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Executive Summary

There is international political momentum for the safeguarding and conservation of biodiversity (e.g. European Marine Strategy Framework Directive; Habitat Directive; Water Framework Directive). Mapping the distributions of all representative species is not possible therefore surrogates are frequently used in mapping efforts as measures of biological diversity. In addition assessments are needed of the status of marine habitats for which the extent, area and condition of habitats needs quantification.

For practical purposes the surrogates are often organised into a classification system. A number of classifications systems have been developed applicable for various depth zones. However, the biological relevance of both the surrogates used, and the divisions or classes defined within each surrogate, are often unknown or merely assumed. Within the context of valorizing geological and geophysical data for habitat mapping, the ecological relevance of both substrate (D10.5 part A) and terrain (D10.5 part B) has been reviewed.

Sediment characterization is a stepwise, multi-faceted activity. Various characteristics can be estimated visually, measured in the field or in the laboratory, or derived from ground-truthed proxies provided by acoustic data or video imagery. An overview is given of the main methods in the context of habitat mapping, as also of the main classification schemes.

For further optimisation of habitat mapping, existing sediment databases and newly collected information could be more fully exploited. To make ‘collect once, use many times’ work, it is imperative that all available data are easily translated to common standards. Within the context of European Directives and the overall request for finer-scale products from end users, databases are made more accessible and standards are adhered to as much as possible. Key is to arrive at flexible sediment parameter mapping making use of the full potential of sediment databases. When interoperability is achieved between data and data products, it is possible to create a common infrastructure for accessing, sharing and exchanging harmonised data and data products.

To obtain reliable sediment maps, digital interpolation and probability mapping needs further investigation. Confidence intervals are needed when quantitative assessments of habitat extent and area are important. Understanding of seabed heterogeneity is critical. Full-coverage acoustic data may shed light on up- and downscaling issues, which needed when striving for increased detail and accuracy.

Different stakeholders have various needs and require differing scales and resolution of mapping products according to their application. In this report, four case studies are presented that discuss sediment characterisation as a function of some of those applications, e.g. related to fish habitats, resources and in support of seabed management (e.g. European Marine Strategy Framework Directive). The scale of the maps vary from broad to intermediate and fine-scale depending on the importance of the sediment characterisation per application and the complexity of the area concerned. The same holds true regarding the desired resolution of the dataset. An important evolution is the increasing need for process and system knowledge to steer monitoring programmes in the most cost- and time efficient way.

To best meet stakeholder requirements, flexible querying and visualisation of data are needed, together with common data access and sharing policies among international database owners and developers. Ideally, a series of linked web services would allow the uploading, viewing, downloading, updating and annotating of harmonized data and data products. Such services offer end users the flexibility to create multiple visualizations or conduct multiple analyses and select from these the ones that best fit their intended use.

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1 Introduction

Marine Knowledge 2020 brings together marine data from different sources with the aim of helping industry, public authorities and researchers find the data and make more effective use of them in developing new products and services to improve our understanding of how the seas behave. This is necessary in order to support implementation of the Marine Strategy Framework Directive (MFSD), the EU Water Framework Directive and the EU Habitats Directive. Important instruments include the e-infrastructure Geo-Seas, EMODnet and the upcoming WISE-MARINE data and information management system.

In this European perspective, two contributions are provided documenting and highlighting how geological data, focussing on sediment and terrain characterization, provide ecologically relevant knowledge about benthic ecosystems, and how these data can be standardized and harmonized. Principle methodological approaches and classification are discussed. The way different resolution of data affects the sediment and terrain characterization is investigated through case studies. Recommendations are provided on the parameters, resolution, confidence, and data query tools to be used for habitat mapping.

This report (deliverable 10.5A) deals with sediment characterization, after discussing general seabed-habitat mapping issues first. The ecological relevance of sediment data for habitat mapping is highlighted, also considering the extent to which sediments have been included in habitat classification systems. Methods for sediment characterization are reviewed next. Case studies from the North Sea, Celtic and Irish Sea are included. Finally, conclusions and recommendations are formulated. A subsequent report (deliverable 10.5B) focuses on improved terrain characterization [1].

1.1 Seabed-habitat mapping

A habitat can be considered “A particular environment which can be distinguished by its abiotic characteristics and associated biological assemblage, operating at particular, but dynamic spatial and temporal scales in a recognizable geographic area” [2]. The mapping of habitats should be considered a process in which their distribution and extents are determined to create a full-coverage map of the seabed with distinct boundaries that separate adjacent habitats. It is about mapping ecologically relevant features and goes beyond mapping purely physical characteristics (e.g. seabed-sediment maps), although the latter can be a surrogate for the habitat.

It is important to realize that a habitat map is a statement of our best estimate of habitat distribution at a point in time, making use of best available knowledge [2].

Seabed habitats have been subject to increasing pressures from human activities such as fisheries, aggregate extraction, dredging/disposal of sediment, and windmill farms. High-quality ecosystem and seabed-habitat maps are needed to spatially plan human activities and designate marine protected areas at key locations. Monitoring practices need optimization, including baseline mapping (e.g. within Europe’s Marine Strategy Framework Directive).

A first coordinated effort to produce a comprehensive guide to habitat mapping was made in 2007 as part of the Interreg IIIb project MESH (Development of a Framework for Mapping European Seabed Habitats). One of its primary goals was to provide a comprehensive overview on habitat definitions, data collection and survey design, map making, and confidence assessment. The importance of abiotic surrogate data was discussed, building bridges between physically and biologically oriented scientists. At that time, simplified seabed-sediment and marine-landscape maps were produced from simple data exchange between the biotic and abiotic worlds (Figure 2). The present document shows how data products can be made more robust, by standardizing sediment and terrain parameterization and how additional data can broaden and strengthen habitat mapping initiatives. It demonstrates the full usefulness of geo-data for habitat mapping, and provides guidance on improving sediment and terrain databases for this purpose.

Figure 1. Habitats are defined by the biological community and the physical structure that supports it [2].

1.2 Standardization and harmonization in seabed habitat mapping

1.2.1 Definition and problem statement

Data harmonization refers to the standardization of data (i.e. providing a standard structure to geographical data) so that they can be matched with other data regardless of the format. During this process data are given consistency and interoperability. Interoperability of data and data products allows the use of different databases and information to accomplish a common task. When interoperability is achieved, it is possible to create a common infrastructure for accessing, sharing and exchanging harmonized data and data products. Common standards are most easily adopted in new data-acquisition activities. The transformation of existing metadata, data and particularly data products has been found to be much more challenging.

In bringing data relevant to seabed habitats together, it is important to realise that these data have been classified in a multitude of ways, more so in the physical than in the biological sciences. In biology, classification at a species level was harmonised by Linnaeus in the 18th century. Classification at an assemblage level is less structured, but generates extensive international exchange of ideas on assemblage-diversity approaches, including Bray-Curtis similarity matrices and multi-dimensional scaling. In geology, where there are no clear breaks associated with most parameters, attempts to agree on common international classifications have mostly failed. Scientists from different regions or institutes tend to remain with familiar classifications, and database managers are daunted by a looming reclassification of enormous numbers of existing measurements and observations that are commonly still on paper rather than in a digital form.

As long as databases were used separately, or merged only at a regional level, this multitude of classification had only limited negative effects. From a European perspective, however, there is a strong and growing need for harmonized data and information. However, one should realise that data and information are only at the lower level of abstraction and knowledge should be strived at. Data on its own carries no meaning. For data to become information, it must be interpreted and take on a meaning. Increased knowledge is the final goal.

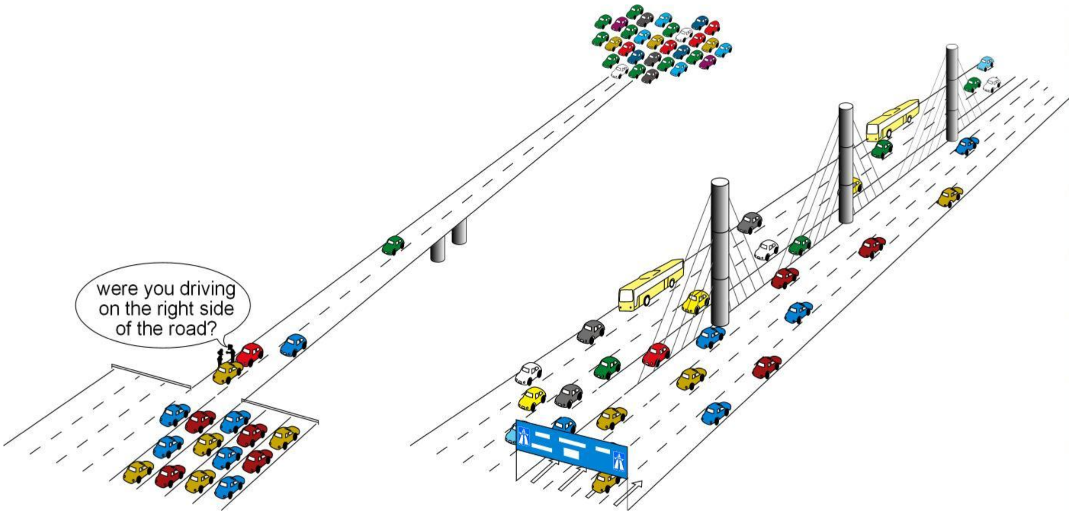

Figure 2. Cartoon of the evolution in habitat mapping approaches. From simple data exchange between the abiotic and biotic world (with lots of misunderstanding) to true multidisciplinary multi-faceted approaches, based on solid environmental databases and increasing numbers of standards.

The dynamic nature of the coastal and marine environment renders national boundaries meaningless. Therefore, effective integrated coastal and marine management requires a transnational to international approach. Common, internationally agreed metadata, data formats, acquisition and analytical protocols, classification and reference systems, quality standards and flags are all key elements in a harmonisation of effort toward uniform data and data products (including habitat maps). .

Mis-matches caused by a lack of harmonisation are difficult to identify from databases directly, but become apparent immediately when data are visualized. Mismatches are most commonly visible along borders of neighbouring countries, due mainly to differences in sampling methodology, analytical techniques and classification and data interpretation.

This pleads for transnational cooperation in finding common solutions to distinguish perceived from real mismatches in datasets. This becomes most challenging when data are qualitatively available only (e.g. visual sediment descriptions) and need transformation into digital data products.

1.2.2 Classification and interpretation issues

In seabed habitat mapping, surrogate data are usually **classified**, e.g. for different parameters cut-off values are chosen to delineate certain classes that are inferred to be relevant for habitat mapping. Classification is most often based on ‘expert judgement’. In this subjective approach, classification follows not from quantitative analysis, but from qualitative system knowledge. Alternatives to this approach are 'random' classification (i.e. defined earlier for a different purpose), and statistics-based classification. Statistical techniques are used mainly to quantify relationships among various biotic and abiotic processes and parameters. They are also very useful in calculating the optimal number of classes and the values of class breaks for a particular dataset or study area. Classes and class breaks can be defined manually or by using software (blind). The range of classification techniques and the infinite number of potential classes and class breaks highlight the need for harmonization.

Even when data acquisition, analysis and classification are carried out consistently, resulting in harmonised data, differences in **data interpretation** (translating data into information) can still result in mismatches of data *products*. Therefore, a consistent use of **abiotic variables** (e.g. substrate, bathymetry, energy and related variables), while essential to ensure harmonised data in habitat-mapping studies, does not ensure harmonisation of data products. Selecting abiotic surrogates is not always straightforward. The variables have to be ecologically relevant, but in some cases the relationships between the physical and biological data are not known. In those cases providing multiple visual data products for a particular dataset may aid the process.

1.2.3 Common habitat classification schemes

Habitat classification schemes are devised to define habitats in a consistent way, such that similar data can be consistently assigned to particular habitat types and data may be compared between geographic areas and/or over time. Different habitat classification schemes exist because the way the environment is sub-divided is linked to the end-user's requirement. Habitat classification schemes are often hierarchical such that broadly-defined habitats are subdivided into finer and finer units to suit end-user needs for differing levels of detail [2].

The **European Nature Information System (EUNIS)** is the most commonly known habitat classification scheme (Figure 3). It is developed and managed by the European Topic Centre for Nature Protection and Biodiversity (ETC/NPB in Paris) for the European Environment Agency (EEA) and the European Environmental Information Observation Network (EIONET).

EUNIS is a hierarchical habitat classification system providing a comprehensive typology for the habitats of Europe and its adjoining seas (http://eunis.eea.europa.eu/habitats.jsp). It distinguishes six hierarchical levels and discriminates between marine habitats, largely based on the concepts of biological zone (littoral, infralittoral, circalittoral etc), substrate type, hydrodynamic energy (i.e. wave exposure, tidal strength), environmental variables (e.g. salinity) and characterizing species.

Figure 3. Examples from the EUNIS hierarchy. The example on the left is a sediment environment and illustrates that level 4 can be attained by modelling using physical data layers only. The example on the right is a rocky environment and shows that to predict to level 4 of EUNIS cannot be done with physical data alone and requires community data [3].

On a broad-scale, seabed habitat maps have been produced following the EUNIS scheme. Most recently, a consortium of partners from across four Marine Regions (Baltic, North, Celtic and western Mediterranean Seas) (EUSeaMap [3]) produced a harmonized seabed map for the entire area. The product built upon the results of the INTERREG projects MESH [2] and BALANCE (www.balance-eu.org) [4], by harmonizing and improving methods used in both projects and extending the methodology to the western Mediterranean basin. Through expert application of the EUNIS classification and improved input data layers and seabed habitat modelling techniques, existing maps were improved upon and refined [3].

On a more detailed scale, the realm of classification schemes expands drastically and, mostly, only locally valid schemes are applied. These are rarely based on standardized geological parameters (e.g. sediment and terrain related). Providing guidelines and recommendations for more common approaches is timely. Challenge remains to arrive at common denominators that are no over-simplifications of reality and remain useful for national seabed management purposes. Five dimensional mapping and modelling digital applications allow setting-up multiple scale data products, flexible designed to meet various end-users' needs.

1.2.4 Towards standardized data products, fit for purpose

Different stakeholders have various needs and require varying scales and resolution of mapping products according to the application. The larger the scale of interest, the less conflicts are expected in joining datasets. However, for joining finer scale mapping products over larger areas, data standardization and harmonization is a prerequisite.

Figure 4 provides an overview of some stakeholder applications in 3 main categories: seabed management, industry and science. Each of them has applications on the broad-, intermediate and fine-scale.

Related to seabed management, habitat mapping information is needed to support the aims and implementation of several international policy instruments, including: EC Habitats Directive (1992); North Sea Ministerial Declaration (1996); EC Water Framework Directive (2000); EC Strategic Environmental Assessment Directive (2001); OSPAR Biodiversity Strategy (2003); EC Maritime Strategy (2007); and EC Marine Strategy Framework Directive (MSFD) (2008). For the latter habitat information is needed for regional to national assessment and monitoring of habitat extent, area and condition. Habitat mapping supports the production of fisheries maps and stock evaluations. It provides additional insight into the amount and quality of exploitable non-living resources. Marine protected areas need delineation based on best available data, at the most appropriate scale. Finer scale mapping approaches allow directly visualising some areas of highest biodiversity.

Industry applications relate mainly to offshore wind energy, marine aggregates or pipeline inspections. From a scientific perspective, habitat mapping provides a basis for increased process and system knowledge, and assists in unravelling biotic-abiotic relationships.

	Seabed Management	Industry	Science	
500 m	**Fisheries** **Regional Assessments**	**Offshore Energy**	**Climate change**	Megahabitats *Landscapes*
50 m	**Resource estimations** **Monitoring**	**Windmill foundation** **Marine Aggregates** **Cables and Pipelines**	**Biotic-abiotic relationships** **>> Habitat Suitability Modelling**	Habitats (Communities) *Probability distributions* *% Cover*
<5 m	**Conservation: MPA's** **Biogenic reefs** **Cold water seeps** **>> MSFD**	**Scour around Pipelines**	**Process studies**	Species *Species distribution*

Figure 4. Examples of stakeholders' needs for seabed habitat mapping.

Clearly, stakeholders are interested in all spatial scales. As such flexible querying and visualization of data are needed. In addition, common data-access and -sharing policies need to be developed among international database owners and developers. Ideally, a series of linked web services would allow the uploading, viewing, downloading, updating and annotating of harmonized data and data products. Such services would offer end users the flexibility to create multiple visualizations or conduct multiple analyses and select from these the ones that best fit their intended use.

2 Sediment Characterization

2.1 Introduction

Every sediment is a mixture of grains of varying sizes and cannot be characterised by a single parameter or proxy. These are simplifications of reality and may not always be representative of the true nature of the seabed. Still, because of limitations in sediment databases, such simple parameterisation is still most often the only option available,.

Even for these simple proxies there have not been uniform standards. There have been different definitions of terms used for the different sizes of individual grains and similarly differing definitions for the terms used to describe the relative proportions of different grain sizes [5]. As such, there are numerous different sediment classification schemes.

For the mapping of substrates or the nature of the seabed (e.g. rock, sand, mud, boulders) most sediment classes are mapped along a scale based on the grain size (e.g. the Wentworth scale, see below) or on the relative proportions of silt, sand and gravel (e.g. the Folk triangle, see below). Both classifications simplify the continuum. The inherent consequence of simplification is a loss of information, which may or may not be critical to habitat mapping. For example the Wentworth scale refers to mean grain size, which is a very poor representation of mixed sediments (e.g. for diamictons, consisting of a wide range of non-sorted to poorly sorted sand or larger size particles, suspended in a mud matrix).

In any case, the critical substratum characteristic will vary considerably between species and habitats and specific continuous variables, such as percentage silt or median grain size may be more biologically meaningful and thus more suitable for habitat modelling purposes. Some of these variables may be derived from remote sensing data through expert interpretation or through automated classifications.

State-of-the-art sediment databases eliminate the need for simplification, because they allow the storage of a more complete description of sediments (e.g. full distribution grain-size curve data). These new databases enable experimenting with different parameters or proxies. In the following section, an overview is given of the traditionally used methods for sediment characterisation, focussing on internationally agreed standards.

2.2 Methods for sediment characterization and relevance to habitat mapping

2.2.1 From observation and sampling to surrogates: a multi-faceted approach

Sediment characterization is a stepwise, multi-faceted activity. Various characteristics can be estimated visually, measured in the field or in the laboratory, or derived from ground-truth proxies provided by acoustic data or video imagery. In developing surrogate maps for seabed-habitat studies, remote observation, sampling, sub-sampling, description, analysis, classification and even interpolation may all be included (Figure 5). Each of these steps can take place in many different ways. The choice of methods is partly a function of equipment availability and cost, but also reflects suitability to particular field conditions or sediment types. In light of this fact, it is not surprising that many characterization standards and protocols exist side by side. When bringing together large, broad-scale datasets collated by many research institutes over an extended period of time, the number of standards represented is virtually limitless. Even when each task is carried out according to a single standard or protocol, as is the case in some on-going state-of-the-art mapping efforts, the number of standards and protocols is at best equal to the number of tasks undertaken.

Classification schemes, which are an integral part of sediment characterisation, have also varied. To understand this variability, both through time and between countries and continents, the rationale behind classification must be considered. Until recently, the focus on classification was not on broad-scale harmonisation, but on optimised schemes that worked best for a particular purpose. Generally, fine-scale studies of relatively uniform areas required a more differentiated classification than broader-scale studies with abundant contrasts in seabed types. As classifications were designed for purposes other than seabed mapping, commonly not even with the marine realm in mind, they do not necessarily provide a good fit for habitat studies.

When considering these standards and classification in the context of seabed-habitat mapping, one must be aware that each characterisation and classification standard has its advantages and limitations. Pros and cons depend on the size and nature of the area studied. As they do not work equally well in all areas, field and analytical methods cannot be applied universally, which explains why there is no common agreement on the system of preference. Clearly, complete harmonisation of all standards and protocols for data acquisition and sample description and analysis is impossible. Broad-scale studies in particular face the challenge of having to bring together data that are not harmonised. Harmonization efforts in these studies should focus on aspects of classification, which can be done best when the standards and protocols used to collect, describe and analyse data are clearly reported in the associated metadata. A harmonized classification is useful only when classes and subclasses are defined at different levels. Such a tiered system provides the flexibility to serve both broad- and fine-scale mapping initiatives.

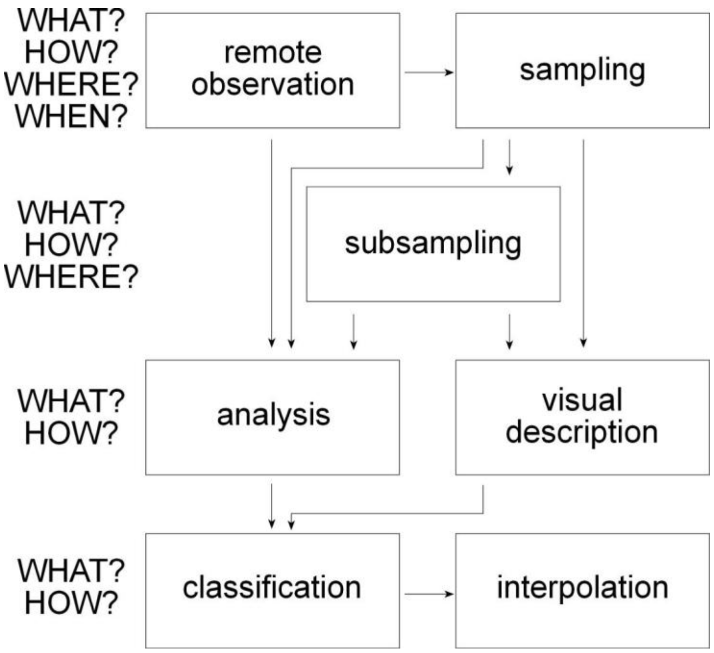

Figure 5. Elements of sediment characterisation and surrogate mapping.

2.2.2 **Remote observation, sampling and sub-sampling**

In both fine- and broad-scale mapping, remote observations and sampling are used to determine sediment characteristics. Depending on the type of remote sensing and sampling methods used, certain characteristics will be more easily and accurately described than others. In a logical flow, and with appropriate means, remote observations are first carried out, followed by sampling based on the outcome of the remote sensing. Sediment characteristics are then measured indirectly.

Remote observations of sediment characteristics

Malthus and Mumby [6] described the challenges of applying remote sensing in the coastal zone highlighting the use of airborne multispectral or hyperspectral technology for sediment characterization. Generally, the relationship between the reflected sunlight and soil properties (e.g. organic matter, soil moisture, soil salinity and grain-size distribution) is widely accepted, e.g. [7] and from this the fine spectral and spatial resolutions of airborne sensors offer optimal capabilities for sediment monitoring. For examples see [8] and [9]; the latter mapping sandy and clayey sediments in the Ribble estuary (UK) using the Daedalus 1268 Airborne Thematic Mapper (ATM). In [10], the CASI scanner is used in a mode with 14 spectral bands to classify the vegetation and sediments into 10 classes representative for the Wash at the East Coast of England. In everyday practice, the combined use of airborne hyperspectral and airborne LiDAR data remains highly innovative.

Likewise, the acoustic backscatter (e.g. from side-scan sonar, single-beam or multibeam technology) is function of the intrinsic nature of the seafloor (e.g. compaction, porosity, sorting, and grain size) and in the case of very-high resolution imagery, sediment types can be mapped in a continuous way, e.g. [11] [12]. Classification of acoustic data is increasingly performed (e.g. [13]), but still discrimination of subtle sediment gradients is not straightforward in an automated way. Reviews are available on optical and acoustic surveying and classification, in combination with adequate ground-truthing in view of habitat mapping [14].

Monteys et al. (Case Study 2, this report) explore the applicability of a generalised backscatter-sediment grain-size model for a range of seabed scenarios by using illustrative case studies from shallow waters. It employs simple and robust statistical assumptions, and attempts to draw general guidelines for using and interpreting backscatter data, particularly in the benthic habitat mapping context. It also briefly discusses model limitations, and potential error sources. Methods are discussed that are used in such analyses, together with the rationale employed when extracting statistical parameters from multibeam backscatter data; sediment textural parameters from seabed samples; and when deriving, empirically, the statistical relationships. Results identified variability in backscatter behaviour depending on seabed type. Soft, fine-grained sediments exhibit strong linear correlations that can be used with confidence when mapping seafloor grain-size properties. In hard substrates the backscatter data signatures are more incoherent, dependent upon the general hardness and textural seafloor parameters of the seafloor. When full-coverage mapping is procured, intermediate- to fine-scale sediment maps can be produced, albeit in combination with ground-truthing.

Information derived from backscatter in this manner has potential applications in a range of marine disciplines including geotechnical mapping, environmental monitoring and, not least, marine habitat mapping.

In any case, the choice of instruments and the settings used depend on the question which sediment characteristic must be measured. Do we need to visualise fine-scale and subtle sediment gradients or broad-scale and coarse variability? Usually, full-coverage mapping is not feasible on a broad-scale. In selecting smaller areas for full-coverage characterisation or larger areas with partial coverage, the aim is to capture all relevant spatial variability in sediment characteristics. The choices made will determine the end result, which will always include elements of interpolation and up-scaling (Figure 6). Choices of location can be optimised by relying on existing data, if available, and on geological expertise in the form of conceptual models and system knowledge. The time and timing of data acquisition also matters. Obviously, all acoustic data must be calibrated, preferably using seabed samples collected specifically for this purpose.

