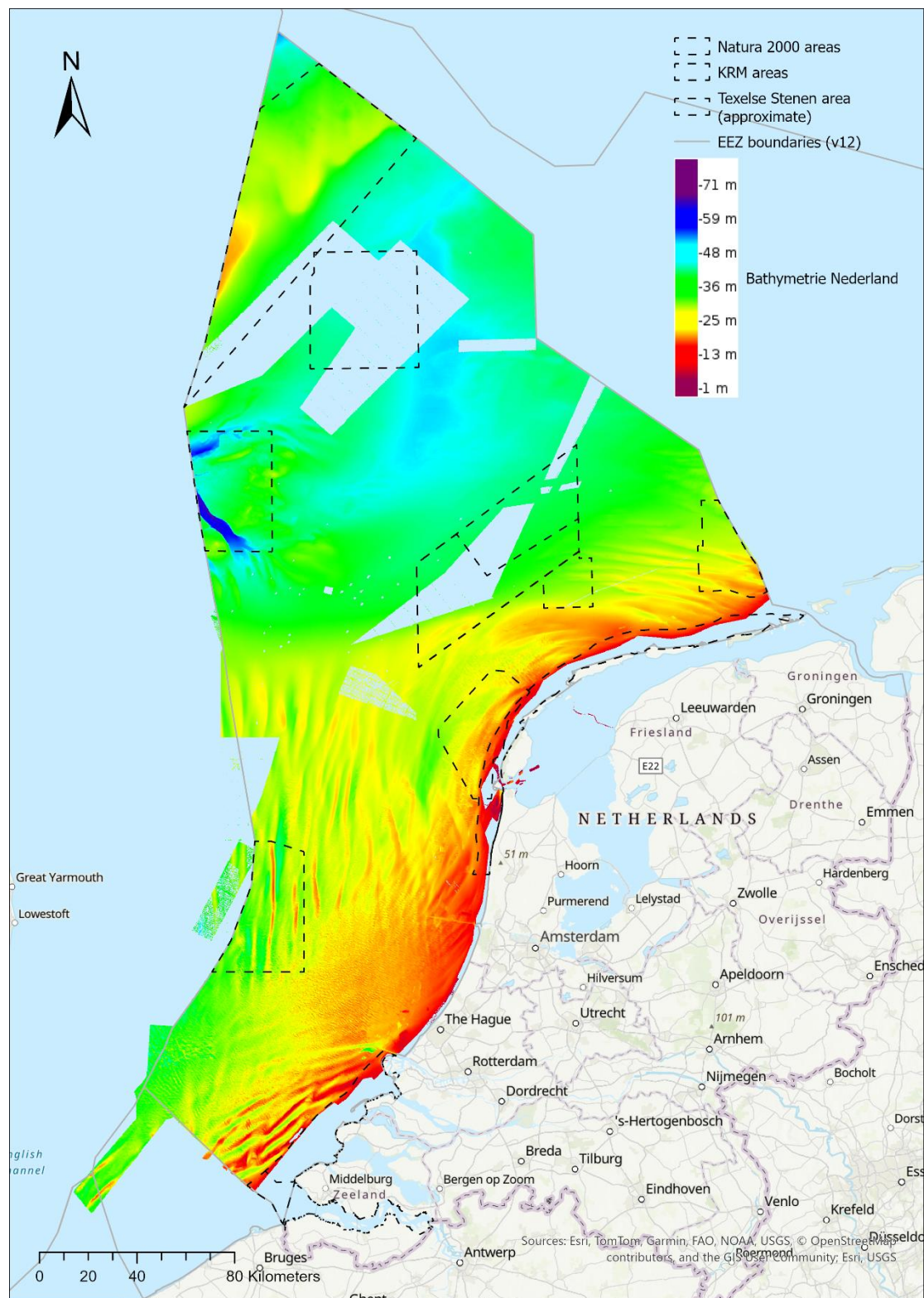


Figure F.17: Regional map with bathymetry of the Dutch North Sea of HS (published on Informatie Huis Marien, [IHM viewer](#)), overlain by the outlines of the selected Natura 2000 and KRM priority areas and the Texelse Stenen area (dashed black lines). Resolution of the bathymetric grid is 20x20 m.