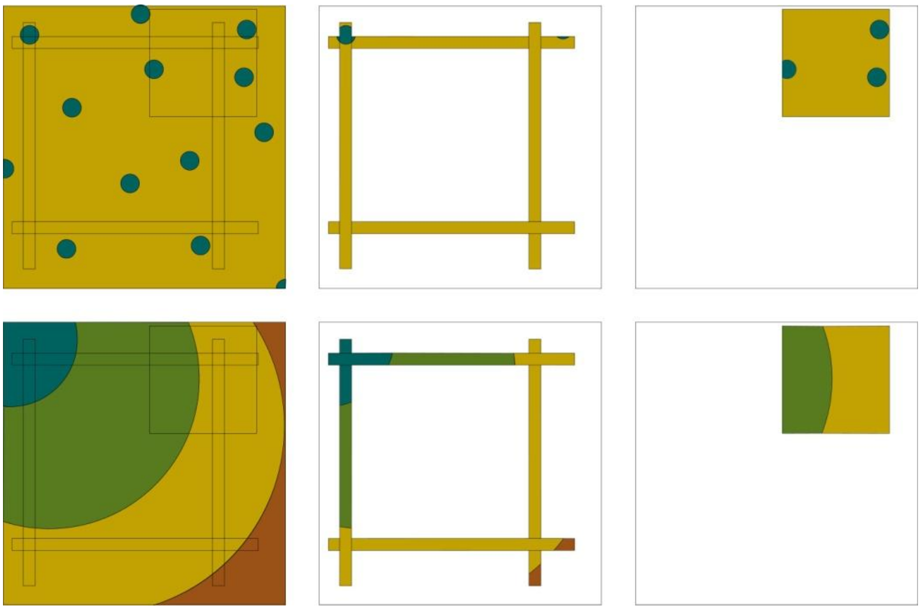

Figure.6. Characterizing seabed variability (left panel) by interpolating partial-cover remote-sensing images (middle panels) or up-scaling of smaller scale full-coverage remote-sensing images (right-hand panels). For laterally continuous patchy areas, full-coverage data acquisition in small subsections may be more useful than surveying along grids. For areas marked by broad-scale changes, the reverse is true.

Sampling and sub-sampling

Seabed samples provide a direct measure of surficial sediment characteristics. There are many different sampling instruments, both hand-operated and mechanical. Some are more suitable for gravel (e.g. Harmon grab) whereas others are better equipped to collect loose sand (e.g. Van Veen grab) or cohesive fine-grained material (e.g. box core). Depending on the purpose, instrument availability, vessel capabilities and cost, a range of instruments may be employed to take either undisturbed samples, which preserve the stratification and other sedimentary structures, or disturbed samples. In practice, it is difficult to take fully undisturbed seabed-sediment samples as the pressure wave and impact of the instrument, upon hitting the bottom, cause a loss of the finest fraction.

Sampling results in point data that commonly do not allow capturing the spatial variability of sediment characteristics. Given this limitation, the choice of sample locations and distribution is crucial (Figure 7). Where acoustic or video data are available, sample locations can be chosen optimally as a function of seabed variability. Elsewhere, knowledge on other seabed parameters (such as depth) and overall geological expertise may be used to obtain the maximum amount of information from a particular number of samples. A random or evenly spread sample distribution is rarely the best option.

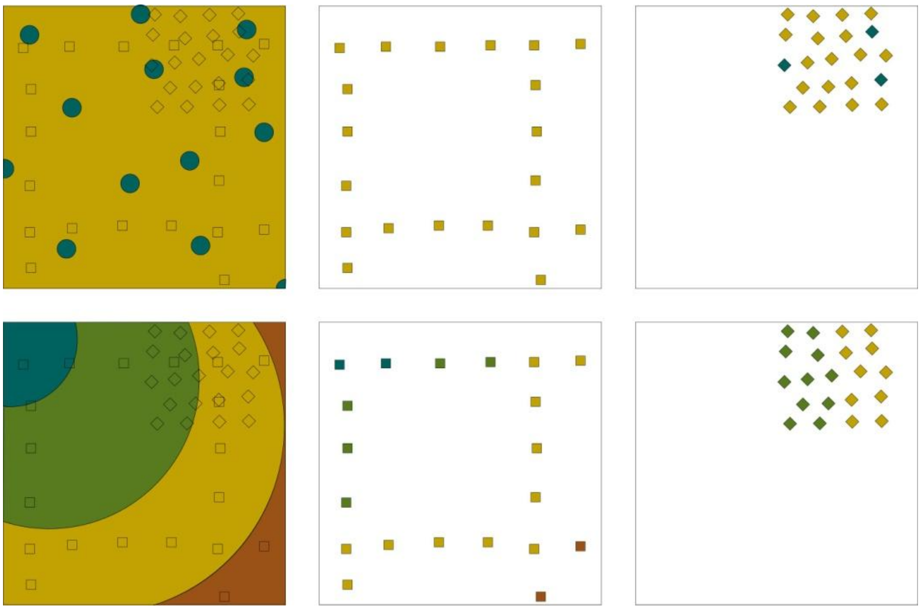

Figure 7. The location and distribution of samples will determine how well the resulting data product captures reality.

Once samples have been taken, they can be described directly or described and analysed following sub-sampling. Sub-sampling is needed when samples are too big for complete description or analysis. Generally, more material can be described visually than can be measured with field or laboratory instruments. The type of sub-sample taken depends on the purpose. For grain-size analysis and sediment composition, both relevant in habitat mapping, sub-samples need to be taken that are representative for the entire sample. This may be difficult, especially when a few coarse clasts are present in a matrix of fines. In small sub-samples, even a single clast may over-represent its size class in the analysis. When no clast is included, it may appear that the sample consists of fines only. The volume of a sub-sample needed to accurately describe or analyse a sample or sub-sample depends on its grain size. For muds and sands, less than 100g is sufficient to carry out particle-size analyses. When gravel-sized particles (including shells and shell fragments) are present, larger volumes are required for representative granulometric measurements. Clearly, different-sized sub-samples should be taken for different analyses, and it is commonly best to assess or measure the coarser gravel fractions before sub-sampling (Table 1).

Table 1. Volume of sediment needed for accurate grain-size measurements [15].

Maximum size of material present in substantial proportion	**Minimum mass of sample to be taken for sieving**
2mm	100g
6.3mm	200g
10mm	500g
14mm	1kg
20mm	2kg
28mm	6kg
37.5mm	15kg
50mm	35kg
63mm	50kg

2.2.3 Description, analysis and classification

Standards for each nation

Many parameters contribute to the sediment characteristics of samples and sub-samples. All of these parameters, including sediment composition, grain size, stratification, and geochemical and geo-mechanical properties, can be assessed or measured in a variety of ways. Generally, and particularly in national seabed-mapping programs, sediment samples and sub-samples have been described and analysed according to internal standards. Expanding reference collections, improved description methods and better and novel analytical instruments have had a positive impact on data quality, allowing ever more detailed characterizations. At the same time, end users are usually unaware of the limitations inherent to many methods, even in direct analysis of sediment. A good example is the measurement of grain size with various laboratory instruments. For a single sample, the grain-size distribution ‘depends’ on the analytical instrument and protocols used (Figure 8). Fine particles may form aggregates upon drying in an oven, and naturally formed aggregates may be broken up by various pre-treatment methods. When indirect proxies of grain size are measured, translating the results to grain size is prone to error. Some models routinely applied to translate laser measurements filter out the fine tails of the grain-size spectrum, thus underestimating mud content. Even when grain size is measured directly, non-spherical particles may skew the results.

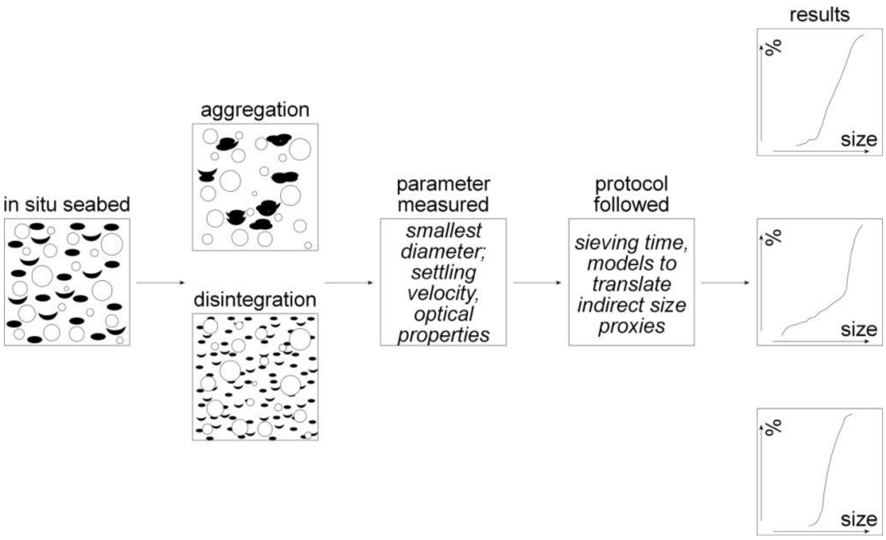

Figure 8. Grain-size distribution curves as a function of sample preparation (with aggregation or disintegration of floccules and faecal pellets), instrumentation and protocols.

Like the standardisation of methods of sediment description and analysis, the associated classification has long been governed nationally, or even institutionally, to meet area-specific requirements. For more than a century, there have been efforts to propose a small number of classification systems with broad validity and relevance, but these have been adopted mainly in the academic realm, where transnational communication and collaboration was more common than in seabed-mapping programs. Even the most successful classification schemes adopted by the academic world have been subject to various modifications to better match the needs of research and mapping. In addition, the increased use and importance of acoustic data and video imagery has necessitated the development of a whole new suite of common classification schemes and protocols.

Existing characterisation and classification issues

The main characterization and classification issues, relevant to seabed-habitat mapping, relate to: (1) visual sample description, which is primarily useful in broad-scale mapping (e.g. EUNIS Level 3); (2) grain-size analysis, which has added value when zooming in on areas where sediment variability is relatively subtle (e.g. species- and habitat-suitability modelling); and (3) acoustic sediment classification, which is particularly useful to characterize patchiness (e.g. from multibeam imagery). The first two provide point observations that need to be interpolated in the creation of habitat maps. The third characterization method provides full-coverage information that needs to be validated by sample descriptions or analyses.

Visual descriptions of cores and grab samples form the backbone of most existing marine geological databases. Generally, descriptions provide more text than numeric values or code. In an increasing number of institutes, text, commonly expressed as parameter characteristics in distinct classes, is transferred to numeric values or code in a process named *parsing* [16]. It may be difficult, however, to link terminology used in text fields to accurate definitions. In the worst-case scenario, terms are poorly defined, and definitions absent. More commonly, well-defined standards have been used, but are not listed in the metadata. When standards have changed in the course of time, it may be difficult to reconstruct which standard was used for a particular visual description, particularly if the metadata do not provide the date of sample description. Even when standard protocols have been followed for uniform descriptions, and are documented in metadata fields, visual descriptions include an inherent component of subjectivity because each geologist is different, and because a well-rested geologist will make a different description than the same geologist when tired or pressed for time. The associated inaccuracy is difficult to quantify. Because of all these limitations, visual descriptions are most useful for, and most commonly used in, broad-scale habitat mapping where harmonisation is carried out at a rather general level. For certain areas, they provide the only sedimentological data available; elsewhere, they are valuable in the interpolation between higher-quality data points (Figure 9).

Any translation from text fields in core descriptions results in a so-called parsed dataset. The values in the parsed data file may be calculated automatically. In the United States the dbSEABED parser was developed [16] [17], assigning field values based on the form and content of a description. Although at first sight the descriptive results in a parsed file may seem less accurate than measured values in the extracted file, they are frequently more representative of the sample and seabed as a whole, as they include descriptions of objects such as shells, stones and other objects that are a textural component of the seabed and that are commonly left out of laboratory analyses.

In many countries, field or laboratory measurements on geological samples are much less abundant than visual descriptions. They add important information on grain-size distribution, age, depositional environment, geotechnical behaviour and chemical composition of the sediment. Commonly, more than one technique is available to analyse a specific characteristic. The methods with which sediment parameters are analysed have also changed and improved in the course of time. The inaccuracy of the analyses is systematic and thus easier to quantify than that of the visual descriptions. Nevertheless, it may be difficult to compare results obtained from one method with those from another.

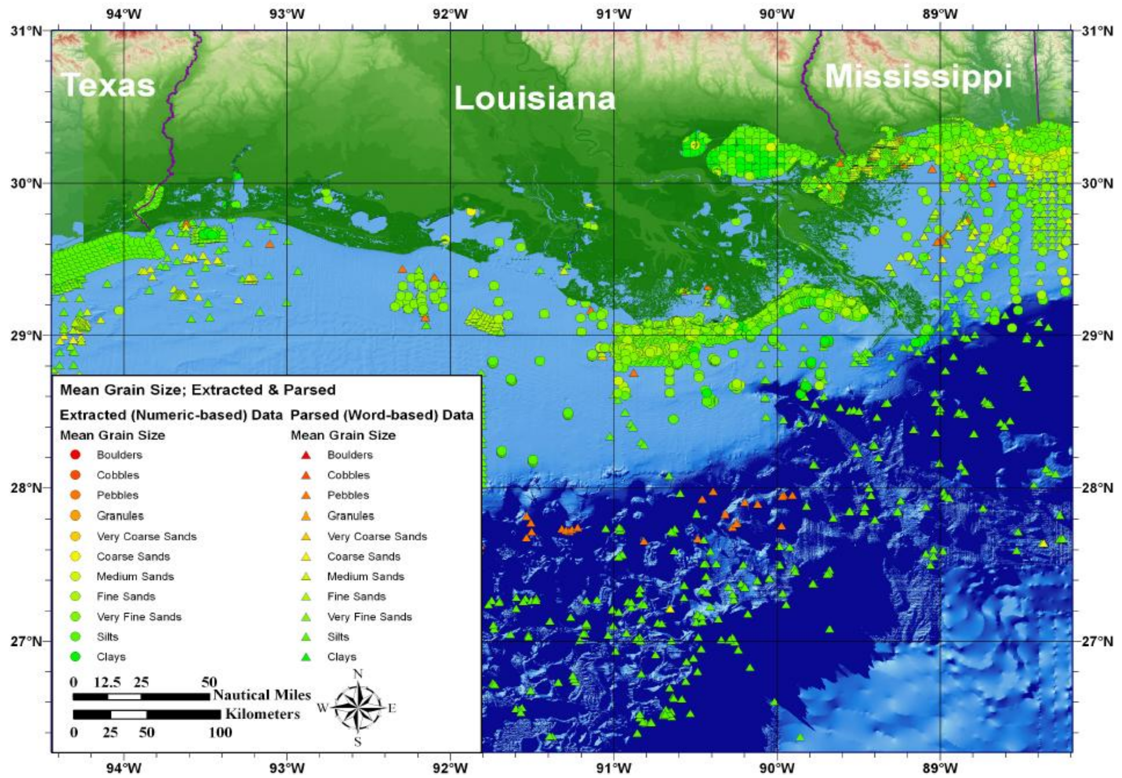

Figure 9. Combination of numeric-based and parsed data for the north-central Gulf of Mexico [17]. Beyond the shelf break and in some areas on the shelf, little or no numeric-based data are available.

Sediment type

Sediment type can be defined from visual observations and from grain-size measurements. It is defined by main lithology and secondary admixtures. The term main lithology refers to the dominant clastic (formed of particles) or organic component in a sediment sample. The most common organic units are gyttja (organic mud consisting of decayed micro-organisms, plant remains, aquatic animals and their faeces) and peat (partially decayed vegetation matter). Clastic units are more diverse. They are described using different classification systems that focus primarily on particle size, the most basic attribute of sediment. Typically, they use broadly the same terminology (be it in different languages), but commonly with different class boundaries and definitions.

The main size categories of clastic sediment are gravel, sand, silt and clay (lutum), which may be subdivided into several subcategories by using modifiers such as fine, medium and coarse. Silt and clay may be grouped as mud. Next to size, the composition of particles is also an element of main lithology, but its use is limited. In the gravel fraction, shells and shell fragments (bioclastic gravel) can be distinguished from siliciclastic clasts (Figure 10). Examples of clastic terms related primarily to composition are shell hash and ooze. The latter being deposits of soft mud on the ocean floor.

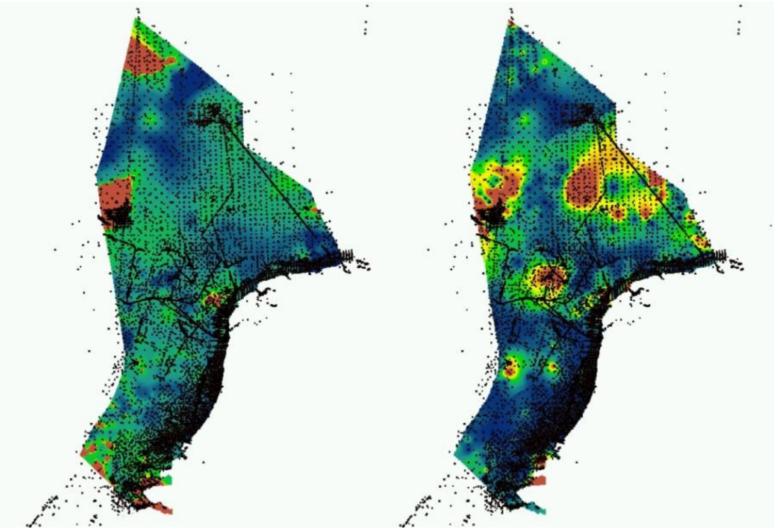

Figure 10. Percentage siliciclastic (left) versus biogenic (right) gravel in the Dutch part of the North Sea. Values decrease from red (>30%) to blue.

Usually, main lithology is not sufficient for characterisation purposes. Most sediments include sizable admixtures of secondary material. Sediments consisting of different clastic components or size fractions are described using various classification systems, not always with different terminology, but commonly with different class boundaries.

In the international academic world, most sedimentologists use the classification systems developed by Shepard [18] and Folk [19] [20]. Shepard [18] made a subdivision using a single ternary diagram with sand (63-2000 µm), silt (4-63 µm), and clay (<4 µm). Since it did not include gravel (>2000 µm), Schlee [21] later modified his scheme and added a second ternary diagram with silt and clay, sand, and gravel (Figure 11). The most commonly used system today is the Folk classification [19], labelling sediment using the relative proportions of its gravel, sand and mud (defined as silt and clay) percentages (Figure 12). In his classification, Folk tried to incorporate a link to maximum current velocity at the time of deposition. Gravel concentration is an indicator of this parameter. Although Folk also used a second ternary diagram to differentiate between clay, mud and silt for non-gravelly sediments, this latter refinement is used much less frequently. It is more challenging to assess the relative proportions of these size fractions accurately in visual descriptions.

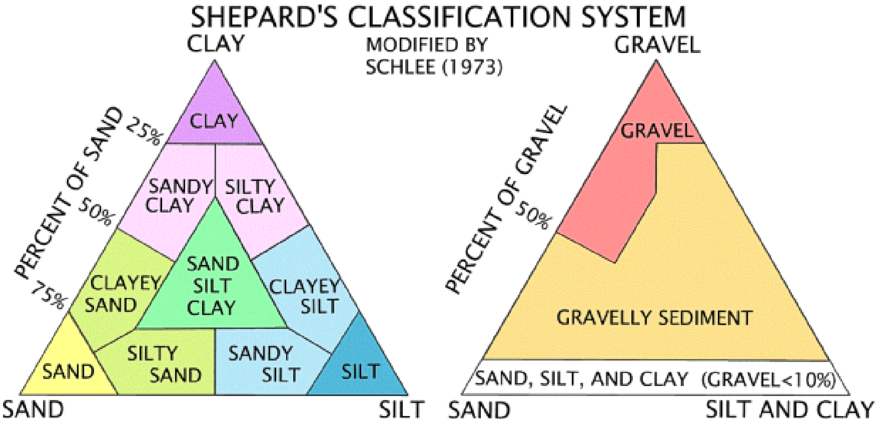

Figure 11. Classification of clastic sediment according to Shepard [18], with modification by Schlee [21] on the right.

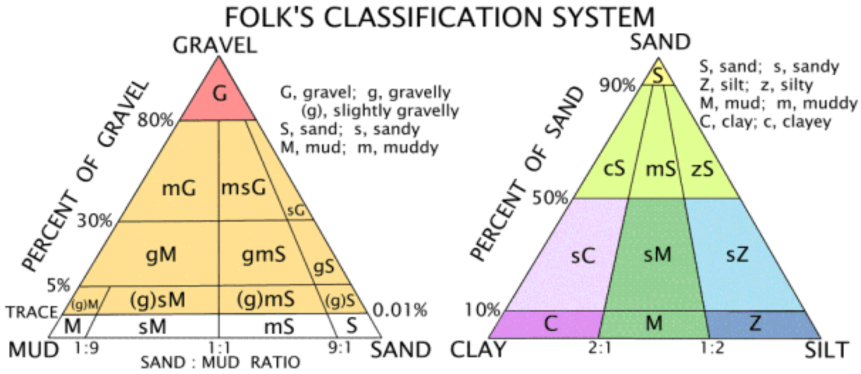

Figure 12. Classification of clastic sediment according to Folk [19] [20].

The Folk terms provide a lot of information without being a complete description and are therefore very useful and understandable for a majority of end users. To optimise the classification, the British Geological Survey changed the percentage gravel subdivision line at 'trace' to a percentage gravel subdivision line at 1% as part of their seabed-mapping programme. As this program was a transnational effort that included contributions from the Dutch and Belgian geological surveys from the 1970s onward, this modified Folk scheme provided a common legend for several transnational 1:250,000 seabed-sediment sheets. Although each organisation continued to carry out the underlying sediment characterization according to its own national standards, core-description protocols had been documented for decades and mapping to Folk was possible. A more recent modification that was also widely adopted was proposed by Flemming [22]. In classifying gravel-free (<1%) muddy sediments, he defined six sediment types on the basis of mud and sand content: sand (<5% mud), slightly muddy sand (5-25% mud), muddy sand (25-50% mud), sandy mud (50-75% mud), slightly sandy mud (75-95% mud) and mud (>95% mud) (Figure 13).

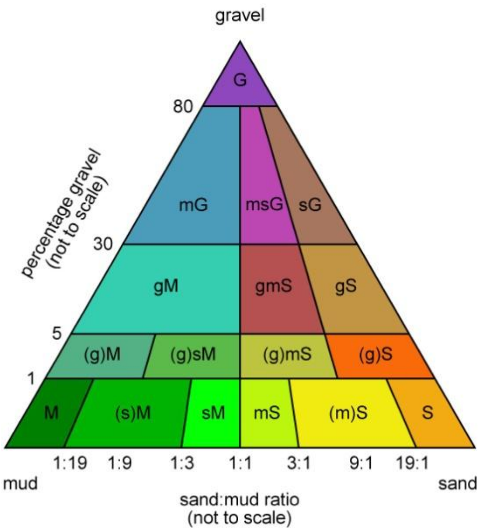

Figure 13. Modified Folk classification (used by the British Geological Survey for their 1:250,000 scale seabed sediments map series and DigSBS250 digital dataset), further adjusted by Flemming [22].

In the conversion from locally-used terminology to the Folk classification (as modified by the British Geological Survey and by Flemming (Table 2)), being the approach recommended for harmonisation of visual descriptions and laboratory granulometry, two translation options are possible (Figure 14 – plot point and area (from Dutch classification) on Folk). When gravel, sand and mud percentages are listed (for example 20-10-70%), they can be plotted directly on the ternary diagram, giving a single class as output (in case of the example, gravelly mud). When information on gravel, sand and mud content has to be derived from code or from text fields (for example, moderately gravelly, clayey silt), the translation depends on the availability of the associated term definitions. When these definitions are available (for example, moderately gravelly means 5-15% gravel), mapping can be based on this constraining information. This translation is less precise than the classification based on numerically expressed relative proportions. When such definitions are not available, mapping is based on assumptions and therefore even less accurate. The latter is particularly true for diamicton: poorly sorted clastic sediment in which gravel-sized and larger clasts are set in a matrix of fines.

Table 2. Modified Folk classification as expanded by Flemming [22]. Adopted as Geo-Seas standard.

Sand:mud ratio	Gravel percentage	Folk class	Code
<1:19	<1	mud	M
1:19 to 1:3	<1	slightly sandy mud	(s)M
1:3 to 1:1	<1	sandy mud	sM
1:1 to 3:1	<1	muddy sand	mS
3:1 to 19:1	<1	slightly muddy sand	(m)S
>19:1	<1	sand	S
<1:9	1-5	slightly gravelly mud	(g)M
1:9 to 1:1	1-5	slightly gravelly sandy mud	(g)sM
1:1 to 9:1	1-5	slightly gravelly muddy sand	(g)mS
>9:1	1-5	slightly gravelly sand	(g)S
<1:1	5-30	gravelly mud	gM
1:1 to 9:1	5-30	gravelly muddy sand	gmS
>9:1	5-30	gravelly sand	gS
<1:1	30-80	muddy gravel	mG
1:1 to 9:1	30-80	muddy sandy gravel	msG
>9:1	30-80	sandy gravel	sG
all ratios	>80	gravel	G

To accommodate for non-siliciclastic components in siliciclastic sediments, additional modifiers are used. There is no single standard with international acceptance for terminology and associated ranges. Peat, for example, is used in the Netherlands for sediment containing at least 25% organics. Elsewhere, minimum values up to 50% are used, e.g., [23]. The International Peat Society uses 30% as the lower limit. Terms like slightly peaty (5-10% organics in the Netherlands) and peaty (10-25% organics in the Netherlands) are even less well defined. Harmonisation is needed. In Geo-Seas, a subdivision into 5-10%, 10-25% and >25% has been proposed. Also, clear international standards do not exist for admixtures of shell and shell fragments. In addition, fragmented shell material is rarely quantified accurately for the sand fraction, and even for the gravel fraction such quantifications are limited. As biogenic sand and gravel behave differently from their siliciclastic counterparts under similar hydrodynamic conditions, there are different implications for depositional environment and bed stress. In Geo-Seas, a classification into little (1-10%) and much (10-30%) has been proposed. Sediments with more than 30% shells are classified as shell beds.

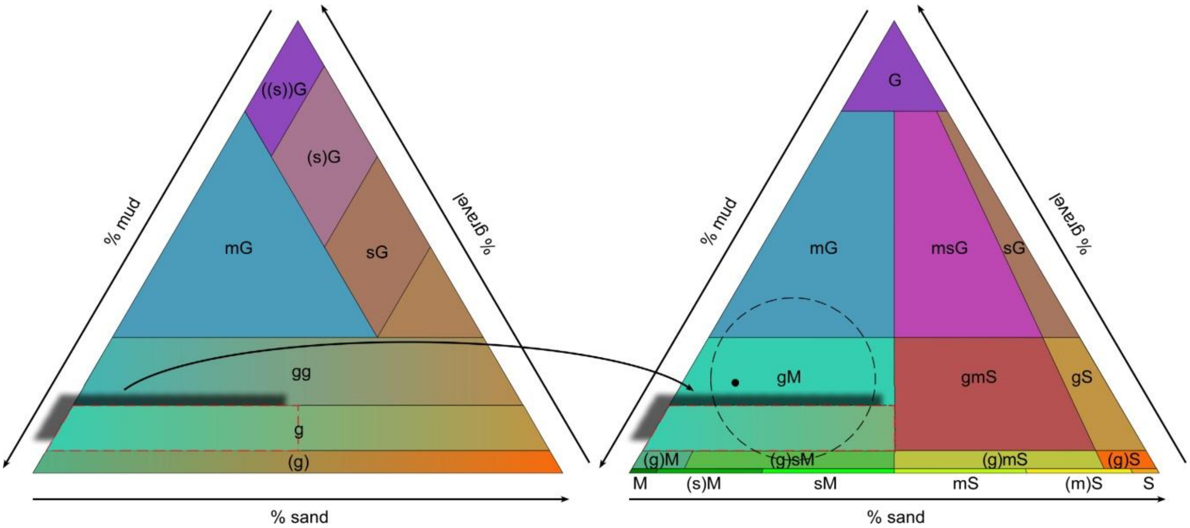

Figure 14. Conversion from local terminology to adjusted Folk classification. Black dot in the Folk diagram on the right denotes a sample description for which gravel, sand and mud percentages are available. Shaded zone in the local classification diagram on the left (NEN5104 norm in the Netherlands), as transferred to the Folk diagram, denotes a sample description for which the gravel, sand and mud ranges are known. Dashed circle in the Folk diagram denotes a sample for which only a textual description of sediment type exists, without a proper definition of its meaning in terms of gravel, sand and mud percentage ranges. Note that the Folk diagram is here to scale, and therefore differs from previous figure.

Grain size

Although grain-size distribution may be determined semi-quantitatively from visual observation, it is best measured using laboratory instruments. Descriptions and measurements of grain size provide the relative abundance of different fractions. Usually, descriptions include text (coarse classification), as well as numeric values (finer classification). From this information, various secondary parameters may be derived, including range, mode (most frequently occurring particle size), median (midpoint of the grain-size distribution) and mean (arithmetic average of all particle sizes in a sample) values, sorting, skewness (asymmetry) and kurtosis (peakedness). In visual descriptions, sorting is commonly determined using an estimation chart (e.g. [24]). This chart allows the distinction between very well-sorted, well-sorted, moderately sorted and poorly sorted sediments, as well as between bimodal sediments. Well-sorted sediments are generally porous, whereas poorly sorted sediments have lower porosity.

Measured grain-size distributions can be obtained through a range of methods addressing either weight or volume of grains per fraction, including sieve analysis, photo-analysis, optical counting, electro-resistance counting, settling-tube analysis, and laser-diffraction analysis. Each of these methods, and associated protocols, will result in a (slightly) different parameterisation of the sediment characteristics; hence, metadata are critical when merging multiple datasets. Comparisons between sieve analyses and laser-diffraction measurements (e.g., [25] [26]) show that the largest differences are associated with the silt and clay fractions.

Traditionally, most end users of grain-size data have worked with a small selection of primary parameters (mostly sand, mud and gravel percentage) and with a limited number of secondary parameters (e.g. median grain size or d50) as listed above (Table 3). These parameters can be determined graphically (read directly from cumulative-frequency curves at five points (5, 16, 50, 84, and 95 percentiles; [27]) or be calculated using the method of moments ([28] [29]). In open-ended distributions, applying the method of moments is probably not justified [20]. Also, some terms, such as median grain size, are loosely applied and may therefore give rise to error. Some organisations describe the median grain size of the sand fraction, whereas others also include gravel and mud. Usually, such differences in definition are not noted until supposedly harmonised data from different data owners are visualised (Figure 15).

Table 3. Overview of classes of sediment sorting, skewness and kurtosis (Folk, [30]). Adopted as Geo-Seas standard.

Sorting classes		**Skewness classes**		**Kurtosis classes**	
standard deviation	descriptive term	skewness	descriptive term	excess kurtosis	descriptive term
<0.35Φ	very well sorted	>+0.30	strongly fine skewed	>0	leptokurtic: sharp-peaked
0.35 to 0.50Φ	well sorted	+0.30 to +0.10	fine skewed	0	mesokurtic: normal-peaked
0.50 to 0.71Φ	moderately well sorted	+0.10 to -0.10	near symmetrical	<0	platykurtic: flat-peaked
0.71 to 1.00Φ	moderately sorted	-0.10 to -0.30	coarse skewed		
1.00 to 2.00Φ	poorly sorted	<-0.30	strongly coarse skewed		
2.00 to 4.00Φ	very poorly sorted				
>4.00Φ	extremely poorly sorted				

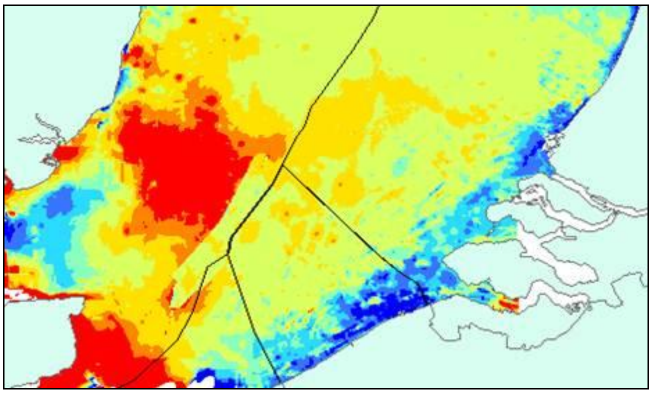

Figure 15. Cross-border incompatibility of d50 maps for British, Belgian and Dutch seabed sediment. Median grain size increases from blue to red. The large red and orange areas in British waters do not continue in Belgian waters. This apparent difference is caused by the fact that the gravel fraction is included in the British and excluded in the Belgian and Dutch d50 calculations. Note that the Belgian map extends beyond its borders [31].

During the past few years, full grain-size distributions have become increasingly available through national databases. When harmonised, these data offer the opportunity to calculate and map any primary or secondary grain-size parameter both consistently and on demand.

This flexibility in calculation and visualisation may prove to be a significant development in habitat mapping.

Harmonisation of grain-size data is the most difficult when numeric information is unavailable. When grain size is characterised in text fields, translation to numeric values is usually not straightforward. Even within individual partner organisations, multiple classification systems may have been used in the course of time. The Geological Survey of the Netherlands, for example, has switched between standards about ten times during the past 80 years (Figure 16). Although only a few of these standards have been used to characterise marine sediment samples, even these few standards show significant differences in class intervals. At 1000-2000 µm, very coarse sand described in 1970 as part of the collaborative mapping with the British Geological Survey is different from very coarse sand described in 2000 using the Dutch national standard NEN5104, which has a corresponding range of 300-420 µm. Similar changes complicate the harmonisation of sorting terms listed in text fields.

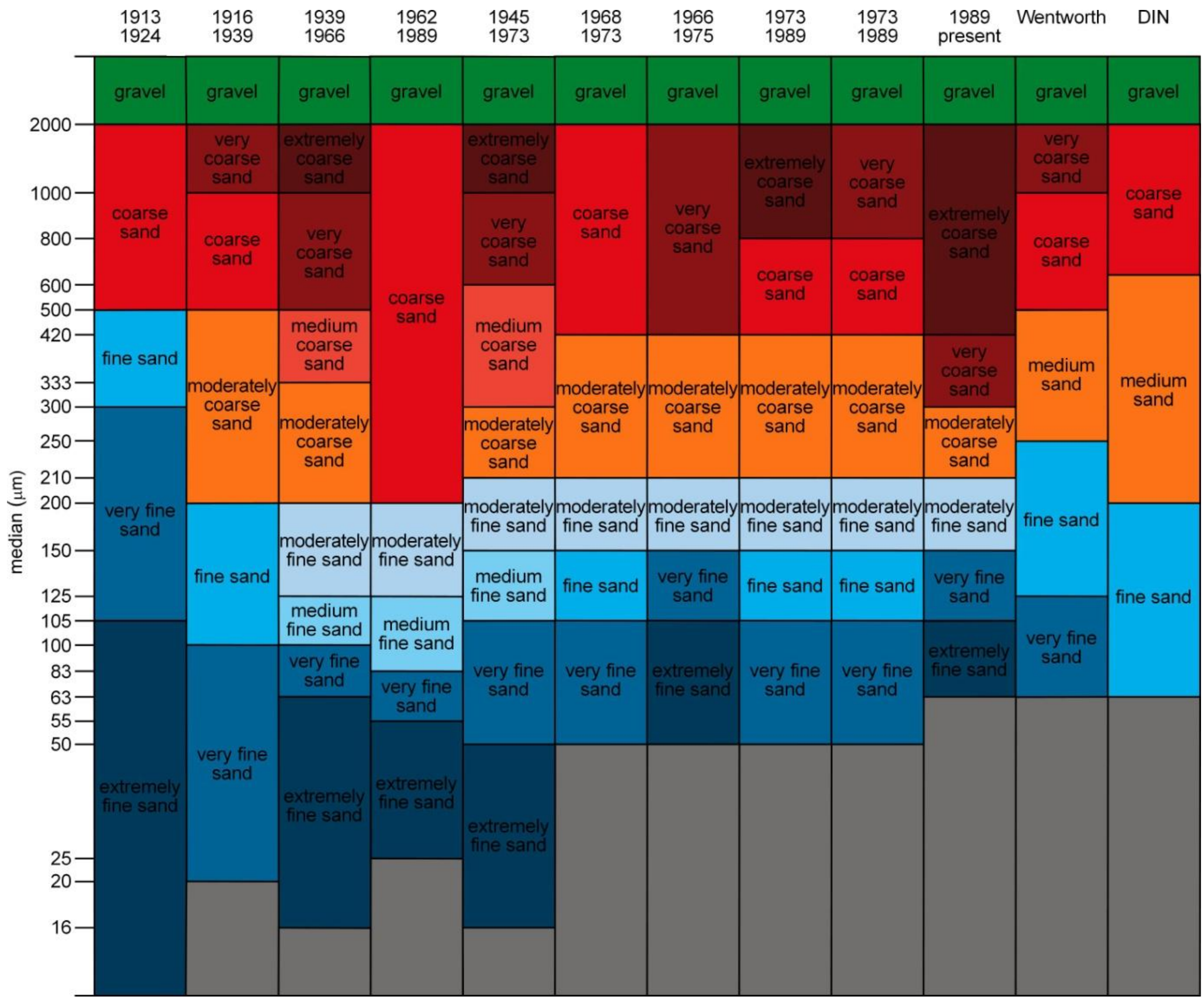

Figure 16. Class boundaries for different types of sand, as used in the Netherlands during the past century. German DIN 4022 classification is shown for comparison (see below).

Internationally, the most commonly used classification system for particle size is the Udden-Wentworth scale [32] [33]. Because it uses clear, universally recognised terminology (Table 4), and provides the maximum resolution achievable in visual descriptions (especially on the fine end of the scale), it has been naturally developed as the standard in academic research, in which transnational communication is important. Its terminology is also incorporated into the Geoscience Markup Language, GeoSciML. This is used to transfer information about geology, and was created by the Commission for the Management and Application of Geoscience Information (CGI) to support interoperability of information served from geological surveys and other geo-data custodians

(https://www.seegrid.csiro.au/twiki/bin/view/CGIModel/ConceptDefinitionsTG).

Table 4. Udden-Wentworth scale.

Size range (mm)	Phi range	Wentworth class
>256	<-8	Boulder
64-256	-8 to -6	Cobble
32-64	-6 to -5	Very coarse gravel (pebble)
16-32	-5 to -4	Coarse gravel (pebble)
8-16	-4 to -3	Medium gravel (pebble)
4-8	-3 to -2	Fine gravel (pebble)
2-4	-2 to -1	Very fine gravel (granule)
1-2	-1 to 0	Very coarse sand
0.5-1	0 to 1	Coarse sand
0.25-0.5	1 to 2	Medium sand
0.125-0.25	2 to 3	Fine sand
0.0625-0.125	3 to 4	Very fine sand
0.0039-0.0625	4 to 8	Silt (mud)
0.001-0.0039	8 to 10	Clay (mud)
<0.001	>10	Colloid (mud)

To harmonise descriptions of main lithology, nationally or locally defined classes used in visual descriptions are best mapped to the Udden-Wentworth standard. In this conversion, two translation options are possible. When numerical grain-size ranges are provided that do not correspond to the Udden-Wentworth classes, their abundances can be used for a recalculation of harmonised fractions. Alternatively, they can be assigned to the most similar Udden-Wentworth fraction (e.g. 250-420 µm would be designated to 0.25-0.5 mm, or medium sand). When sediment is characterised in code, or in a text field (for example, moderately fine sand), the translation depends on the availability of the associated term definition. When this definition is available (e.g. moderately fine sand has a grain-size range of 250-420 µm), mapping can be based on this numerical information (in case of the example, 0.25-0.5 mm, or medium sand). When such a definition is not available, mapping is generally no more than a translation of terms and little is known about its accuracy.

Information on grain size has allowed German researchers to produce seabed-sediment maps that show more detail than the corresponding Folk map (Figure 17). Figge [34] differentiated between three different sand fractions, using mud percentage as a modifier. Tauber [35] further differentiated the sand, worked with several silt classes, and added sorting as a modifier. The amount of detail and the degree of systematics in the maps produced at a regional level, as well as on a national scale suggests that visualising a combination of harmonized grain-size parameters and sediment type may have added value elsewhere in Europe and world-wide.

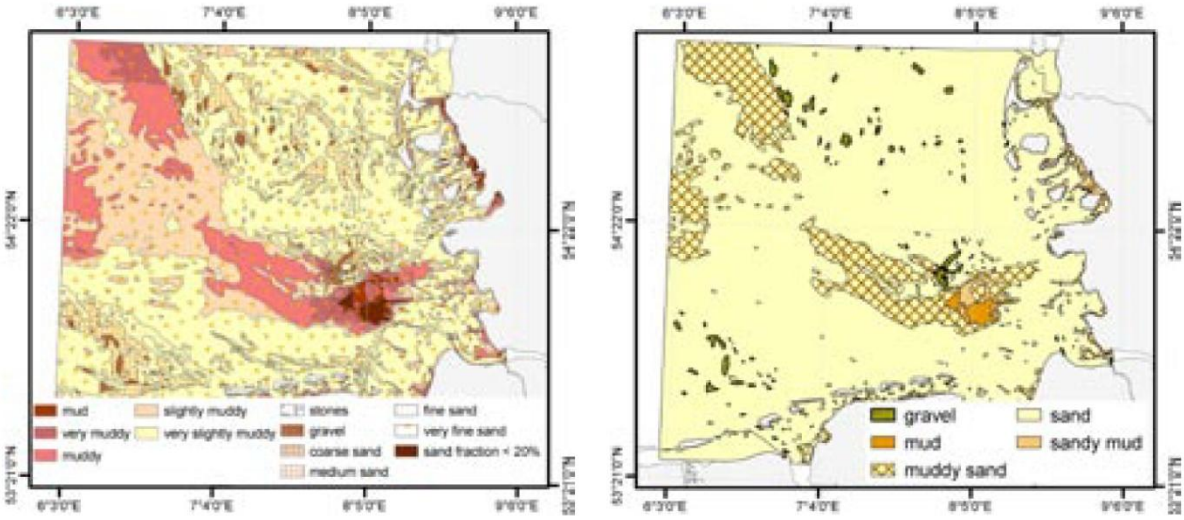

Figure 17. Original sediment map of the German Bight [34] applying the Wentworth [33] classification scheme (left) and aggregated sediment map of the German Bight [34] applying the Folk [30] classification scheme (right).

Other parameters of sediment characterisation

The colour of sediment provides information on depositional conditions such as aerobic and anaerobic environments, availability of organics and tropical influences. Colours are commonly assigned using subjective methods, and entered as text. For common definitions, these subjective text terms can be linked to the ISCC-NBS System of Colour Designation, a system for naming colours based on a set of 12 basic colour terms and a small set of adjective modifiers. It was first established in the 1930s by a joint effort of the Inter-Society Colour Council, made up of delegates from various American trade organisations, and the National Bureau of Standards, a US government agency. An objective method for assigning colour is the Munsell colour system, a colour system space based on three colour dimensions: hue (similarity to red, green, blue and yellow), value (lightness), and chroma (colour purity). It was adopted by the USDA as the official colour system for soil research in the 1930s. When not provided as code, harmonisation of the colour field involves a two-step process of translating text fields in the source language to English and mapping translated text to Munsell code or ISCC.

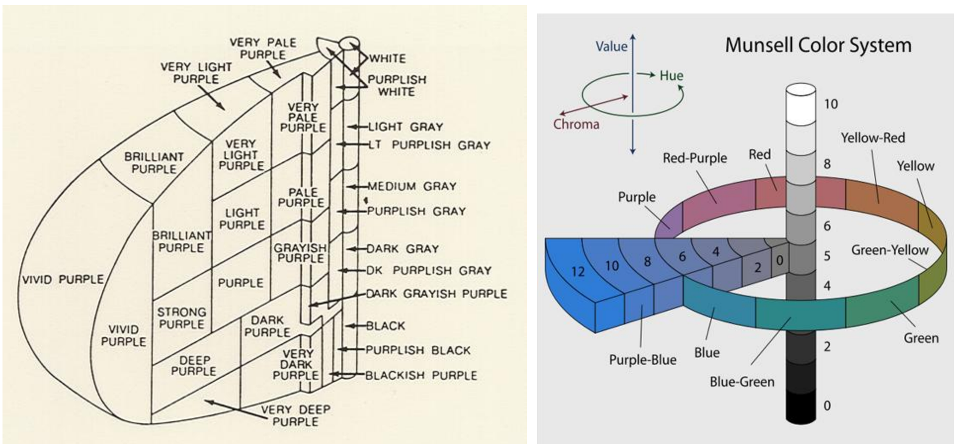

Figure 18. Purple section of the ISCC colour system (left) and Munsell Color System (right).

Sedimentary structures, visible in undisturbed cores, are important in determining depositional environment of a unit. They provide information on the vertical variability of sediment type. Examples of some common sedimentary structures are provided in Table 5).

Table 5. Sedimentary structures.

Class	Type
planar stratification	laminated bedding
planar stratification	graded bedding
planar stratification	massive bedding
cross-stratification	cross-bedding
cross-stratification	flaser or lenticular bedding
cross-stratification	hummocky bedding
irregular stratification	convolute bedding
bioturbation	burrows
bioturbation	root casts

2.2.4 Digital interpolation and probability mapping

Most maps and all grids created to visualise seabed-sediment parameters include an element of interpolation. The only exceptions are full-coverage acoustic images, where limited interpolation is needed, and maps showing only point values (where no interpolation is attempted). Interpolation adds an additional element of uncertainty to maps based on described and measured seabed-sediment data that are already associated with various components of random and systematic error. Therefore, interpolation must be optimised.

A first key element in accurate interpolation is the incorporation of sedimentological expertise. It may seem straightforward to interpolate between two locations with different sediment characteristics, but assumptions on some degree of linearity between sedimentological parameters at adjacent locations are not always warranted. An example is the case in which seabed samples classified as mud are found adjacent to seabed samples classified as gravel. The possible conclusion that an area of sand (coarser than mud and finer than gravel) would have to be present in between is clearly erroneous. When maps were still made on paper, incorporation of such system knowledge and the associated logical reasoning was almost guaranteed, as sedimentologists were always directly involved. In the present age of digital mapping, however, it is increasingly possible for non-experts to create their own maps from database compilations.

A second key element is an assessment of interpolation-related uncertainty. Whereas mapping on paper provided the advantage that sedimentological expertise was inherently included in the resulting data products, digital mapping makes it easy to present different renditions from the same dataset, and to generate updates when new data become available. Software allows the use of a variety of analytical tools to apply different interpolation techniques and to statistically compare the results of interpolated results with a subpopulation of the database that was not used in the interpolation (Figure 19).

An alternative approach, which also allows the visualisation of probability, involves Sequential Indicator Simulation (SIS [36]) using the Isatis modelling software package [37]. Sequential Indicator Simulation is a well-established method to simulate lithofacies distributions; it requires modest computation time and is easy to use. In the case of seabed sediment, SIS would result in multiple, statistically equally probable simulations of the distribution of sediment type or grain-size class. It uses sample descriptions and analyses as hard data and searches the neighbourhood for all remaining grid cells (Figure 20).

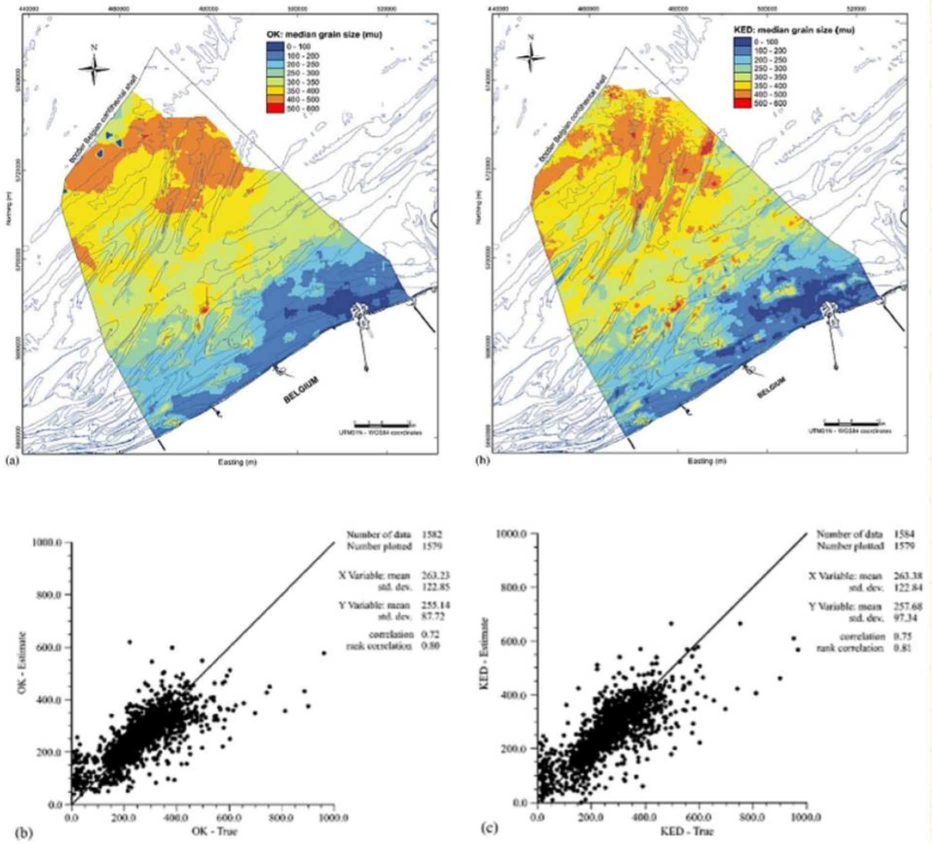

Figure 19. Interpolation of Belgian grain-size data through ordinary kriging (left) and through kriging with external drift (right) [38]. Kriging with external drift uses a densely sampled auxiliary variable (in this case water depth) to estimate a target variable. Statistically, kriging with external drift performed as well as ordinary kriging, and both were significantly better than linear regression. External drift is a viable component in optimisation, but correlations are usually applicable to limited areas only.