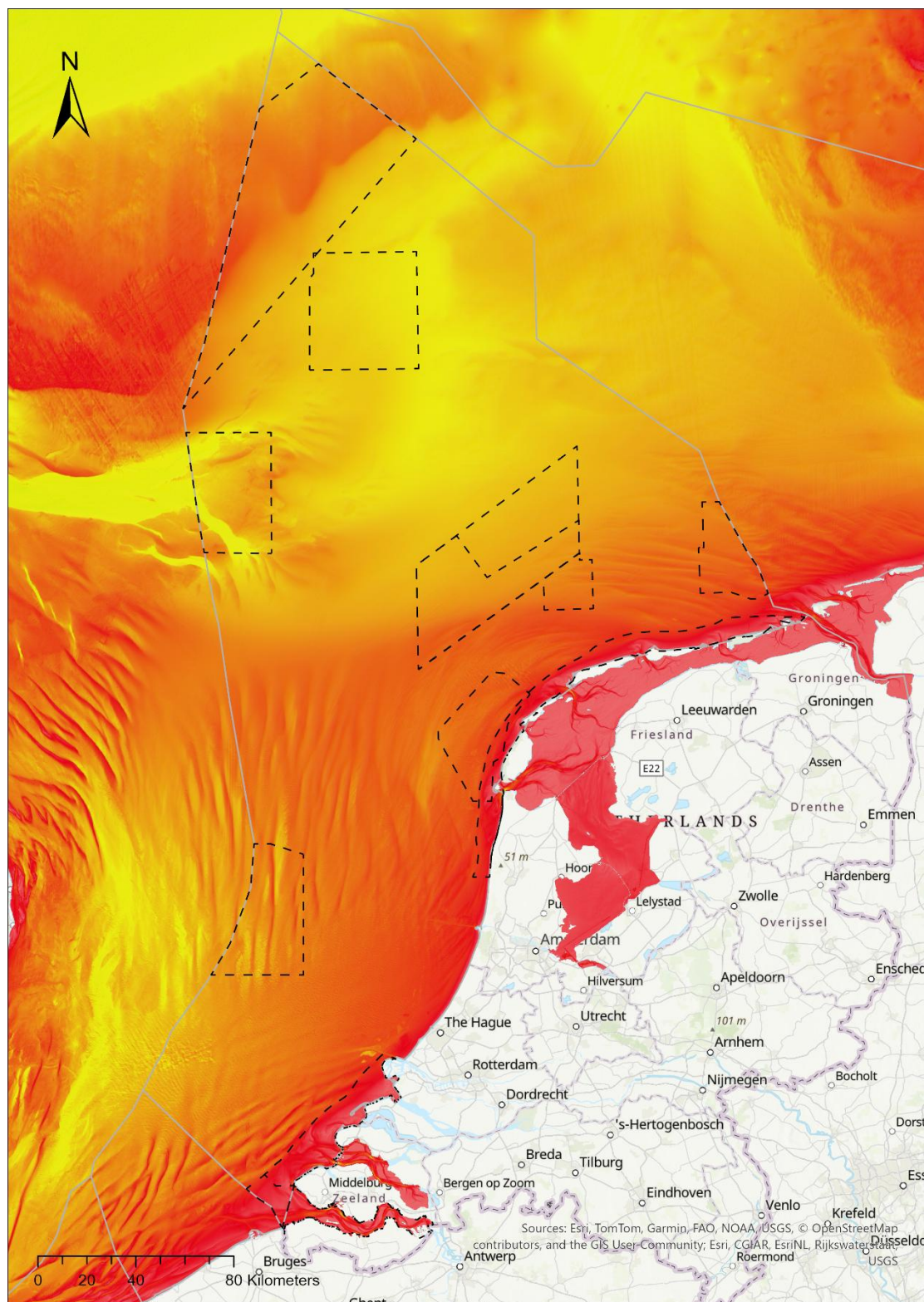


Figure F.18: Regional map with EMODnet bathymetry of the southern North Sea, including the coastal zones, Wadden Sea and part of the Zeeuwse estuaries. Overlay of the outlines of the selected Natura 2000 and KRM priority areas and the Texelse Stenen area (dashed black lines). Resolution in the order of 100x100 m. Linear colour range from red to yellow of the bathymetry corresponds with an average water depth ranging from 0 m to 90 m in this image.

Appendix G

Delivered files

Table G.1: Overview of files delivered to LVVN

File	Description
Folk 16.tiff	Seabed-sediment map – Folk 16 classification system
Folk 16 likelihood.tiff	Probability of seabed-sediment map – Folk 16 classification system
Folk 7.tiff	Seabed-sediment map – Folk 7 classification system
Folk 7 likelihood.tiff	Probability of seabed-sediment map – Folk 7 classification system
Folk 5.tiff	Seabed-sediment map – Folk 5 classification system
Folk 5 likelihood.tiff	Probability of seabed-sediment map – Folk 5 classification system
mud.tiff	Seabed-sediment map – mud percentage
mud IQR.tif	Seabed-sediment map – interquartile range
samples.parquet	Sample locations and values for Folk 16, Folk 7, Folk 5 and mud percentage
DINO_extractie_public_Grind_lith30perc.shp	Locations with high concentrations (>30%) of coarse sediment (gravel) at or just below the seabed. The attribute table contains columns with related information such as sampling method, measurements or estimates of the other fractions (mud, silt and sand), and NEN5104 classifications of the relevant sediment sample.
DINO_extractie_public_Schelp_lith30perc.shp	Locations with high concentrations (>30%) of shells at or just below the seabed. The attribute table contains columns with related information such as sampling method, measurements or estimates of the other fractions (mud, sand and gravel), and NEN5104 classifications of the relevant sediment sample.
BorkumseStenen_Stone_density_map_100m_UTM31N.tif	Spatial distribution of stone density at the seabed of Borkumse Stenen, mapped on a 100 m × 100 m grid
TexelseStenen_Stone_density_map_100m_UTM31N.tif	Spatial distribution of stone density at the seabed of Texelse Stenen, mapped on a 100 m × 100 m grid
Klaverbank_Stone_density_map_100m_UTM31N.tif	Spatial distribution of stone density at the seabed of Klaverbank, mapped on a 100 m × 100 m grid

Defence, Safety & Security

Oude Waalsdorperweg 63
2597 AK Den Haag
www.tno.nl