From such simulations, probabilities of occurrence for each sediment type or grain-size class may be calculated (Figure 21). Such probability mapping provides an indication of model uncertainty. In addition, probabilities may be used to compute an optimised mean model for various sediment characteristics using the averaging method [39]. The individual simulation results remain available for further use.

Probability mapping is possible only when standardised coding systems are used and corresponding uniform datasets are available. Depending on data density, the grid-cell size chosen will still be associated with considerable residual heterogeneity linked to smaller-scale variability. Understanding such sub-cell heterogeneity is an important task for marine geologists, and for seabed mapping in particular. Full-coverage acoustic data may shed light on up- and downscaling issues, which is needed when striving for increasing detail and accuracy.

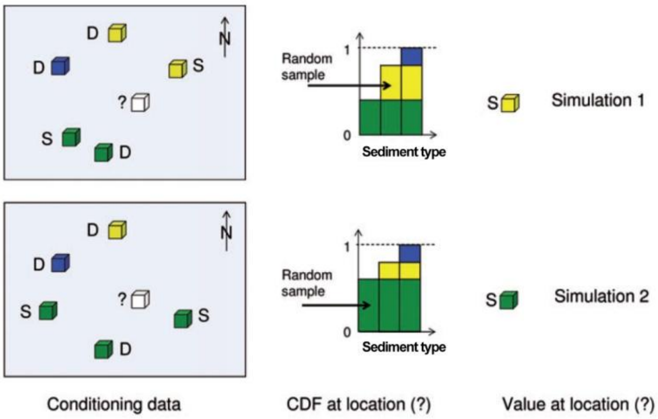

Figure 20. Two simulations of sediment type for the same target grid cell using SIS. The sample data are first migrated to the closest grid cell and considered as hard data afterwards (marked 'D'). All the remaining grid cells are scanned using a random path. A neighbourhood is established, centred on the target grid cell (marked '?'). Within this neighbourhood, the procedure searches for the hard data from the samples and for grid cells that are already simulated (marked 'S'). The neighbourhood is searched using a variogram model so that the data most closely correlated with the target grid cells are given the greatest weight. The data are then coded into a set of indicators. For each sediment type, the indicator is set to 1 if the data belongs to the sediment type and to 0 if not. The next step in SIS consists of a co-kriging phase (block kriging) taking into account the previous information, resulting in a probability between 0 and 1 for each sediment type. The values are plotted in a cumulative distribution function (marked 'CDF'). Then a random value between 0 and 1 is drawn and compared to the cumulative distribution function. The simulated sediment type at the target grid cell corresponds to the rank of the interval to which the random value belongs.

2.2.1 **Ecological relevance of sediment characterisation in habitat mapping**

Surrogacy

In habitat mapping, surrogates are biophysical variables that can be mapped with a quantifiable correspondence to the occurrence of benthic species and communities [40]. With respect to sediment properties, surrogacy concerns those sediment characteristics that best explain the species assemblage in a particular space and at a particular time. Thus, sediment characteristics can be used to predict (with some known probability and uncertainty) the occurrence of species assemblages in unexplored areas and between sparse biological observation points. Their indicative value depends on the nature of the study area. Databases on sediment characteristics are much more voluminous than their biological counterparts, and new seabed-sediment data are obtained more easily and cost-effectively than benthic data.

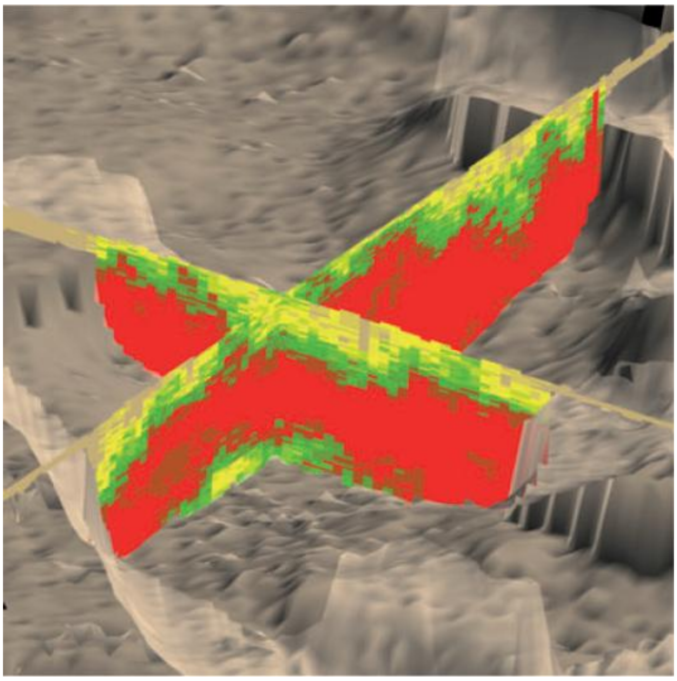

Figure 21. Image of a tidal-channel fill in the Zeeland estuary, showing the probability that a grid cell belongs to the tidal-channel lithofacies. Data uncertainty (for instance errors associated with sediment sampling, description and analysis) is not represented.

Seabed sediment is only one of the main, direct variables determining the ability of a species or assemblage to prosper. It puts constraints on the maximum distribution of organisms, but most species are unable to fully exploit this so-called fundamental niche. Sediment characteristics may therefore be used to delineate zones with correct habitat suitability, but not to predict the actual distribution of the associated species and assemblages within these potentially suitable areas.

Sediment characteristics play a role in all broad-scale habitat-classification schemes [41]. Both individually and jointly, they form environmental indicators at specific hierarchical levels within these schemes (Table 6). Reviews of classification schemes for deep-sea habitats are also available [42].

Table 6. Role of sediments in different broad-scale classification systems.

Classification scheme	Region	Parameter and level/scale
Roff et al. [43]	Canada	sediment type (gravel, sand and mud content) at scale of 10 to 100 km (level 8)
EUNIS [44]	Europe	ratio between gravel, sand and mud at scale of habitat complexes (level 3)
Greene et al. [45]	western North America	grain size and sediment cover at scale of microhabitats (centimeters or less)
NOAA CMECS [46]	North America	sediment type at macrohabitat scale of 100 to 1000 km^2 (level 6)
Integrated Australian Classification Scheme [47]	Australia	sediments (middle levels)

Present use

In broad-scale studies (e.g. use of EUNIS in the MESH [2] and EUSeaMap [3] projects), sediment type was most frequently and successfully used. As part of MESH, a simplified Folk classification was defined as a surrogate for the habitat complexes at EUNIS level 3. On the basis of expert judgement, comparing species-assemblage distributions and Folk substrate maps, the originally defined Folk classes [19] [20] were grouped into 4 main categories: mud to sandy mud, muddy sand to sand, mixed sediments and coarse sediments. In addition to this simplification, the sand:mud ratio to separate mud to sandy mud from muddy sand to sand was changed from 9:1 into 4:1, allowing better separation of mud-dominated habitats (Figure 22). In the adjusted scheme, seabed sediment may have up to 79.9% sand and still be assigned the habitat characteristics of mud and sandy mud.

A more harmonised seabed-sediment map was produced as part of EMODnet-Geology [48] and was further used to model seabed habitats within EUSeaMap [3]. The simplified Folk scheme was used, though three additional classes were added (diamicton, boulder and bedrock) as they were not or poorly represented in the Folk classification. The substrate map provided was the first continuous harmonised substrate map covering northern Europe, extending from the Baltic out to the Atlantic off the west coast of Ireland.

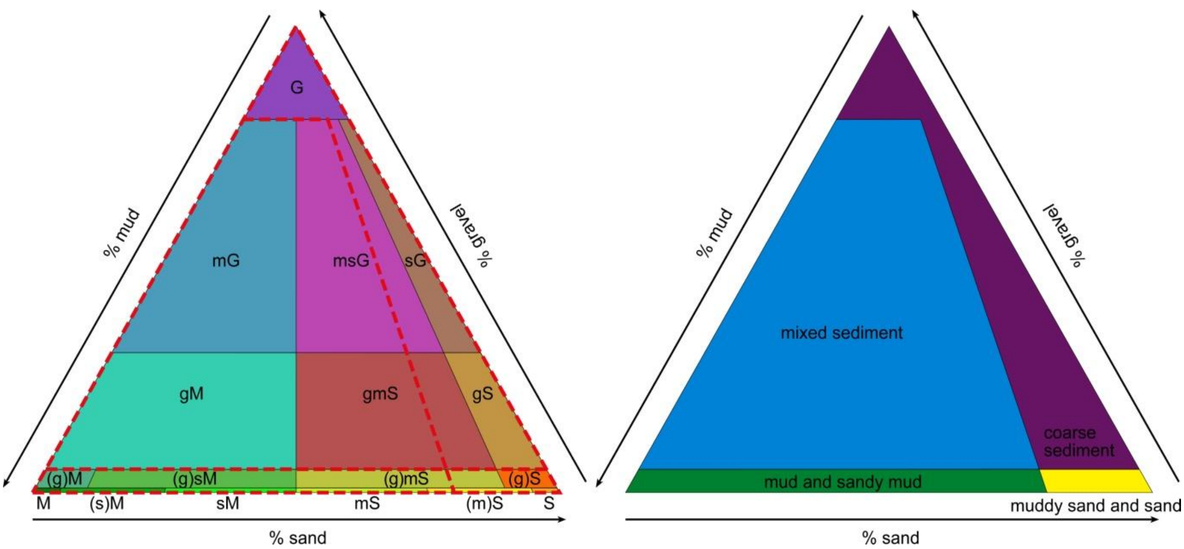

Figure 22. Simplified Folk classification as defined in MESH and EUSeaMap for broad-scale habitat mapping, projected onto the modified Folk classification as used by the British Geological Survey as part of its 1:1,000,000 and 1:250,000 seabed-mapping program. Right panel (to scale) shows dominance of mixed sediments.

Mixed sediments form the largest group within the ternary diagram, representing the broadest range of gravel:sand:mud ratios. This is rather unfavourable since mixed sediment consisting of uniform, laterally continuous 79% gravel, 18% sand and 3% mud is part of an entirely different habitat than mixed sediment consisting of uniform, laterally continuous 94% mud and 6% gravel. In addition, the term ‘mixed sediment’ is commonly used in a wider sense, creating the danger of wrong interpretations. In some countries, it is used to characterise seabed areas with fine-scale patchiness, in others to describe the presence of mud-sand alternations in the shallow subsurface [48].

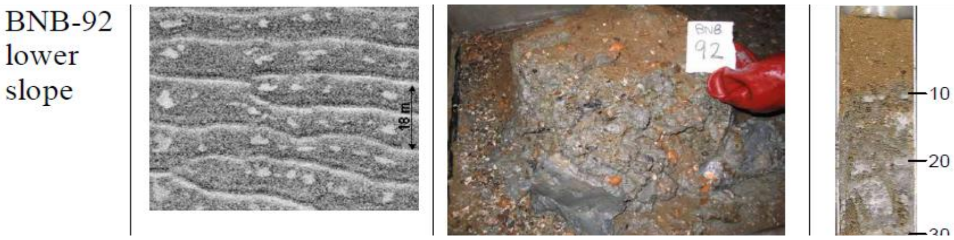

Figure 23. Fine-scale patchiness in the swale of the Brown Bank tidal ridge in the southern North Sea [49]. Here, the seabed sediment generally consists of consolidated mud covered by a thin layer of sand. In some places, the mud lies directly at the surface.

The issues with the mixed sediments do not affect broad-scale habitat mapping so much, because small spatial details are filtered out of the final data products. In finer-scale habitat mapping, where patchiness may be visualised, there has been a stronger focus on less simplified classifications, both for sediment type and for other sediment characteristics. Several surrogacy studies in which species assembly was analysed against abiotic variables have found sediment properties to be good predictors of benthic communities (Table 7).

Table 7. Key results of surrogacy studies finding sediment characteristics important [40].

Study	Most important variables	% variability	Statistical process
Post et al. [50]	% mud, % gravel, disturbance, depth	59	BIOENV
Beaman et al. [51]	slope, % gravel, % $CaCO_3$	75	BIOENV
Beaman and Harris [52]	slope, % gravel, turbidity	62	BIOENV
Stevens and Connolly [53]	% mud, distance to ocean	30	Spearmans
Gogina et al. [54]	depth, total organic carbon	50, 43	BIOENV/Spearmans

For habitat assessments on a national level, broad-scale approaches may not provide sufficient detail. This is the case in areas with subtle sediment gradients (e.g. transition from mud to sands), but also where seabed heterogeneity is high (e.g. patches of coarse sediments). Finer scale mapping is required, as also finer scale classification systems. Figure 24 provides an example of a classification of sandbanks along the Belgian area of the North Sea, based on very-high resolution acoustic imagery [55]. This case illustrated well how sediment characteristics determined the occurrence of macrobenthic communities (seabed organisms larger than 1mm), regardless of the terrain.

Based on the detailed information on benthos in combination with sediments and other environmental variables, median grain size and mud content were found to be the most discriminating variables to predict the occurrence of the main soft substrata macrobenthic communities in Belgian waters. A habitat suitability model was developed [56] using continuous gridded sediment datasets and the model was further successfully applied for southern North Sea habitats up to the Doggerbank [31]. Other examples are available on the use of sediment parameters as surrogates for the mapping of the occurrences of (macro)benthos [57] [58] [59].

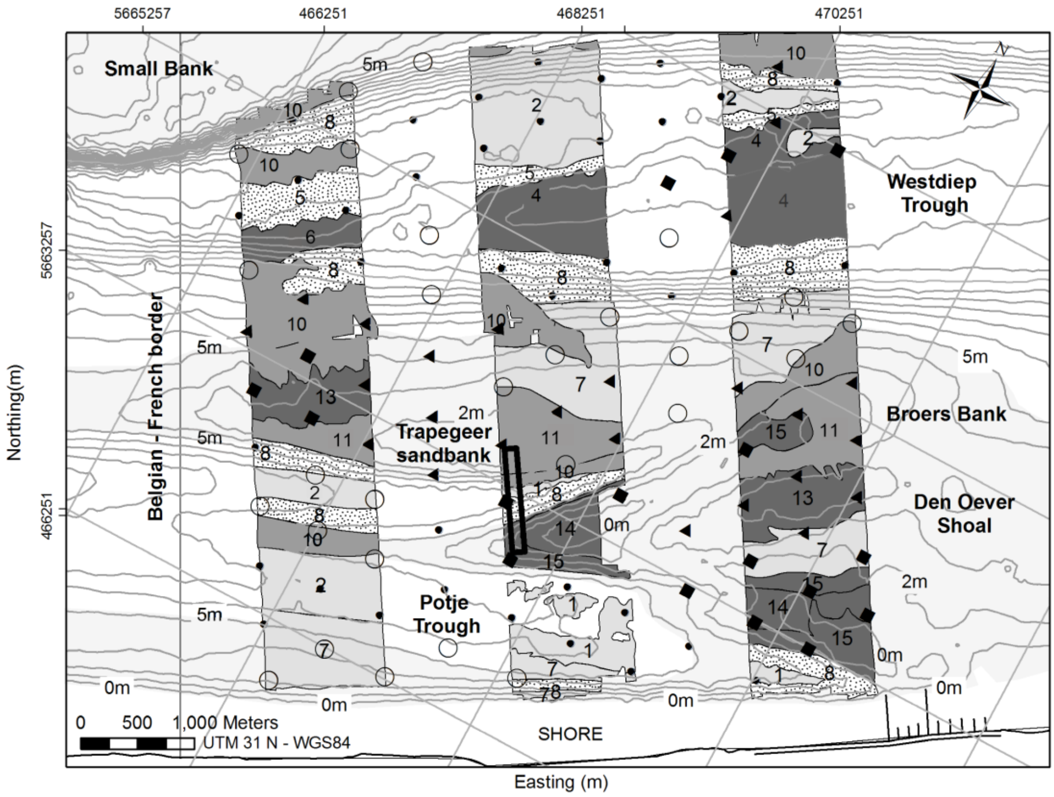

Figure 24. A shallow sandbank-gully system (0-15m) in the near coastal area of the Belgian part of the North Sea. Based on very-high resolution side-scan sonar data, 15 acoustic classes were defined discriminating sediment types based on reflectivity, texture and patterns of the acoustic image. These sediment types were further translated into macrobenthic community preferences [55].

Future perspectives

Although sediment characterisation has proven valuable in broad- and fine-scale habitat mapping, it is unlikely that it has been used to its full potential. For further optimisation of habitat mapping, existing sediment databases and newly collected information could be more exploited. Therefore, it is imperative that all available data are easily translated to common standards. Within the context of European Directives and the overall request for finer-scale products from end users, databases are made more accessible and standards are adhered to as much as possible. There is an incentive to agree on classification schemes that combine Folk and Wentworth, which separately have proven their value in broad-scale habitat mapping. In addition, geochemical and geo-mechanical properties will receive increasing attention.

The key to using sediment character to its full potential is a continued effort to find and quantify relationships between abiotic and biotic parameters at various spatial scales. On a fine scale, this can be done by linking sediment and benthos analyses from single samples as part of local, project-related studies (Figure 25). On a broad scale, samples collected for other purposes, typically within the framework of geological mapping programs, can be reused in new ways, by creating multiple surrogate grids that can be compared to biotic parameters as derived from samples or databases (‘collect once, use many times’). However, to optimise the chance of finding least biased relationships, benthos data can best be analysed against those areas where the probability of the occurrence of a certain sediment type is highest. The chance for success is maximised in a multidisciplinary cooperation.

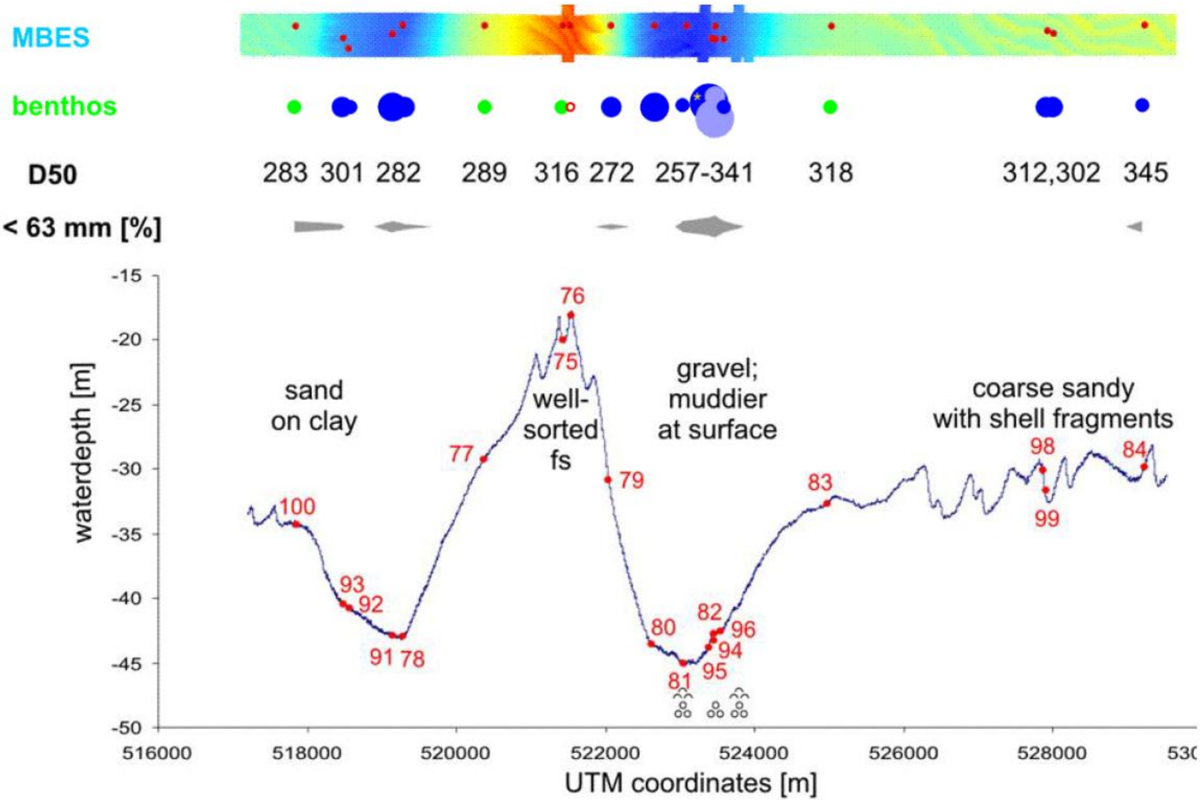

Figure 25. Relationships among seabed morphology, median grain size, mud content and benthic assemblages across the Brown Bank tidal ridge in the southern North Sea [49].

Uncertainty and other limitations

Even with single samples, finding relationships between sediment characteristics and biotic parameters may be complicated. Correlations at individual locations are confounded by the complexity of marine ecosystems. Species and species assemblages respond to a range of abiotic parameters, spatially and temporally varying. A seabed habitat may not be a function of static and uniform conditions, but rather be defined primarily by seasonal or event-driven changes at the surface. Coarse sediments temporarily exposed at the surface by storm waves are covered by fines during fair-weather periods. Habitats may also be defined by textural variability in the top layers of the sediment. Some species need dynamics or the presence of different sediments (laterally or vertically) for successful feeding and dwelling, and the favourable habitat may change when larvae and juveniles develop into adults.

Relationships between sediment properties and benthos are also blurred by data- and interpolation-related uncertainty. It is important to realise that sediment characteristics, as available in databases or incorporated into data products, are not hard numbers that should be used to question known and proven relationships. And even when size data are reliable, links to other abiotic parameters should be considered. Density and shape differences between biogenic and siliciclastic particles explain why two samples, similar in grain size, have different implications for bed stress.

Confidence in data and data products, therefore, must be considered in a broad perspective, and include a valuation of sedimentological system and process knowledge. On the one hand, it indicates which limitations are associated with using available sediment characteristics as surrogates for benthic communities. On the other hand, it should provide a clear warning not to put too much weight in the absence of explicit, quantifiable links between sediment properties and biotic variables, especially on the fine scale. Even with the perspective of new, ground-breaking observation and analytical tools, finding such links will always be easier in broad-scale transitions, well covered by samples and acoustics, than in fine-scale patchy areas with relatively few benthos analyses that need to be matched with sediment data from different locations and collected at different times.

2.3 Multiple scale sediment characterization – case studies

Case studies based on examples from the North Sea, Celtic and Irish Sea are presented in this report. They demonstrate seabed sediment mapping with relevance to habitat mapping at a wide range of scales – from broad-scale studies to detailed studies with 5 metre or finer grid cell sizes, derived from multibeam bathymetry. For broad-scale sediment mapping reference is also made to the EMODnet-Geology substrate map that was used to produce broad-scale habitat maps (EUSeaMap). Leth (Geological Survey of Denmark and Greenland) adds value to this broad-scale mapping through an integration of various high resolution geological datasets. Kupschus et al. (CEFAS, UK Centre of Fisheries and Aquaculture) have tested the added value of datasets with different sediment resolutions for the mapping of fish habitats. Monteys et al. (Geological Survey of Ireland) developed a methodology for finer scale sediment mapping, based on multibeam backscatter data. Finally, Van Lancker and van Heteren (Management Unit of the North Sea Mathematical Models; Geological Survey of the Netherlands) discuss broad- to fine-scale sediment mapping for habitat assessments in the context of Europe's Marine Strategy Framework Directive. Following, a summary of each of the case studies is given; the full texts can be found in the section on Case Studies.

2.3.1 **Multiple geological data sets used for inferring the distribution of the lesser sand eel (*Ammodytes marinus)* in the North Sea**

Introduction

A broad-scale study has been conducted on predicting the distribution of the lesser sand eel habitat, based on geological data (Leth, Case Study 1). The lesser sand eel is a vitally important food source for many high order predators, numerous seabirds and marine mammals [60]; as such they are considered as a critical link between zooplankton and higher order marine predators [61]. Sand eel is subject to the largest single species fishery in the North Sea region. It is the target of an economically important fishery, with landings fluctuating between more than 1 million and 200,000 tonnes during the past 25 years [62].

The relationship between the density of the lesser sand eel and environmental variables such as sediment characteristics, depth and water circulation has been studied during the last decades. In the North Sea their preferred substrate is medium to very-coarse sand (median particle size between 0.25 to 2 mm) with a content of the silt and clay fraction (< 63 μm) lower than 10% [63]. Further, sand eels prefer seabed structures associated with an abundant supply of sand with a maximum current flow of 1 m/s and water depths between 30 and 70 m.

Methodology

Based on newly acquired multiple high resolution data sets consisting of bathymetric, seismic, sidescan sonar data and information from sediment samples a national habitat mapping programme has been performed in the Danish North Sea [64]. In this context a specific focus has been on the Quaternary stratigraphy and the palaeo-environment to describe and understand the geological development and the distribution of the seabed sediments.

Results

Four overall seabed types have been recognised: Hard substrates of till and coarse grained sediments formed during the Saalian and Weichselian glaciations; Glacio-fluvial sandur deposits of Late Weichselian age forming substrates of sand and gravel; Holocene marine sand, locally forming sand ridge and sand wave deposits; Holocene, marine mud and muddy sand deposits. These data have recently been integrated with the European EMODnet-Geology substrate map

(published via http://onegeology-europe.brgm.fr/geoportal/viewer.jsp).

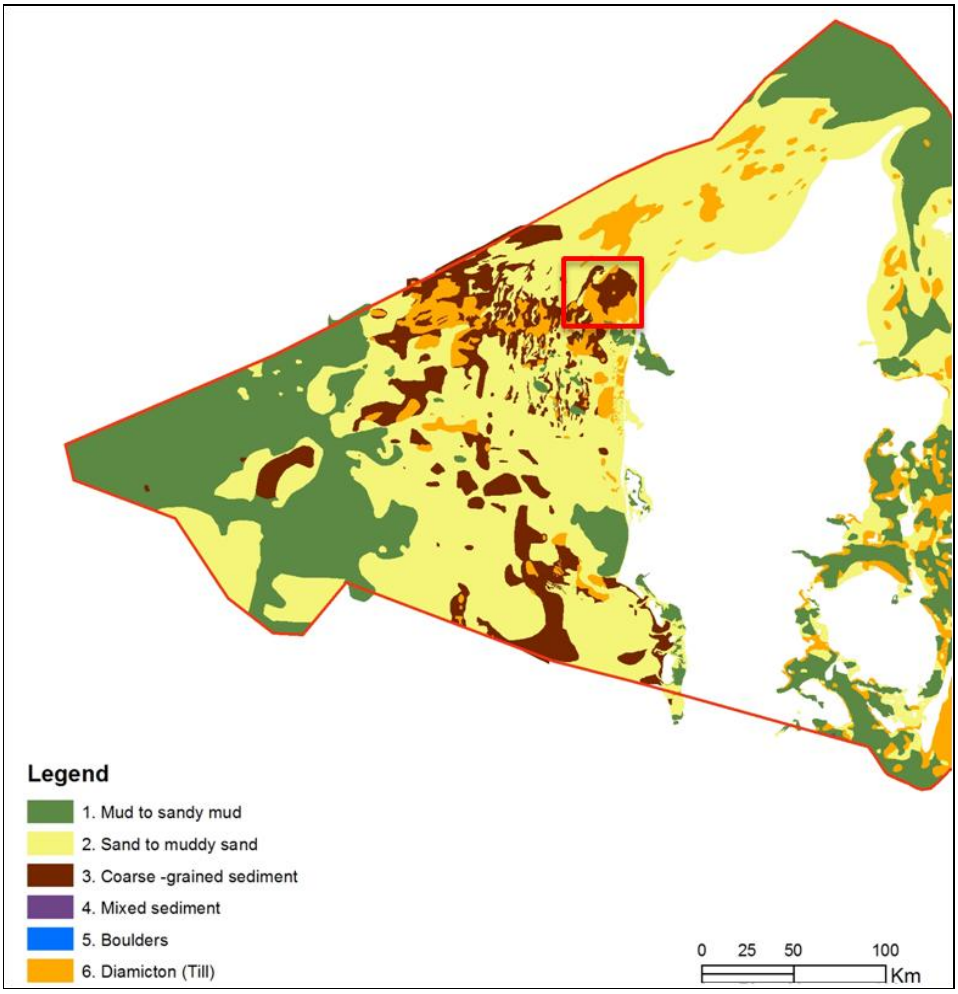

Figure 26. Substrate distribution of the Danish North Sea (red polygon) compiled on the basis of all available geological data. Sediment classes follow the EMODnet Geology classification scheme. Red box indicates the case study area.

Integrating all available data (bathymetry, seismic, side-scan sonar, surface sediment samples and borehole information), in combination with literature, led to the conclusion that the sand eel habitat largely coincided with the distribution of elongated large-scale morphological ridges, i.e. relict tidal sand ridges, dating back to the early Holocene. This is an important result given the widespread occurrence of sandbank habitats in the English Channel and along the Belgian and Dutch offshore area. Still, sand eel fishing grounds may disappear from one year to another and adds to the discussion whether or not protecting the habitat and balancing the pressure from fishing. Apparently many of the habitats are located close to shallow seabed areas with substrates of till. During storms these areas are exposed to wave action which by erosion mobilise fine-grained material which is transported into the nearby sandy sand eel habitat. This influence of fines in the well-sorted sandy burying sand eel habitat areas most likely causes a change of the physical environment by increasing the amount of silt/clay to a level exceeding the requirement for the sand eel.

A better understanding of the factors that drive the sand eel abundance variations is strongly needed to assist the management of the very sensitive species. Further geological approaches (i.e. better sediment and morphological maps) are needed to test further biotic-abiotic relationships and predict better potential burying sand eel habitats in the North Sea.

2.3.2 Using sediment data from the Geo-Seas database to examine the effects of sediment on the species composition in beam trawl samples in the Western English Channel

Introduction

A broad-scale case study is provided on the mapping of fish habitats in the western English Channel (Kupschus *et al*., Case Study 2). Many studies (e.g. [65] [66] [67]) regard sediment type an important variable to explain the distribution of fish habitats, and it was attempted to determine the utility of available sediment information to derive the species composition of fish in beam trawl samples. Through the Geo-Seas project sediment data were provided with different levels of detail, allowing testing of their ability to predict fish distributions and improving the understanding of ecosystem processes. With increased understanding of such sediment preferences, the production of improved and more standardised fish habitat maps is envisaged.

Methodology

Multivariate statistics were used to analyse patterns in species composition from catch samples and sediment classifications, as also to correlate species and sediment information. The same procedure was followed for five sources of sediment data. The first three were quantitative, providing information on the particle size distribution of the sediment in different detail: (1) **fine** with 36 classes, one for each 0.5 phi particle size in the range 0.5µm to 63mm; (2) **medium** with 12 classes, one for gravel, one for silt clay and the other ten for the 0.5 phi size classes relevant to sands; (3) **coarse** with 5 classes, one each for gravel and silt/clay and the remaining three for coarse, medium, and fine sand; (4) **Folk**, a classification identifying 15 sediment classes (e.g. muddy sand, muddy gravel, sandy gravel) according to the relative proportion of mud, sand and gravel in the samples; and (5) **EUNIS system**, corresponding with the EUNIS habitat classification (see above), and having 4 classes only: coarse sediment, mixed sediment, sand and mud. For this study, Folk and EUNIS codes were assigned following the habitat map of Coggan and Diesing [68]. It needs emphasis that data availability differs drastically between the different levels of detail. Folk and EUNIS system data are widely available now (e.g. through EMODnet-Geology), though the availability of finer detail data may be very scarce and spatial coverage on a large scale is likely very poor.

Conclusions

Although sediment distribution is regarded important in explaining the distribution of fish communities, the clustering of species composition and sediment samples within 12 miles of trawl stations suggested a poor definition of species composition based on sediment types.

The predictive power of the sediment data was poor, regardless of the detail of the sediment classifications used. However, knowing that sediment and species data present continua, rather than discrete patterns suggests that the information is still valuable to determine likely species composition on the basis of sediment type in the western English Channel. However, for the production of more standardised fish habitat maps, it is clear that other variables, such as benthic species composition, bathymetry and hydrodynamic indices, need to be incorporated.

Future research should attempt to predict species composition on the basis of sediment samples and compare these with independent collections of fish communities. When data are compiled, the problem remains that sediment data originates from different sampling gears and is not always consistently treated in space and in time. Further investigations will be required to determine if this causes bias or artefacts in the analyses. Especially, in this study the distribution of different gears has a very strong spatial correlation that is consistent with the spatial distribution of species. In part this is because different gears are employed on different habitats, but this does not preclude further effects.

2.3.3 **Seabed characterization in shallow waters using multibeam backscatter data**

Introduction and methology

For intermediate to fine-scale sediment mapping of the seabed, in view of habitat mapping, backscatter data can be used obtained with multibeam technology. On the basis of data from the Geological Survey of Ireland, Monteys et al. (Case Study 3) modelled, in a number of case studies, the multibeam backscatter - seabed type relationship to accurately predict a number of key seabed indices. A linear regression model was used, empirically derived from large, marine-acoustic databases and hundreds of seabed samples. The model chosen has proven robust and uncomplicated, potentially offering, to the wider marine community, a reliable yet simple template for seabed classification using multibeam backscatter.

Results and conclusions

The study focussed on the relationship between sediment grain-size parameters and backscatter characteristics. The model that is proposed indicates a consistent, strong, linear relationship between mean grain size and backscatter, particularly for the finer-grained sediments (Silt to gravelly sand range). Caution is needed with shell fragments blurring the backscatter-sediment relationship.

For gravel-dominated seabed facies, the results suggest that predicting mean grain size using such a model may be problematic. Indeed, unpublished studies of the Geological Survey of Ireland failed to find a simple correlation pattern between backscatter data and sediments with large clast sizes. This seems consistent with theoretical expectations which contend that backscatter returns at this wavelength and in this type of seafloor, are dominated by surface roughness parameters. Similarly, rock outcrops are difficult to differentiate using backscatter alone; bathymetric textural parameters may provide better discrimination of rock types.

Finally, it is highlighted that sonar system specifications, acquisition settings and calibration issues often result in across-platform inconsistencies in backscatter datasets, therefore the empirically derived models presented in Case Study 3 should be used for guidance only, particularly when considering seabed scenarios which differ from the case studies. Table 8 presents an overview of the main results.

Table 8: Summary of main findings relating multibeam backscatter to sediment types.

Seabed Hardness	Sediment Type	Textural Categories (Folk's)	Acoustic Scattering	Backscatter Levels	Statistical Relationship backscatter / grain size
Soft	Unconsolidated, fine grained sediments	Mud to sand (unimodal to multimodal grain size distribution)	Interface and volume (subsurface penetration)	Low	Strong, linear correlation between backscatter and grain size parameters
	Unconsolidated, mixed sediments (fine dominated)	Gravelly-sand **/** gravelly-mud (bimodal grain size distribution)	Interface and volume (subsurface penetration)	Moderate	Strong, linear correlation between backscatter and grain size parameters
Hard	Unconsolidated, coarse dominated sediments	Sandy, muddy-gravel or gravel (unimodal to multimodal grain size distribution)	Interface (negligible suburface penetration)	Moderate - High	Gravel fraction dominates backscatter. Weak correlation between sandy fraction and the backscatter
	Rock or hardgrounds	Bedrock, hardgrounds, carbonate crusts and other hard surfaces	Interface (no subsurface penetration)	High	No consistent relationship between rock type and backscatter parameters

2.3.4 **Revisiting the spatial distribution of EUNIS Level 3 North Sea habitats in view of Europe's Marine Strategy Framework Directive**

Introduction and methodology

An intermediate to fine-scale sediment mapping case study is presented, based on a combination of full distribution curve data from the Belgian part of the North Sea (Belgian database sediCURVE@SEA [69] up to 52° in the Dutch sector of the North Sea (database Geological Survey of the Netherlands) (Van Lancker and van Heteren, Case Study 4).

Firstly, a comparison is made between the distribution of the modified Folk classification, as used in the EMODnet-Geology sediment map, and the distribution of the original Folk classes. Mapping to original Folk classes was done using the USGS sediment tool (http://woodshole.er.usgs.gov/pubs/of2007-1186/OFR2007-1186.pdf)), an ArcGIS extension tool, producing a Folk grid, based on interpolated grids of the percentages of gravel, sand, silt and clay.

Secondly, the full range of data has been explored calculating any desired percentile of the sediment distribution (e.g. d10, d35, d50 or d90), as also of the Folk parameters mean, sorting, skewness and kurtosis. Parameters were calculated on the full data, as well as on the sand fraction alone. This narrowing of the data range can be useful when studying temporal sediment changes.

Some results are compared to information obtained from very-high resolution multibeam backscatter data (<5m). The relevance of this **flexible sediment parameter mapping** is demonstrated in function of the need of increasing process and system knowledge, as prescribed in Europe's Marine Strategy Framework Directive. With regard to the descriptors biodiversity, food webs, and seafloor integrity, some countries suggest maintenance of the distribution and area of habitat types, distinguished at EUNIS Level 3, as indicator of good environmental status. Additionally, it may also be desired to maintain the extent of biogenic substrates and gravel beds. This implies that reference situations are known, as also their degree of natural variability. However, ranges of uncertainty are hitherto not addressed.

Results and conclusions

Comparing a suite of sediment parameter maps, in combination with geological and hydrodynamical data, suggests that quantifying habitat area and extent in function of assessments is not an easy task. Proposing maximum changes in the distribution of EUNIS Level 3 habitat types, although seemingly attractive for their clarity as an objective, must be considered in relation to the uncertainty and natural variability of the reference situation used. The objectives of suggesting such an indicator should be well considered if the indicator is to be used to ensure the sustainability of aggregate extraction, dredge-spoil dumping and other human activities.

Aside from increasing efforts to monitor, understand (by generating system knowledge) and model natural variability as one measure of uncertainty (limitations in sampling, sample analyses and data interpolation being others), a way forward in the short term would be to select representative seabed types at key locations and monitor their change, and to determine how such observations can be up-scaled to larger areas. An example would be to follow-up the distribution of sand cover and epifauna in gravel areas in the near and far field of extraction sites.

3 Conclusion

Sediment characterization is a stepwise, multi-faceted activity. Various characteristics can be estimated visually, measured in the field or in the laboratory, or derived from ground-truthed proxies provided by acoustic data or video imagery. An overview is given of the main methods in the context of habitat mapping, as also of the main classification schemes.

For further optimisation of habitat mapping, existing sediment databases and newly collected information could be more exploited. To make 'collect once, use many times' work, it is imperative that all available data are easily translated to common standards. Within the context of European Directives and the overall request for finer-scale products from end users, databases are made more accessible and standards are adhered to as much as possible. Key is to arrive at flexible sediment parameter mapping making use of the full potential of sediment databases. When interoperability is achieved between data and data products, it is possible to create a common infrastructure for accessing, sharing and exchanging harmonised data and data products.

To obtain reliable sediment maps, digital interpolation and probability mapping need further investigation. Confidence intervals are needed when quantitative assessments of habitat extent and area are important. Understanding of seabed heterogeneity is critical. Full-coverage acoustic data may shed light on up- and downscaling issues, which is needed when increasing detail and accuracy is strived at.

Different stakeholders have various needs and require varying scales and resolution of mapping products according to their application. In this report, 4 case studies are presented that discuss sediment characterization in function of some of those applications, e.g. related to fish habitats, resources and in support of seabed management (e.g. European Marine Strategy Framework Directive). The scale of the maps varies from broad-, intermediate to fine-scale depending on the importance of the sediment characterization per application and the complexity of the area of concern. The same holds true regarding the desired resolution of the dataset. An important evolution is the increasing need for process and system knowledge steering monitoring programmes in a most cost- and time efficient way.

To best meet stakeholder requirements, flexible querying and visualisation of data are needed, together with common data-access and -sharing policies among international database owners and developers. Ideally, a series of linked web services would allow the uploading, viewing, downloading, updating and annotating of harmonized data and data products. Such services would offer end users the flexibility to create multiple visualizations or conduct multiple analyses and select from these the ones that best fit their intended use.

Case study 1: Multiple geological data sets used for inferring the distribution of the lesser sand eel (*Ammodytes marinus*) in the North Sea

Example of broad- to intermediate-scale sediment mapping

Jorgen Leth

Geological Survey of Denmark and Greenland.

Introduction

The relationship between the density of the lesser sand eel and environmental variables such as sediment characteristics, depth and water circulation has been studied during recent decades [70] [63]. The post-settled sand eels actively select specific substrates for burying. They live with a close association to sandy substrate in which they live between September and March with the exception of spawning in December and January. Sand eel tend to emerge only during daylight hours in order to forage close to their burrows in the sandy sediment. They will burrow rapidly if alarmed by predators. Their preferred substrate in the North Sea is medium to very coarse grained sand (median particle size between 0.25 to 2 mm) with a content of the silt and clay fraction (< 63 μm) lower than 10% [63]. Further, sand eels prefer seabed structures associated with an abundant supply of sand with a maximum current flow of 1 m/s and water depths between 30 and 70 m.

The lesser sand eel is a vitally important food source for many high order predators, numerous seabirds and marine mammals [60]. They are therefore considered to be a critical link between zooplankton and higher order marine predators [61]. Furthermore, sand eel is subject to the largest single species fishery in the North Sea region. It is the target of an economically important fishery, with landings fluctuating between more than 1 million and 200,000 tonnes during the last 25 years [62].

Little is known about the large-scale distribution of sand eels or the mixing between their habitat areas. However, detailed information collected directly from the fishery has been used to map fishing grounds [71] and to reflect the foraging habitat of the species i.e. the non-burial state. Still very little is known about their burial habitat even though information exists concerning specific habitat requirements. Documenting the spatial distribution and extent of suitable burying habitat in the North Sea will lead to a better understanding of how the different factors influence the sand eel abundance variation.

Mapping of sand eel habitats in the North Sea

Based on newly acquired multiple high resolution data sets consisting of bathymetric, seismic, sidescan sonar data and information from sediment samples a national habitat mapping programme has been performed in the Danish North Sea [64]. In this context a specific focus has been on the Quaternary stratigraphy and the palaeo-environment to describe and understand the geological development and the distribution of the seabed sediments. In addition to the mapping programme a case study has been performed to study the relationship between the sand eel fishing habitats and the underlying geological structures. For this study fishing ground information collected from the fishery (Figure C1-1) has been combined with the geological and bathymetry data.

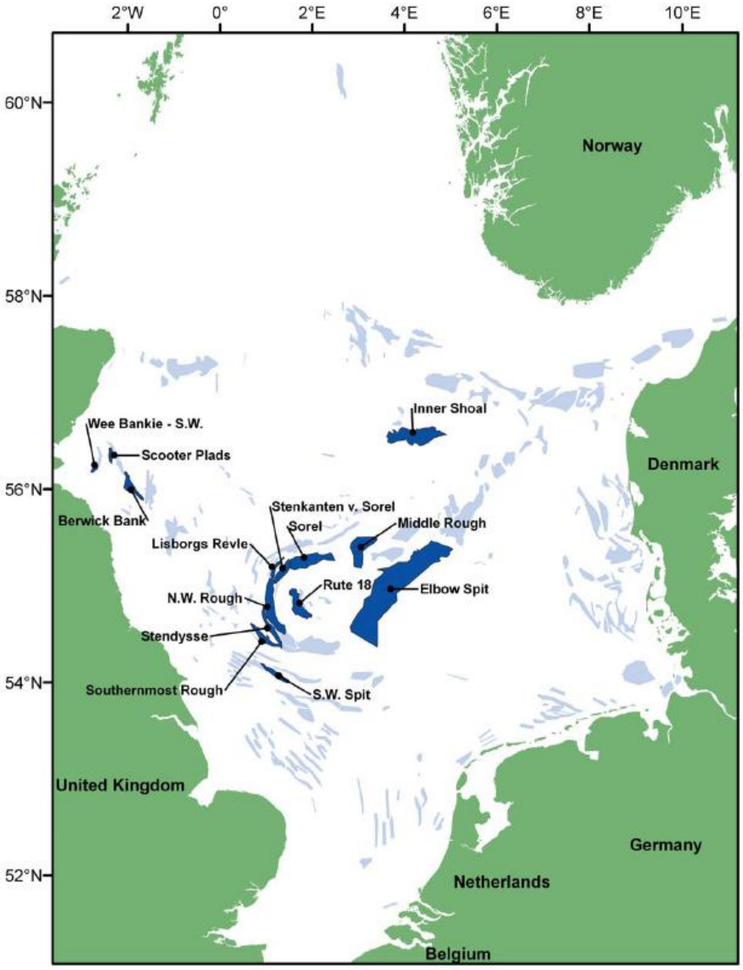

Figure C1-1. Sand eel habitat areas (areas with potential high density of non-burial sand eel) and the location of the most important fishing grounds in the North Sea [71].

Geological results

The general sediment distribution of the Danish North Sea region reflects the geological processes acting during the last glaciations and the post-glacial sea level fluctuations (figure C1-2). Four overall seabed types have been recognised: Hard substrates of till and coarse grained sediments formed during the Saalian and Weichselian glaciations; Glacio-fluvial sandur deposits of Late Weichselian age forming substrates of sand and gravel; Holocene marine sand, locally forming sand ridge and sand wave deposits; Holocene, marine mud and muddy sand deposits. These data have recently been integrated with the European EMODnet-Geology substrate map

(published via http://onegeology-europe.brgm.fr/geoportal/viewer.jsp).

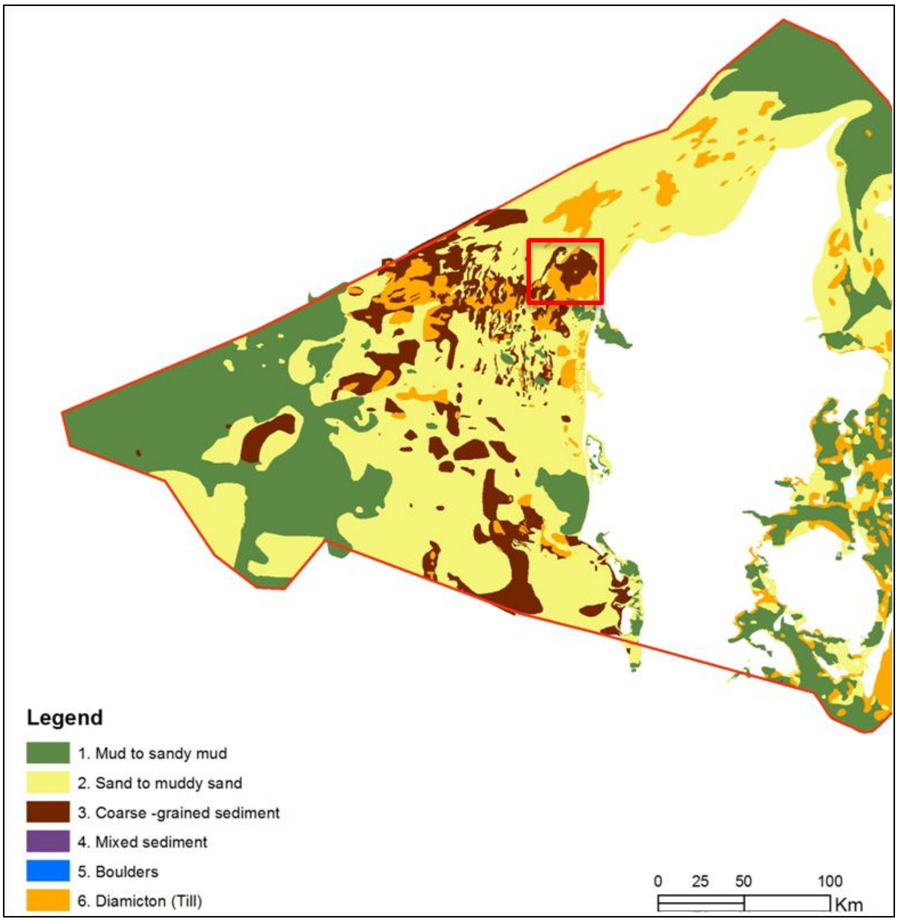

Figure C1-2. Substrate distribution of the Danish North Sea compiled on the basis of all available geological data. Sediment classes follow the EMODnet Geology classification scheme. Red box indicates the case study area.

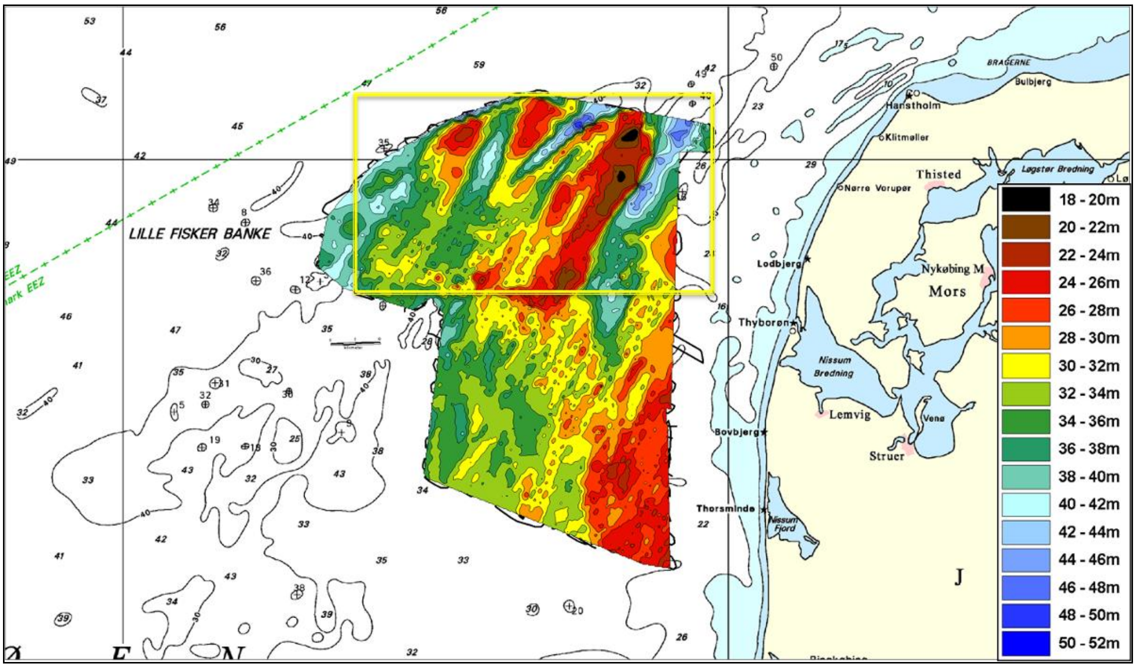

Figure C1-3. Bathymetric map of the north-eastern part of Danish North Sea showing the presence of three elongated ridges striking northeast-southwest.

During an integrated analysis of the available data (bathymetry, seismic, sidescan, surface sediment samples and borehole information) combined with studies of relevant literature it is concluded that the elongated large scale morphological ridges (see Figure C1-3 and 5) are relict tidal sand ridges dating back to the early Holocene.

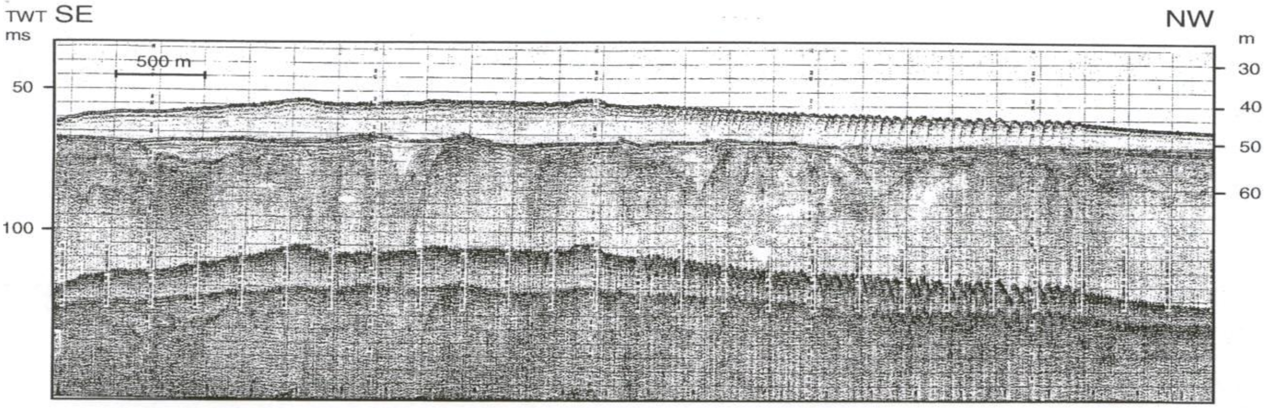

Figure C1-4. Example of an Early Holocene tidal sand bank north of the study area. Water depth 30-50 m. Dimension L= 2-10 km; H= < 25 m; W: 5 km [72].

Figure C1-4 shows a supplementary example of a relict tidal sand bank from the area to the north of the study area.

From previous studies of the Holocene development [72] [73] it has been suggested that the period from around 10,000 to 5,600 years BP the area was under strong tidal influence. During the Holocene period the shoreline successively moved across the study area due to the of the global sea level rise (Figure C1-5).

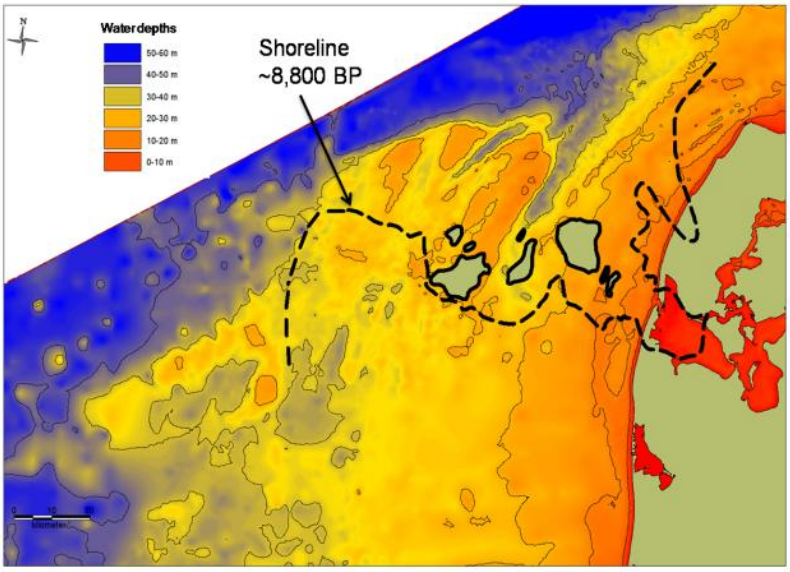

Figure C1-5. Shoreline in the study area 8,800 y. BP.

By the end of the period around 5,600 years BP the hydrography in the area changed to the present open marine conditions due to the final drowning of the archipelago like glacial landscape. The tidal amplitude decreased dramatically at this time because of interference between the two North Sea amphidromes over the area.

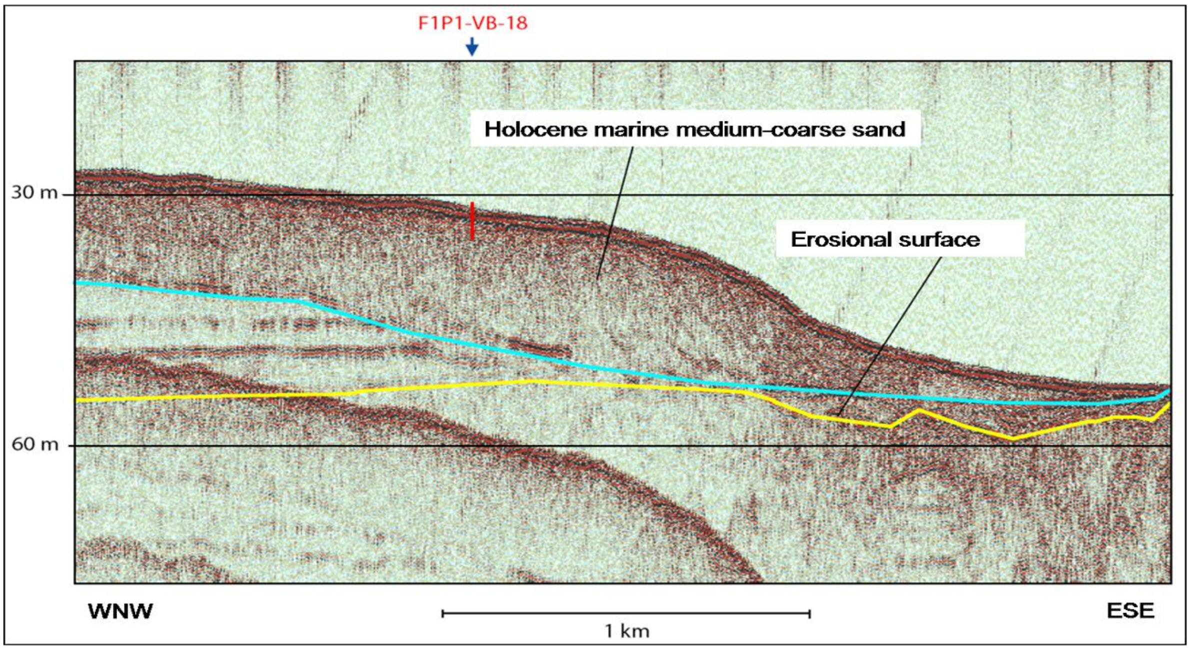

Figure C1-6. Seismic section crossing a relict tidal sand ridge in the study area (for location see Figure C1-7). Thickness of the sand ridge is 10-15 m. Red line indicates the location of a vibrocore.

From sediment cores and surface samples it has been documented that the sediments consist of well-sorted medium to coarse sand with a very low content (< 5%) of silt and clay. The well-sorted properties of the sand ridges are the result of several phases of reworking with repeated high current flow velocities. Thus, after deposition in the Early Holocene the shape of the tidal sand banks has been slightly modelled adapting to the changing hydrographic conditions. The sediment transport across the large scale bedforms is still active. Sidescan sonar and seismic data yield evidence of the recent sediment transport by the presence of sandwaves and megaripples (Figure C1-4 and C1-7).

Sand eel fishing grounds and geology

From the analysis of the relict tidal sand banks in the study area it has been documented that geological data can provide useful information on the physical properties of the burying sand eel habitat [63]. Overlapping the fishing ground information collected from the fishery [71] on top of the geological and bathymetric information it is evident that the sand eel fishing grounds are linked to the large tidal sand ridge deposits in the north-eastern part of the North Sea (Figure C1-7). The presence of sandwave fields and other bedforms documented from the sidescan sonar recordings show that flow velocities periodically reach 1 m/s or more and is responsible for keeping the upper sand layer well-oxidized. The water depth of the mapped sand banks between 20 and 45 m and the relative steep slope are also in-line with the habitat requirements.

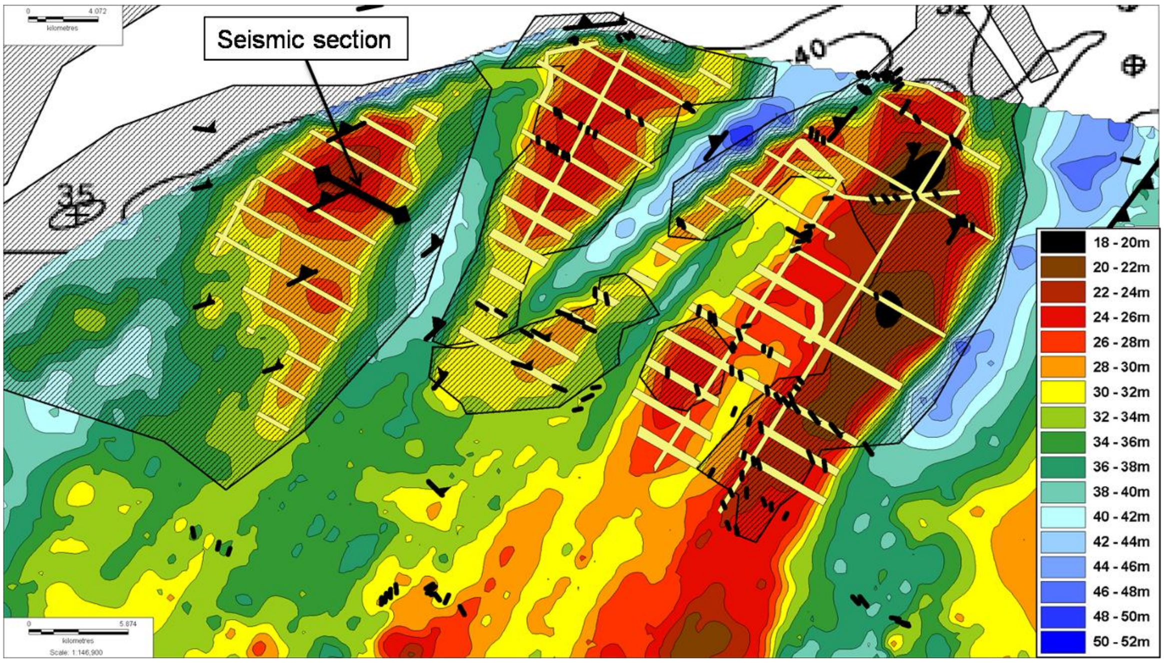

Figure C1-7. Bathymetric map of the case study area (depth interval as Figure C1-3) including information on sediment and dynamic structures. Light yellow lines = indicate areas of medium-coarse sand; black lines with triangles = sandwaves, short black lines = megaripples; hatched area = sand eel fishing habitats.

Conclusion and perspectives

Based on a geological analysis of existing data is has been documented that tidal sand banks meet the conditions of burying sand eel habitats. The distribution of sand eel fishing banks overlap with the mapping of burial habitat properties. Similar settings can be found in other areas of the North Sea e.g. in the English Channel and offshore the Belgian and Netherland coast where tidal sand banks also host foraging sand eel habitats (Figure C1-1).

From previous studies of the sand eels in The North Sea it has been assumed that the foraging areas are located close to the burial habitat. Furthermore, it has been documented that there is a limited exchange between nearby foraging habitat areas [71].

The sudden disappearance of sand-eel fishing grounds from one year to another is a matter of discussion in relation to protecting the habitat and balancing the pressure from fishery. Apparently many of the habitats are located close to shallow seabed areas with substrates of till. During storms these areas are exposed to wave action which by erosion mobilize fine grained material which is transported into the nearby sandy sand-eel habitat. This influence of fines in the well-sorted sandy burying sand eel habitat areas most likely causes a change of the physical environment by increasing the amount of silt/clay to a level exceeding the requirement for the sand-eel.

A better understanding of the factors that drive the sand eel abundance variations is strongly needed to assist the managing of the very sensible species. A geological approach will help to gather information and predict potential burying sand eel habitats in the North Sea.

Case Study 2: Using sediment data from the Geo-Seas database to examine the effects of sediment on the species composition in beam trawl samples in the Western English Channel

Example of broad- to fine-scale sediment mapping

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Executive Summary

- Five different sediment classifications of varying resolution were employed to determine the level of detail necessary to describe the preferences of fish and commercial species to characterize communities.
- Multivariate analyses suggested that sediment data is an important driver in determining species distributions, but other currently unknown factors also play an important role as there were further trends in species composition which these data did not explain.
- Clustering species composition and sediment samples within 12 miles of trawl stations suggested a poor definition of species composition based on sediment types. However the low cluster consistency between sediment and fish samples was a result of where the division of clusters were drawn in the two datasets and not a poor correlation between species composition and sediment type as illustrated by the ordination methods.
- Classification systems with greater resolution (more sediment classes) did not provide improvements in the ability to predict fish communities.
- Knowing that both sediment and species data present continua, rather than discrete clusters, suggests that the information is still sufficient to determine likely species composition on the basis of sediment type in the Western English Channel.
- Future research should attempt to predict species composition on the basis of sediment samples and compare these with independent collections of fish communities. Further investigations will be required to determine if different sediment sampling methodology is causing bias/artifacts in the analysis completed.

Introduction

The aim of this study is to determine the utility of the available sediment information in the Western English Channel in understanding the species composition of fish in beam trawl samples collected in a stratified random sampling design. Species composition has been found to be highly ordered throughout the area, however little is known regarding the prevailing physical conditions that underlie this order. The Geo-Seas project aims to provide geological and geophysical data in an internationally coordinated database in order to allow more effective use of such data, which will help in improving our understanding of ecosystem processes. One such outcome is the provision of improved habitat maps delineating the distribution of individual fish species for the purposes of conservation and spatial management of the marine environment. However, nationally held sediment information is available at different levels of resolution and is potentially biased by the different gears used to collect such information. This study will examine the trade-off between the increased availability of samples and the potential ‘cost’(loss of information) of lower precision that is caused by the need to reduce sampling information to the lowest common denominator in order to extend the spatial scale. In addition analyses will use faunal composition information rather than species abundance data. This will provide a more general ecological analysis, rather than one based on an individual species that may or may not have very precise, and therefore easily detectable relationships between abundance and sediment type.

Methods

Catch data

Catch data from the first-quarter south west beam trawl survey (Q1SWBeam) undertaken using RV Cefas Endeavour for the years 2006-2011 were collated in the form of a species abundance matrix. This survey is designed to collect information on the abundance of commercially important ground fish species particularly such as sole and plaice. Log - abundance per sample of the forty most abundant species among all surveys was analysed using various multivariate techniques.

Sediment data

Sediment data from Cefas, British Geological Survey (BGS) and Ifremer were combined. Resolutions differed between these three data sources and were instructive in producing the different classifications tested (see below). Some of the Ifremer data is transformed, but no transformation was completed for BGS and Cefas data. This meant that there are considerably less data available for the highest resolution tested which is one possible limitation to the work completed for this study.

In the 2009 survey there was an opportunity to collect sediment samples along the same tracks as the trawl samples. Typically, three sediment samples were collected, targeting the first, mid and last thirds of the trawl track. As the samples were taken from a syringe sub-sample from a 0.1m^2 corer (NIOZ, Netherlands Centre of Sea Research) along a trawl track several miles long, there was a large discrepancy in the spatial scale sampled by the different gears, and this raised issues for the analysis. It was reasoned that using an average value from the three sediment samples would imply a different scale of sediment variance for samples taken in 2009 compared to other samples. Consequently, the sediment sample nearest to the starting position of the tow was chosen to be indicative of the conditions along the tow. For trawl samples collected at other times, sediment information was inferred from other sources of information, including grabs, cores and dredges from around the fishing area. Each trawl was matched to the closest sediment sample within a 12 mile radius of the starting position of the tow. There is little evidence of the distance over which sediment samples are truly independent in the western English Channel. Our 12 mile radius was arbitrary, but informed by our prior knowledge of the areas fished. Trawl samples that had no sediment sample within 12 miles of the trawl site were excluded from the analysis.

Statistical methodology

Multivariate methods are highly effective at identifying shared components in associated data and consequently provide an efficient method of reducing very large datasets into a few essential key components. Moreover, because they use the available information on many species the methods are much less sensitive to the sample variability than univariate methods. Unfortunately these analyses are not strictly quantitative in the statistical sense as they do not deal with sample error explicitly. It is therefore not possible to determine the significance of a specific trend in species composition. Assuming that there are at least some significant trends in the community data the key components can then be linked to specific environmental variables. The significance of any relationship can then be tested using traditional regression techniques in a canonical ordination analysis to attain a better understanding of the factors that coincide with changes in the species distribution. In this study clustering [74] and ordination [75] analyses have been used.

Dependent on the analysis and the measure of distance chosen between samples some general principles for data transformation need to be considered. Using only the more abundant species would reduce the effects of rare species in the cluster analysis. For rare species absence is not necessarily an indication of the lack of suitability of the sampling location, but is often more associated with the probability of encounter. Log transformation is intended to reduce the effects of the highly abundant species, which can particularly dominate the correspondence analysis as this is a variance based technique that has no formal means of accounting for sampling variance. This variance is likely to be much higher for abundant than less abundant species due to the mean-variance relationship associated with catch statistics.

The combined effects of high abundance and a contagious error distribution of poor cod (*Trisopterus minutus*), even if log-transformed, tended to order samples merely on the basis of the abundance of poor cod ignoring the contributions of other species to multivariate analyses [76]. The species was therefore excluded from the analysis.

The analysis focused on fish species, but also included some invertebrates of commercial importance such as scallops and cuttlefish which had been collected consistently over the whole time series.

Both sediment and species composition data were initially analysed using cluster analysis based on the Bray-Curtis distance measure [77] and Ward's method [78] for combining the samples. However, clusters formed by the sediment data did not prove to be a particularly reliable predictor of the clusters formed by the biological data, so alternative methods of analysis were applied. Correspondence analysis is a common method of investigating species composition, although much more rarely applied to sediment data, as a particular grain size is not usually thought of as having an optimum condition along an environmental gradient as modelled in correspondence analysis. Given the strong tidal influence and the paucity of sediment sources in the area, sediment distribution mostly reflects the deposition and suspension routes driven by environmental gradients. In this sense a specific particle size is representative of a relatively narrow band of environmental conditions so that a correspondence analysis of sediment particle size can be interpreted akin to that of a particular species.

Canonical correspondence analysis explains the variation in community data on the basis of covariates, which here we used to investigate the correlation between species and sediment information. The covariates used were either gradients from the correspondence analysis on sediment data or the raw classification information for the pre-classified sediment information (see below). The subset of variance along the first three canonical gradients was then attributed to a category / cluster using the ordination scores to calculate a Euclidian distance matrix which was then used to grow clusters using Ward's method.

A diagram of the multivariate statistical approach to the problem is provided in Figure C2-1. The figure also relates specific figures in this report to steps in the process which is not always immediately clear from the diagrams themselves as for example ordination plots look very much alike whether canonical (showing only the proportion of the variance in species composition that can be explained by environmental covariates, in this case sediment information) or unconstrained (not using environmental covariates) and dendrograms are similar independent of the underlying distance measure and cluster splitting routine.

The same procedure was followed for five sources of sediment information. The first three were quantitative, providing information on the particle size distribution of the sediment at different resolutions governed by the number of size bins examined. The fine resolution had 36 bins, one for each 0.5 phi particle size in the range 0.5µm to 63mm, based on Cefas data. The medium resolution had 12 bins, one for gravel, one for silt clay and the other ten for the 0.5 phi size classes relevant to sands, based on some BGS data. The coarse resolution had 5 bins, one each for gravel and silt/clay and the remaining three for coarse, medium, and fine sand, based on remaining BGS data. Ifremer data was transformed to this resolution only.

The last two information sources were qualitative. The first used the Folk classification, as used by the BGS in its 1:250,000 scale seabed sediment digital maps [79], identifying 15 sediment classes (e.g. muddy sand, muddy gravel, sandy gravel etc.) according to the relative proportion of mud, sand and gravel in the samples. The last system used a radical simplification of the Folk diagram into just 4 sediment classes, namely coarse sediment, mixed sediment, sand and mud, which underpins the European marine habitat classification developed by EUNIS (the European Nature Information Service) and detailed in Long [5]. The EUNIS system is hierarchical and uses these four sediment classes in the higher levels of the classification, together with information on light availability and energy regime (current speeds & wave exposure) to classify marine habitats according to their physical properties. This classification system has been applied by Coggan and Diesing [68] to produce a modelled habitat map of the English Channel, and this was used to assign one of the four sediment classes to each of the trawl sampling sites.

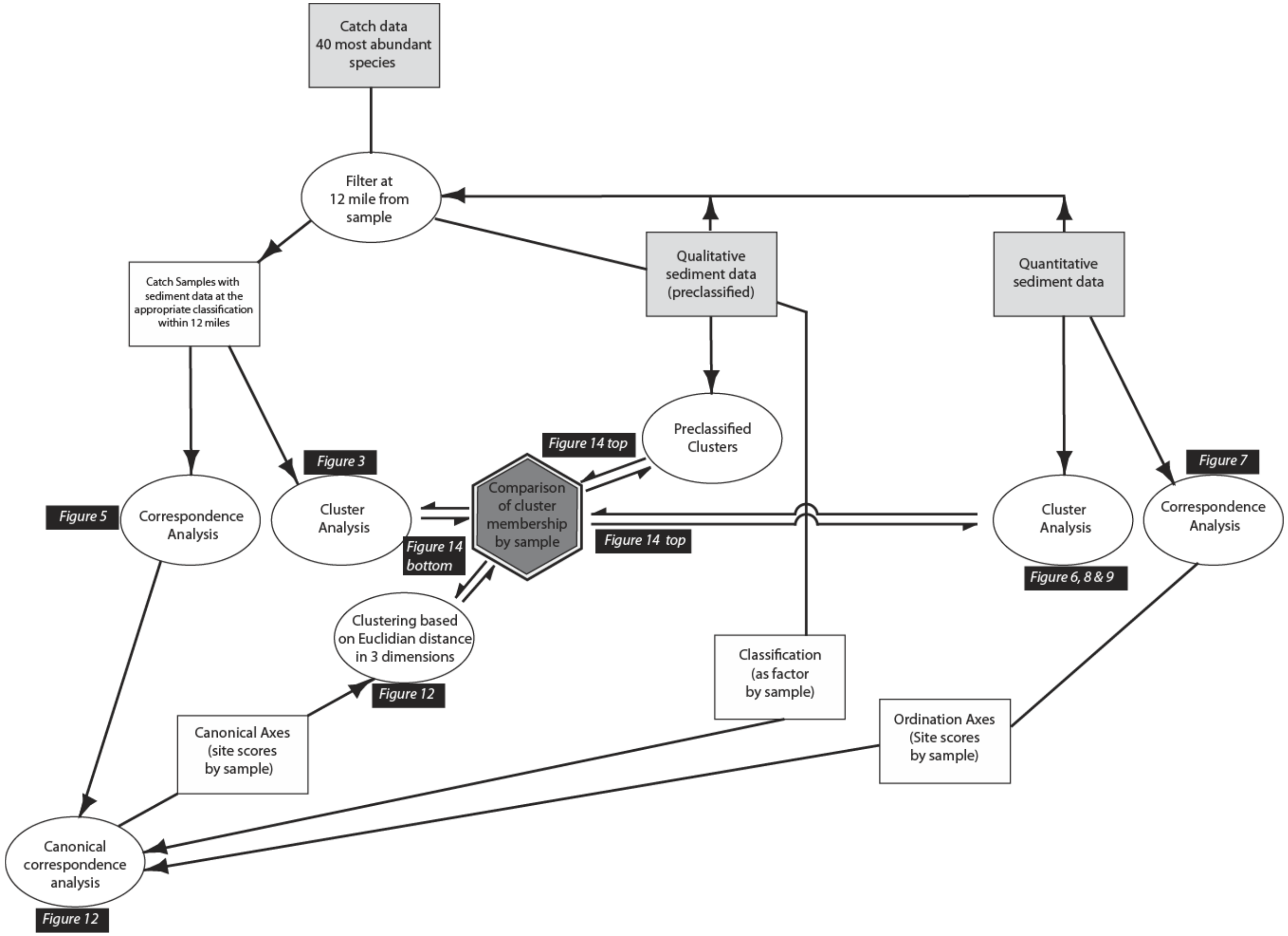


Figure C2-1: Flow diagram of the analytical procedure with key points of analysis to illustrate the difference between the different methods of attempting to provide a useful proxy of species composition of demersal fish species on the basis of various types and resolutions of available sediment information. The figure also indicates the conceptual position of other figures in the paper to facilitate differentiation of figures, despite very similar appearances.

Results

Species

A total of 478 samples were used in the analysis. The species composition of catches is shown in Figure C2-2 as pie plots, while Figure C2-3 shows the dendrogram of the respective cluster analysis, and identifies the ten cluster groups that are formed by applying Wards method of defining clusters. The results of the cluster analysis are plotted spatially in Figure C2-4. A substantial degree of spatial segregation of communities that is apparent in the pie plots is confirmed by the cluster analysis particularly in the northern section of the survey area, whereas in French waters there seems to be more spatial overlap between cluster 6 and 9 and clusters 8 and 10. The latter two pairs of clusters as well as clusters 5 and 7 are split closer to the x-axis suggesting these clusters are more similar to each other than to the remaining groups so complete spatial segregation is less likely for these closely related clusters.

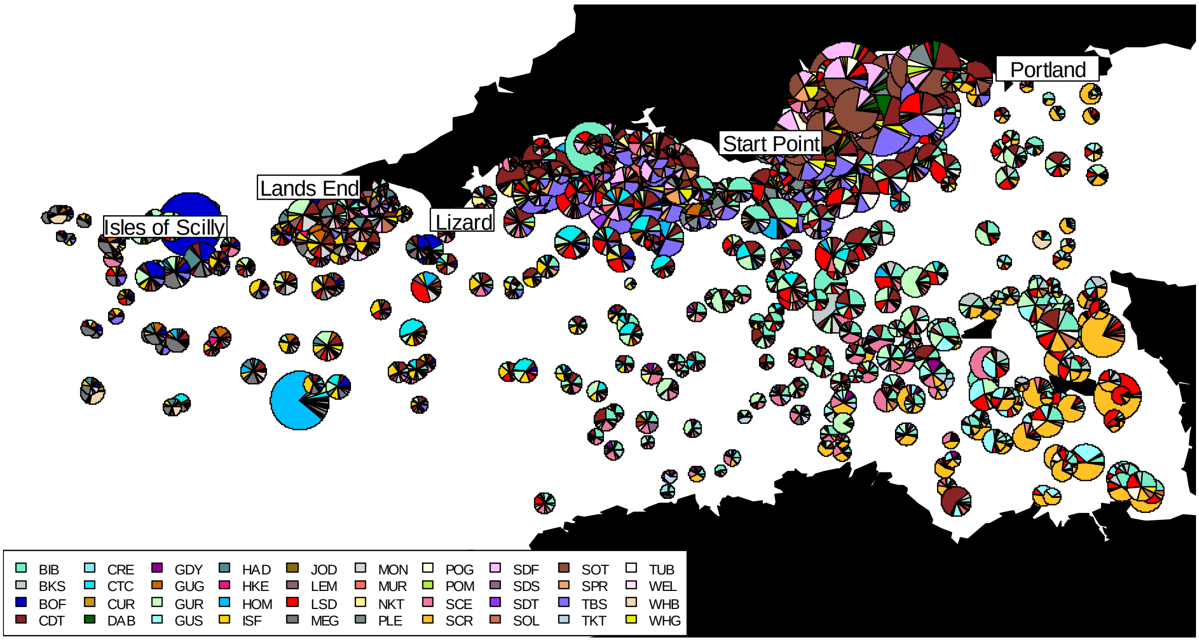


Figure C2-2: Pie-plot of species compositions of beam trawl catches from the Q1SWBeam survey. The size of the pie is proportional to the square root of the total abundance, with the relative contribution by each species being represented by the size of the segments. Although individual species are difficult to distinguish with this many species the plot illustrates the spatial consistency of species composition on a regional scale.

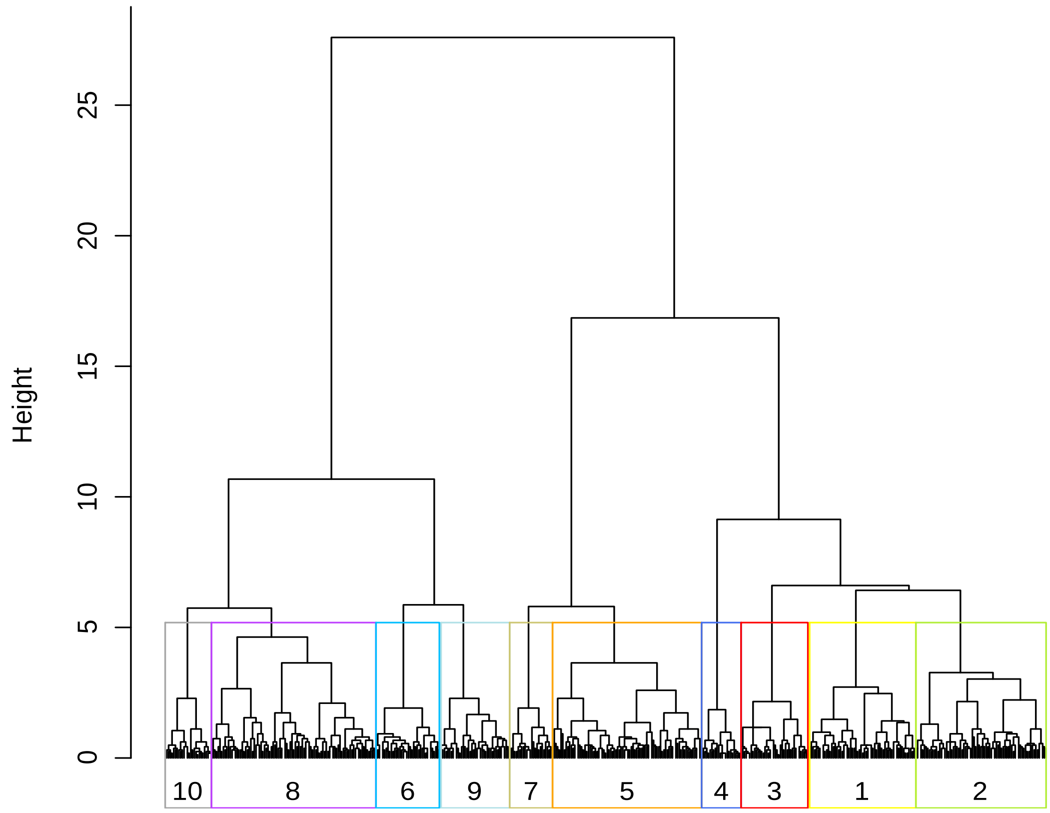


Figure C2-3: Dendrogram of species composition of the Q1SWBeam survey catch compositions. Similarity is based on Bray-Curtis index, and clusters are joined using Ward's method.

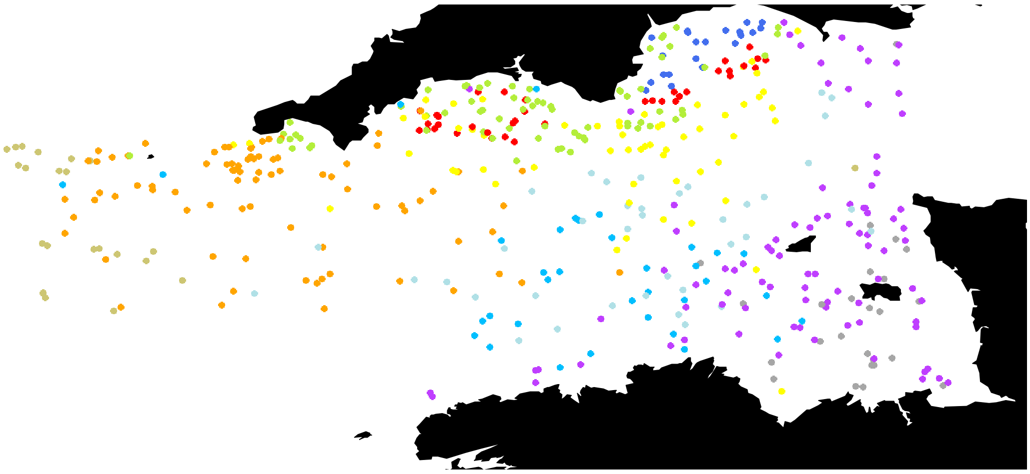


Figure C2-4: The spatial distribution of samples of the Q1SWBeam survey with species composition of each sample characterized by cluster analysis. Beam trawl sample positions are shown indicating the spatial distribution of the clusters determined by the cluster analysis on species composition only. Sample colours correspond to those identifying the clusters in Figure C2-3.

The correspondence analysis of the same data suggested that the species composition of trawl catches changed gradually in relation to the two primary axes presenting a single ‘envelope’ of varying faunal composition rather than a number of discrete, distinct communities (

Figure C2-5).

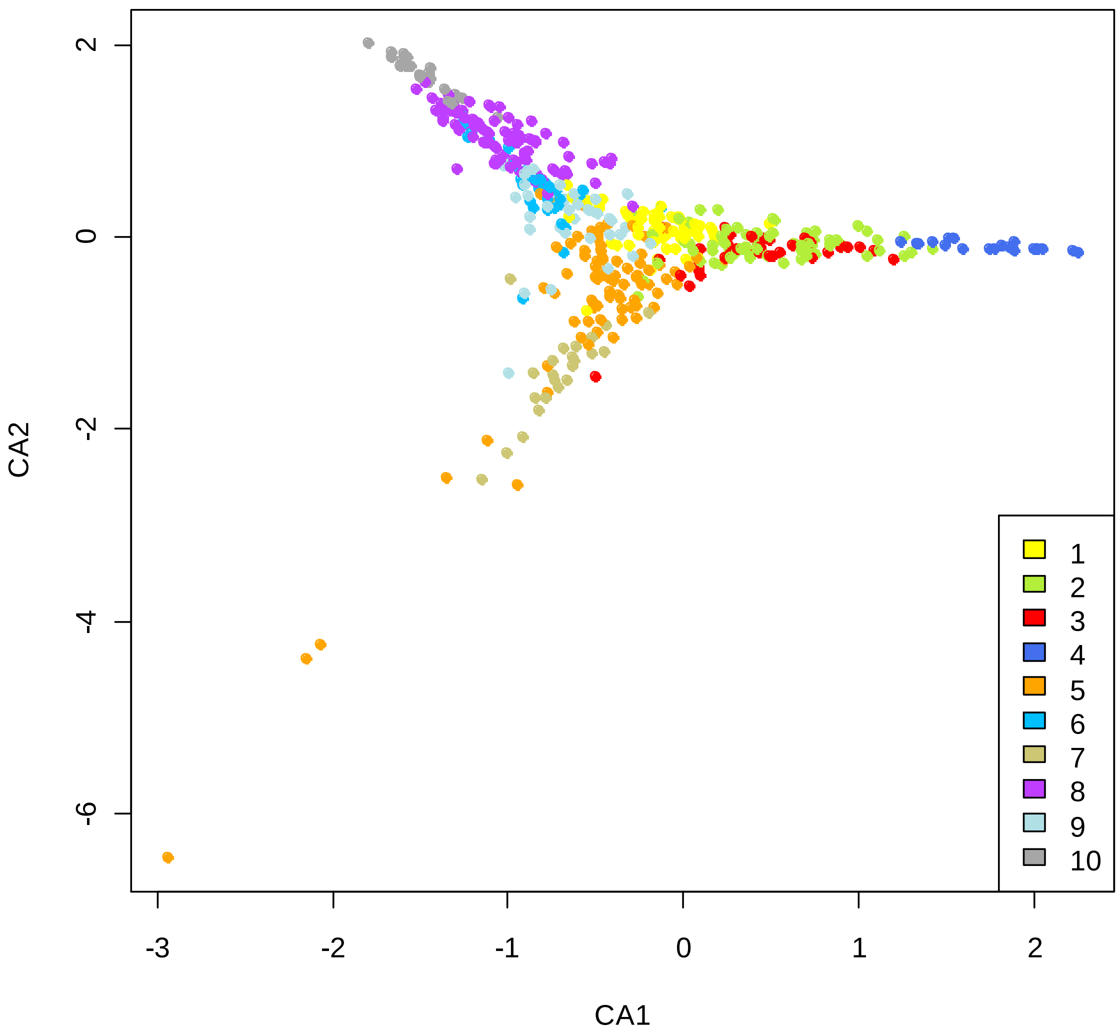


Figure C2-5. Ordination plot of the first two axes of the correspondence analysis of the species composition data. Colours of samples correspond to the cluster association indicated for each sample as shown in Figure C2-3. The fact that clusters remain grouped indicates reasonable agreement between the cluster and correspondence analysis, but the fact that the transitions are continuous suggests that there are no obvious breakpoints between samples.

Sediment

The results of the sediment analysis for the three different qualitative systems of sediment classification are presented in order of decreasing resolution. Figure C2-6 shows the dendrogram and the spatial distribution of clusters based on the fine resolution sediment information. Generally speaking, clusters 6, 9 and 10 are located inshore, close to the UK mainland and Scilly Isles while clusters 1 and 2 are located further offshore. The dendrogram shows that these clusters are very dissimilar to the remaining clusters, being separated from them at a dissimilarity of about 35%. Clusters 7, 5 and 8 represent a west to east gradient in sediment type, at or near mid channel. Cluster 3 has a much broader distribution that seems to be uncoupled from distance offshore, occurring inshore in the west, but offshore in the east. The ordination plot, Figure C2-7, for the first two axes of the correspondence analysis showing the centroids of each particle size which indicate that clusters 5 (orange dots) and 8 (purple dots) represent samples with the coarsest sediments and the largest spread in ordinal space, while the other clusters suggest much greater similarity, both within and between clusters. A further discrimination between Phi classes is evident around Phi= 0 on the secondary ordination axes. The relative importance of each ordination axis is shown in Table C2-5 long with those for the ordinations at other sediment classification levels.

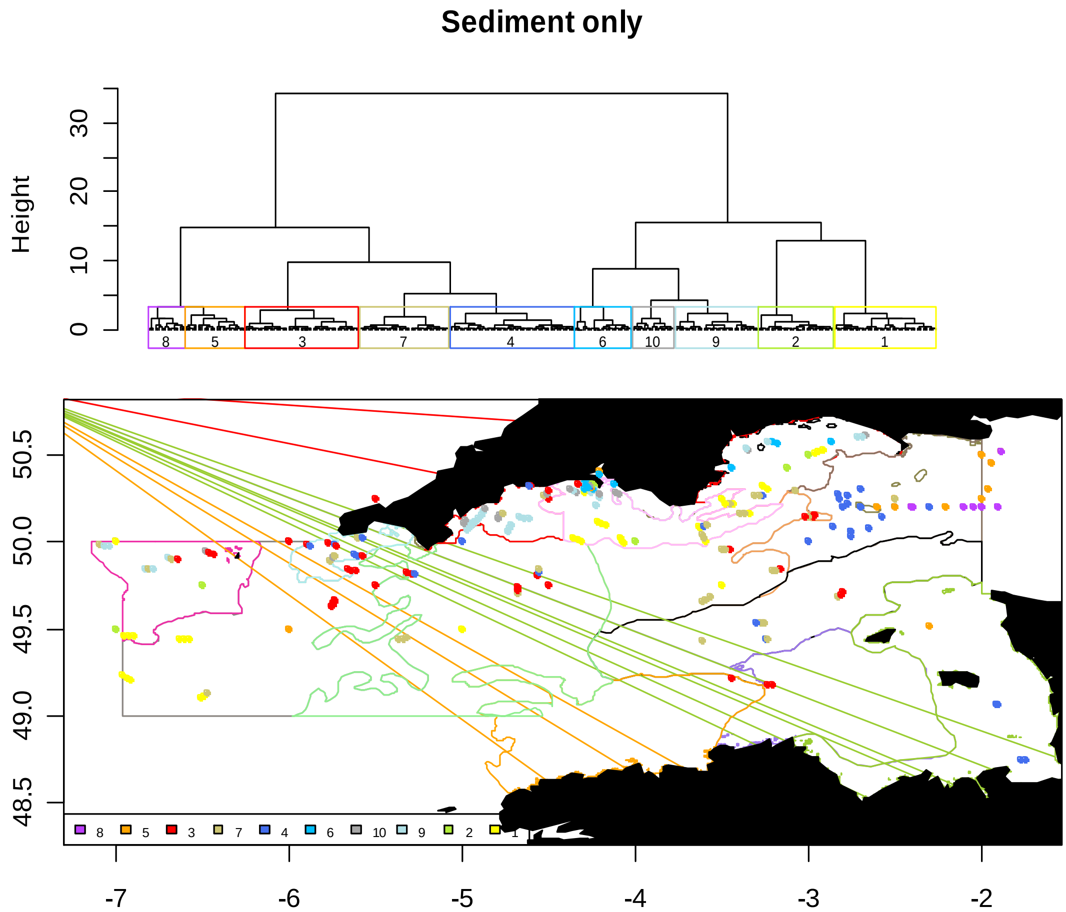


Figure C2-6: Dendrogram of the available sediment data at the fine resolution range (top) with the associated spatial distribution of clusters (bottom) both using the same colour coding for plots.

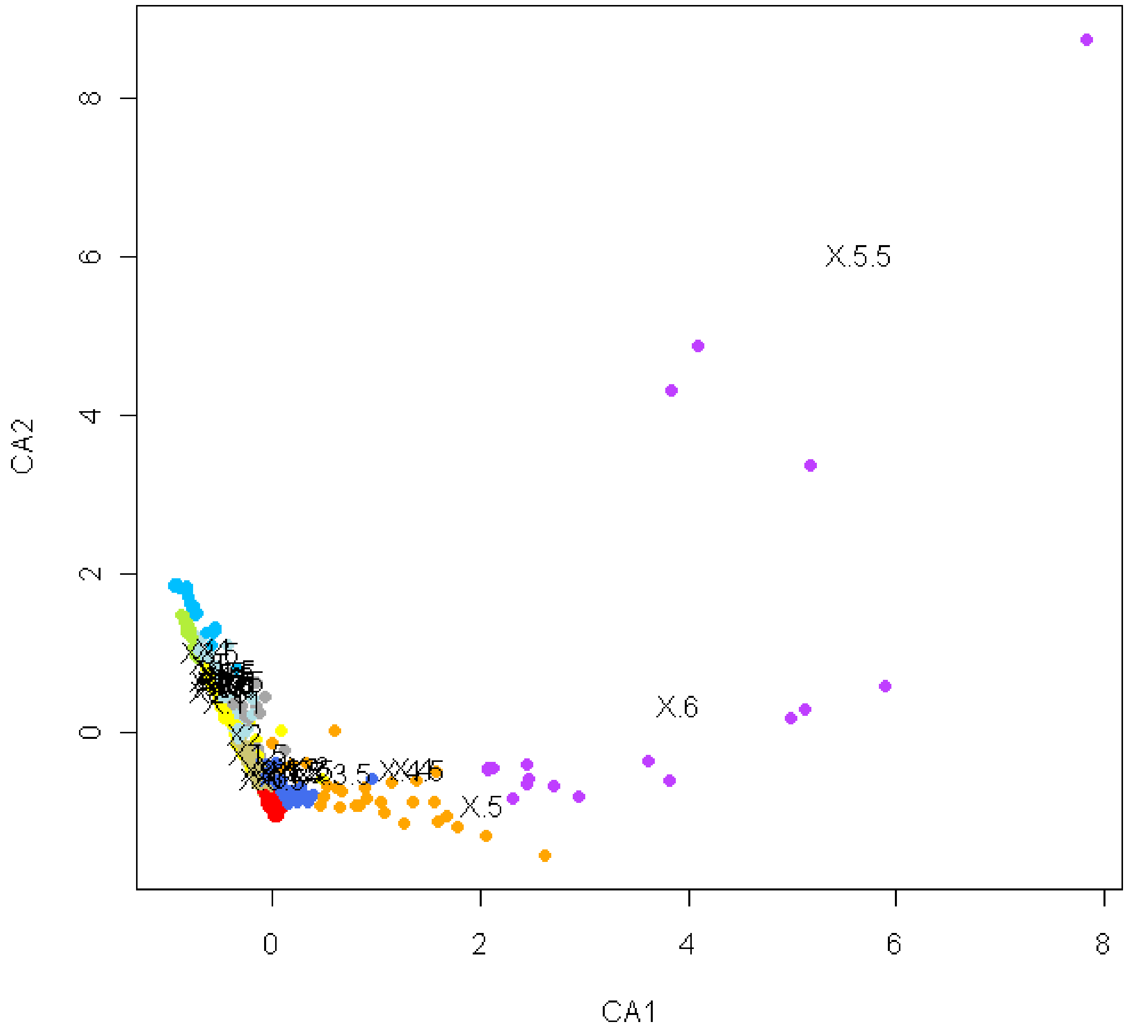


Figure C2-7: Ordination plot of the first two ordination axes. Text indicates the mean position of sediment particle sizes (in phi) prefaced by X and X. for negative values while the colour represents the associated cluster based on the sediment cluster analysis. Purple and orange samples (cluster 8 and 5) represent the coarsest sediments and are located on the eastern part of the survey grid.

Table C2-1: Results of the sediment only correspondence analysis for the quantitative sediment classifications for the first eight (where applicable) ordination axes. Eigenvalues are indicated in bold; underneath the proportion of the total variance explained is given. This shows that the complexity of the sediment composition data can be efficiently reduced to a much smaller number of linear components irrespective of the resolution of the chosen resolution.

	Total inertia (variance in community space)	Ordination axis							
		1	2	3	4	5	6	7	8
Fine resolution	**2.781**	**0.612**	**0.477**	**0.442**	**0.311**	**0.286**	**0.162**	**0.127**	**0.089**
		0.220	0.171	0.159	0.112	0.103	0.058	0.046	0.032
Medium resolution	**2.128**	**0.598**	**0.455**	**0.304**	**0.279**	**0.175**	**0.124**	**0.082**	**0.051**
		0.281	0.214	0.143	0.131	0.082	0.058	0.039	0.024
Coarse resolution	**0.893**	**0.448**	**0.231**	**0.134**	**0.081**				
		0.501	0.258	0.150	0.091				

With the next coarser level of sediment classification, using medium resolution data classes (Figure C2-8), clustering again shows a considerable spatial segregation with clusters 2, 7 and 10 being located inshore, and cluster 5 located in the east, corresponding to the coarser sediments there. However, clusters 1, 6 and 8, which occur in the central part of the dendrogram show less spatial demarcation. Clusters 8 and 3 which split high up in the dendrogram, appear to be occurring in similar geographic locations. The ordination plot for the data (not shown) is similar to that for the fine resolution plot (Figure C2-7), although the larger particle sizes are not so clearly separated from the smaller ones.

With the coarse resolution system of sediment classification, having just five classes (gravel, coarse-, medium-, fine-sand and mud) a significantly greater number of sediment samples become available, particularly from the BGS dataset and a significant amount of French data provided by Ifremer (Figure C2-9) is available at this coarser resolution. Clusters 1 and 3 show a distinct spatial patchiness with cluster 3 adjacent to or surrounded by cluster 1 and found in both the UK 'great bay' systems (the Lizard to Start Point and Start Point to Portland = Lyme Bay) and SE of the Scilly Isles. Outside this area cluster 6 also shows a distinct patchy distribution and is generally more associated with the samples found further offshore and which occur in the right arm of the dendrogram. Clusters 2, 5, and 8 appear to show some patchiness, but tend to be more evenly spread throughout the central part of the channel and east of the Channel Islands. Cluster 4 is largely found to the west of Start Point with clusters 7 and 9 located across the breadth of the channel in the east. The ordination plot (Figure C2-10) suggests that a more even distribution of the variance components between samples, covering the triangular extent of samples in ordinal space more evenly when compared to the finer resolution data (Figure C2-7) where the samples containing finer sediments are densely aggregated in the bottom left of the plot. In addition, the sediment cluster analysis appears to separate samples along very similar lines to the ordination. The first 2 axes of the correspondence analysis account for 76% of the total variance (Table C2-5), although of course the total numbers of degrees of freedom are limited by the number of sediment bins (n=5 for coarse resolution data used here) available for the analysis.

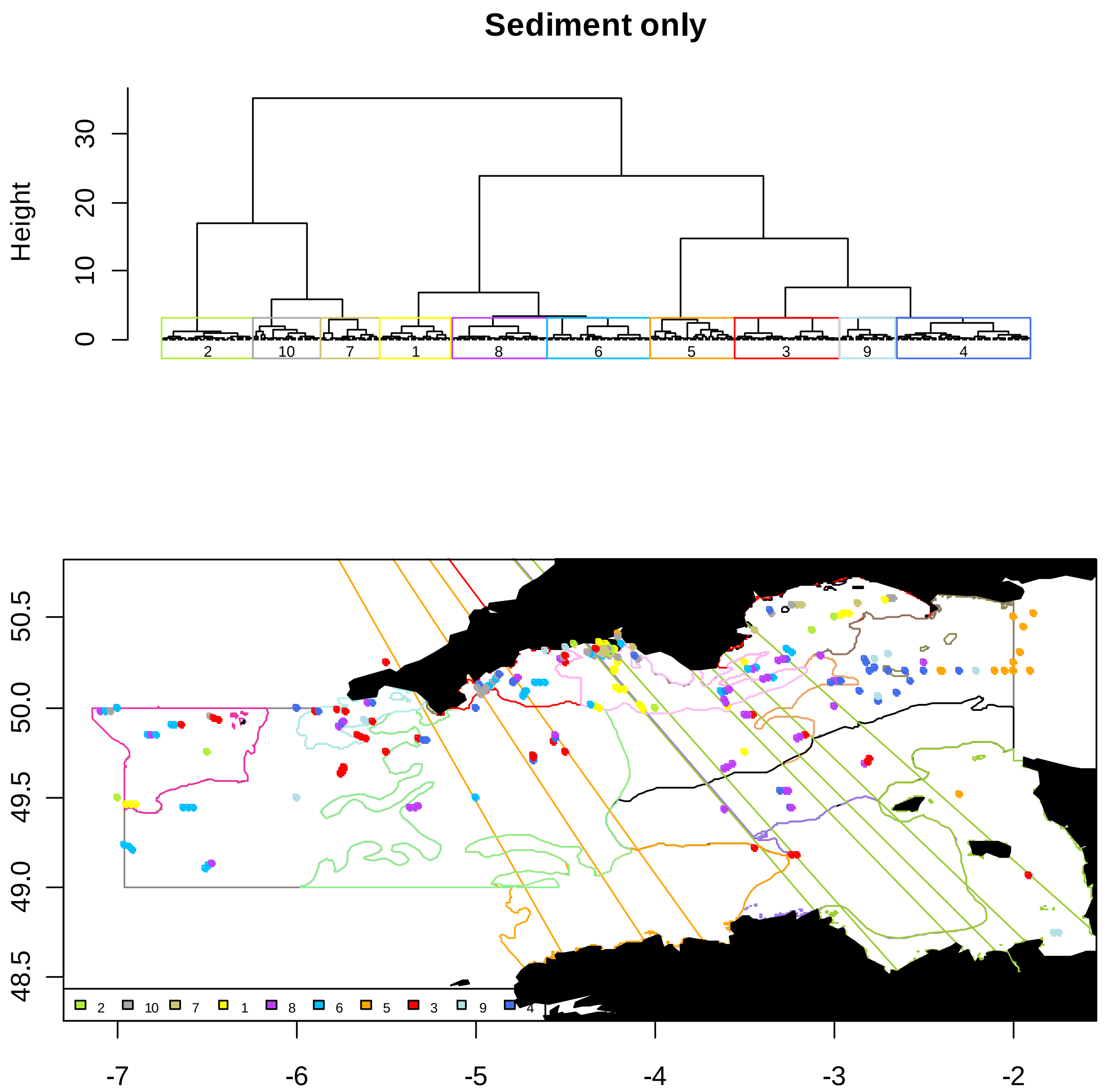
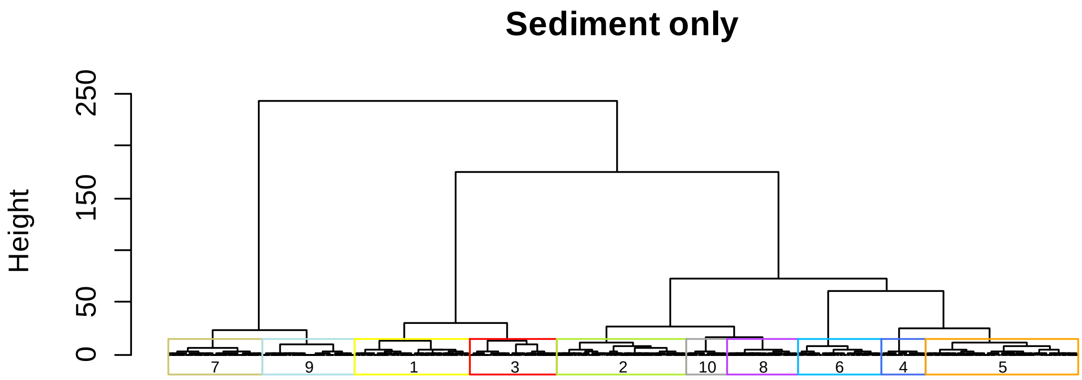


Figure C2-8: Dendrogram of the available sediment data at medium resolution (top) with the associated spatial distribution of clusters (bottom) both using the same colour coding for plots.

Samples containing gravel and sandy gravel are dominant in the eastern portion of the study area, with sandy gravel also common outside of the 'great bays' westwards to Lands End (

Figure C2-11). Westwards the proportion of sandy habitat increases. The inshore area in Lyme Bay shows a patch of muddy sand surrounded by gravelly muddy sand before turning sandy further offshore.

There is a good agreement between the EUNIS marine habitat classification for the sampling points (Figure C2-12) taken from the predictive habitat map of Coggan and Diesing [68] and the survey strata used in the trawl study although this is not particularly surprising as both are constructed using (*inter alia*) sediment and depth information.



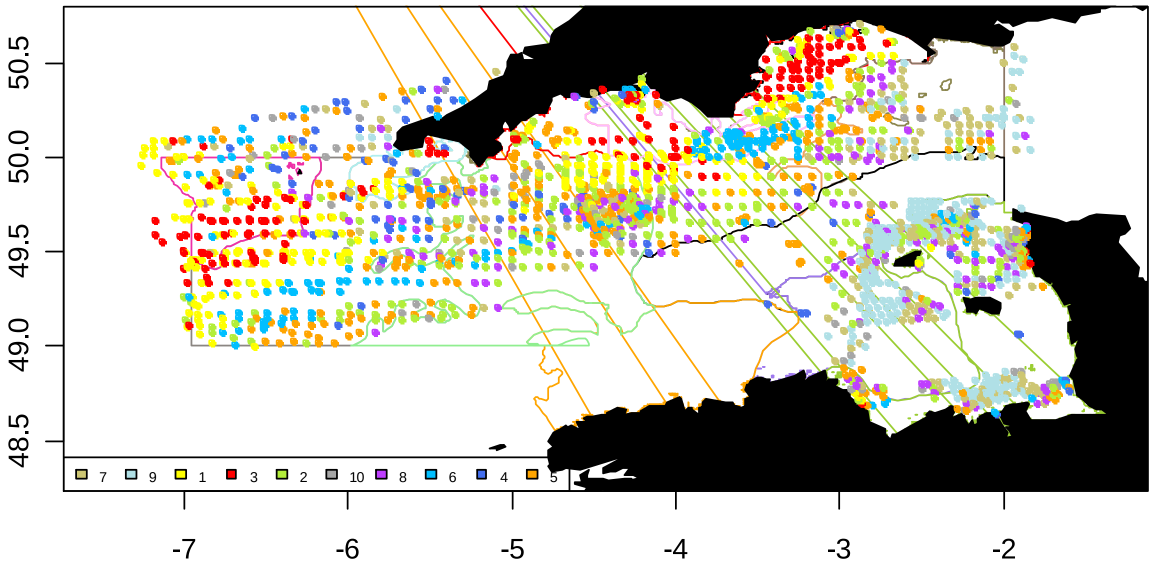


Figure C2-9: Dendrogram of the available sediment data at the coarse resolution range (top) with the associated spatial distribution of clusters (bottom) both using the same colour coding for plots.

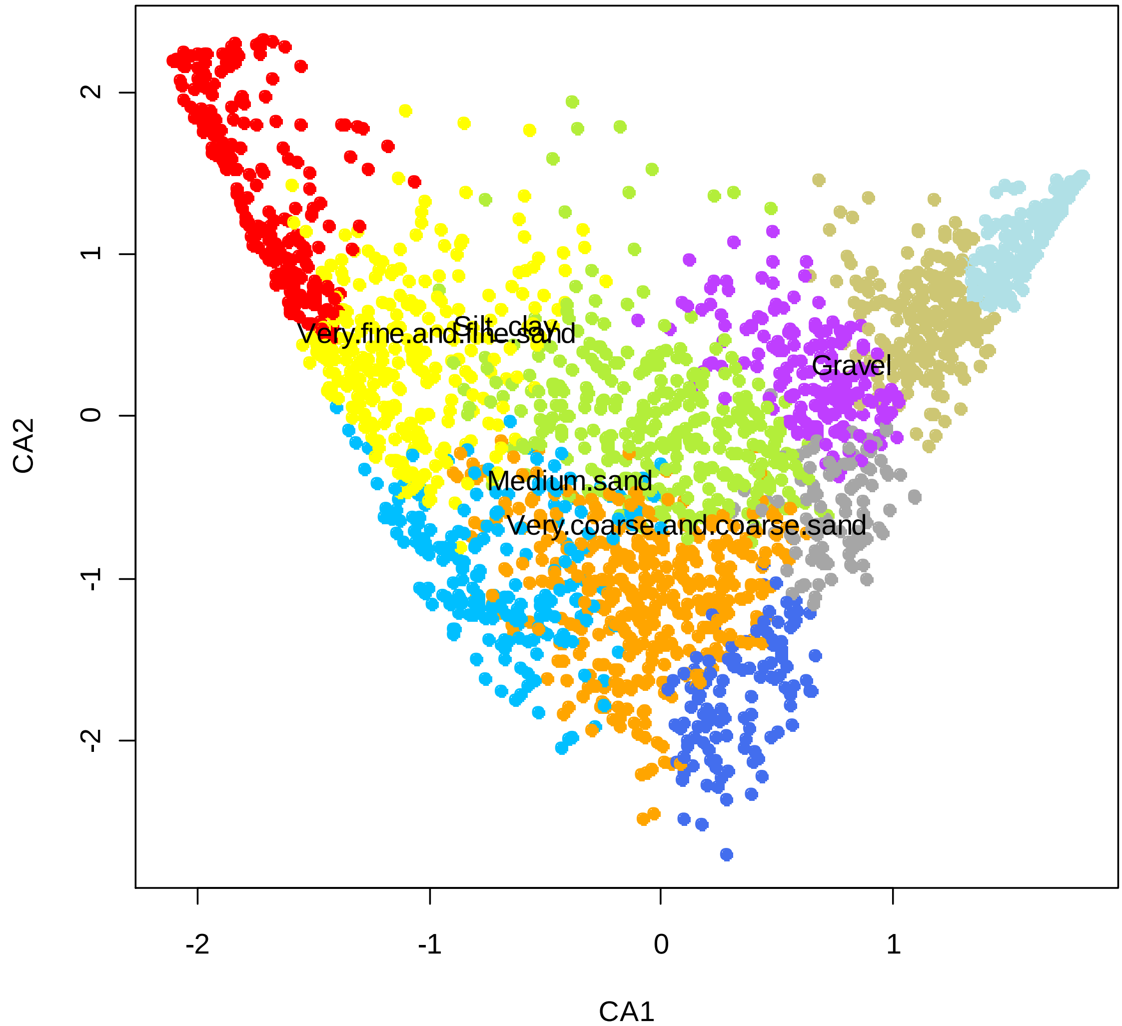


Figure C2-10: Ordination plot of the first two ordination axes. Text indicates the mean position of sediment particle sizes (in the coarse resolution range) while the colour represents the associated cluster based on the sediment cluster analysis. Variation in relative contribution of the coarsely aggregated sediment types is spaced evenly through ordination space compared to higher resolution sediment information.

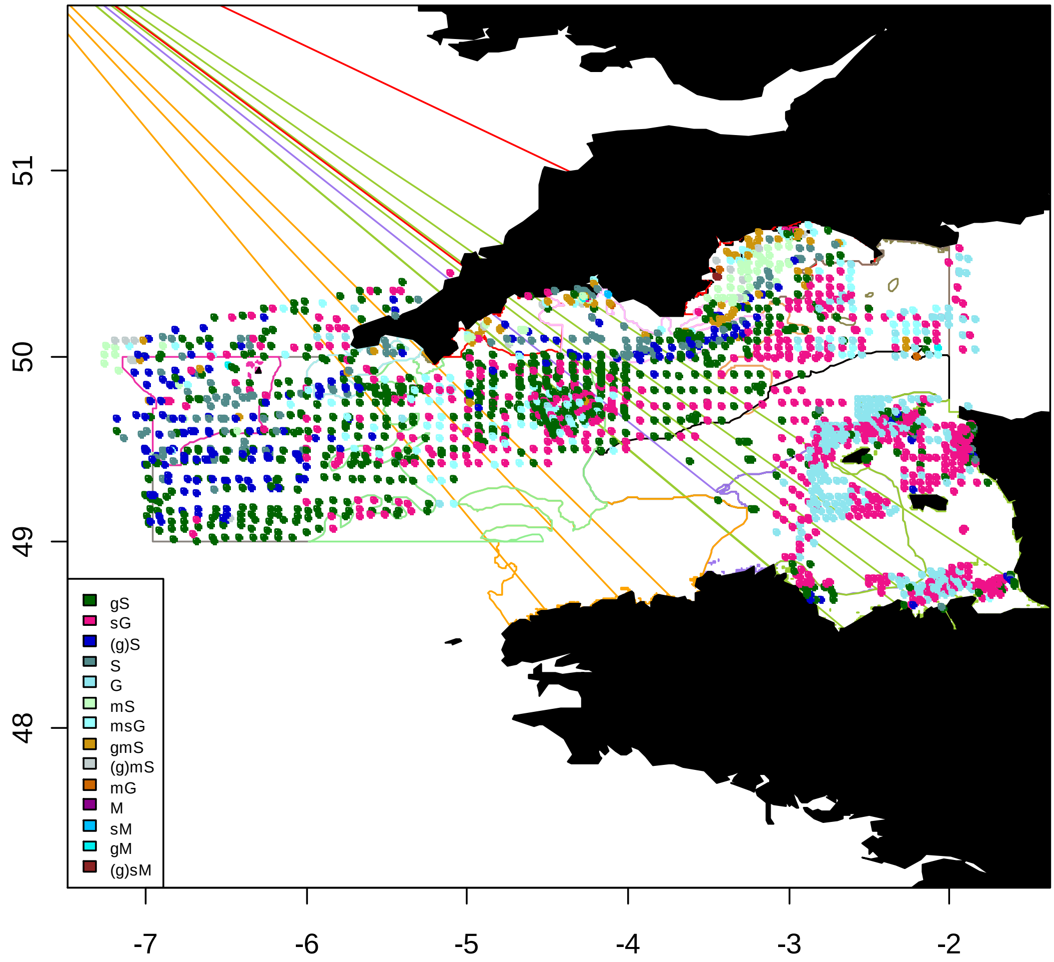


Figure C2-11: Spatial distribution of available sediment samples with colours indicating appropriate Folk classification.

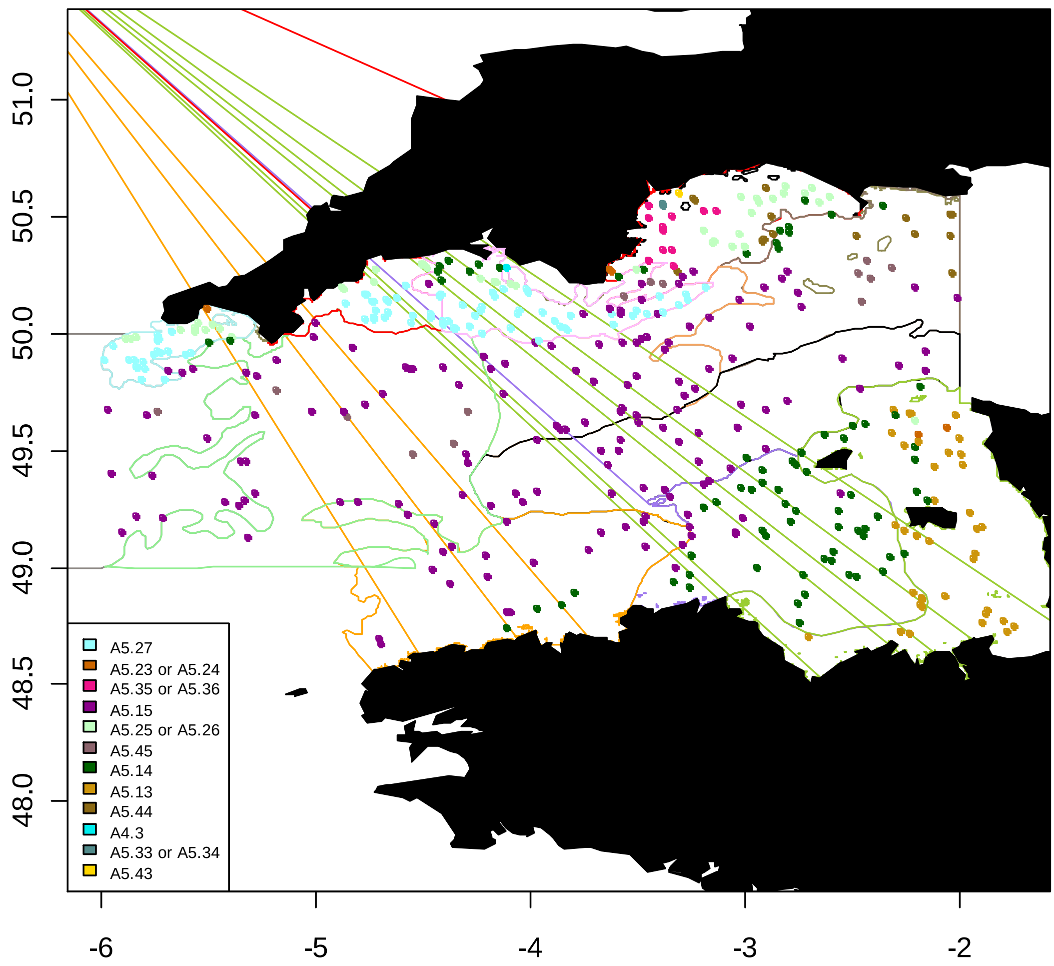


Figure C2-12: Spatial distribution of catch samples with colours indicating corresponding EUNIS classification as provided in Coggan and Diesing [68].

Species and sediments combined

Canonical ordination is designed to isolate the common component in changes in species composition and environmental conditions. The analysis is 'constrained' to show only the changes in species composition that can be accounted for by associated environmental variables. Using the sediment ordination information it is possible to determine the degree to which patterns in the sediment data explain the observed patterns in species composition. An example of the canonical analysis using the course resolution data is shown in Figure C2-13. Irrespective of the level of aggregation (i.e. the fine, medium and coarse resolution sediment data) or the pre classification system (Folk or EUNIS) the first canonical axes explained about 8% of the variation in species composition of trawl samples and the second around 7% with the remaining axes in sediment data providing very little in the way of explanatory power leaving around 80% of the variation in catch composition (inertia) unexplained or unconstrained (not attributable to measured environmental effects - (unconstrained inertia in Table C2-2).

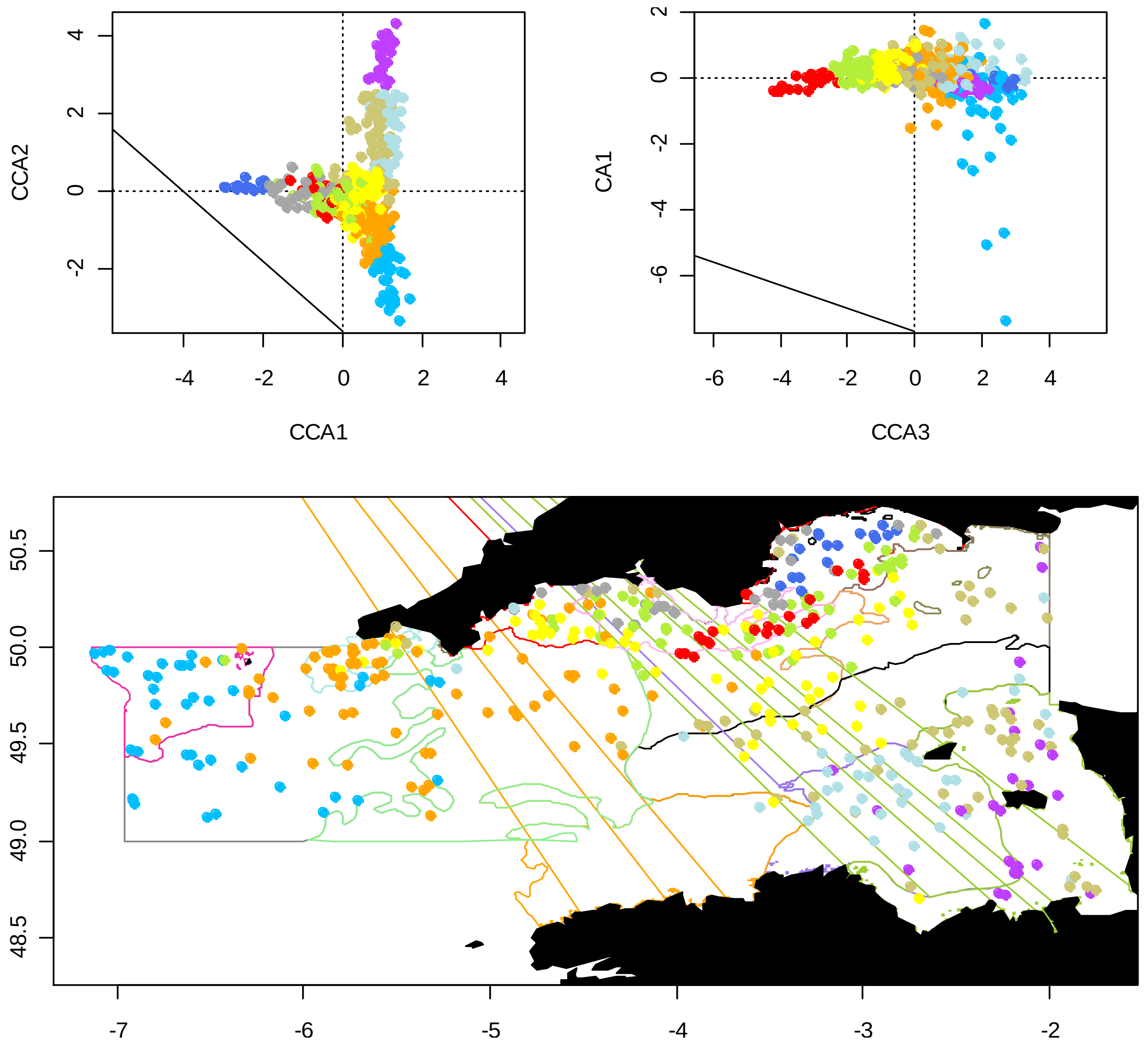


Figure C2-13: Canonical ordination of the first three constrained axes and the first unconstrained axes (top left cca axis 1 vs 2, top right cca axis 3 vs unconstrained axes) using the coarse resolution sediment data. Colours indicate the canonical clusters merged on the basis of Euclidian distance in ordinal space along the canonical axes using Ward's method. Spatial distribution of the ordination clusters indicates good overall agreement with the clustering on species distribution only. Coloured lines indicate the current survey stratifications.

Table C2-2: Results of the canonical correspondence analyses for the different sediment classification resolutions showing the eigen values and the importance (proportion of total inertia) of the first five canonical axes and the first three unconstrained axes. The difference in total inertia is due to the difference in the number of catch samples included due to the availability of sediment information at the appropriate level of classification.

	Inertia			Constrained Axes					Unconstrained Axes				
	Total	Constrained	Unconstrained	CCA1	CCA2	CCA3	CCA4	CCA5	CA1	CA2	CA3	CA4	CA5
Fine	**4.526**	**0.724**	**3.802**	**0.382**	**0.230**	**0.056**	**0.050**	**0.005**	**0.611**	**0.300**	**0.266**	**0.241**	**0.208**
		0.160	0.840	0.085	0.051	0.012	0.011	0.001	0.135	0.066	0.059	0.053	0.046
Medium	**4.526**	**0.738**	**3.788**	**0.385**	**0.241**	**0.058**	**0.049**	**0.006**	**0.610**	**0.300**	**0.262**	**0.238**	**0.207**
		0.163	0.837	0.085	0.053	0.013	0.011	0.001	0.135	0.066	0.058	0.053	0.046
Coarse	**5.004**	**0.960**	**4.043**	**0.436**	**0.347**	**0.109**	**0.055**	**0.014**	**0.527**	**0.348**	**0.298**	**0.252**	**0.212**
		0.192	0.808	0.087	0.069	0.022	0.011	0.003	0.105	0.070	0.060	0.050	0.042
Folk	**5.004**	**0.816**	**4.083**	**0.403**	**0.327**	**0.071**	**0.048**	**0.023**	**0.557**	**0.341**	**0.293**	**0.281**	**0.234**
		0.184	0.921	0.081	0.065	0.014	0.010	0.005	0.111	0.068	0.058	0.056	0.047
EUNIS marine habitat	**4.598**	**0.784**	**3.605**	**0.410**	**0.321**	**0.110**	**0.053**	**0.027**	**0.367**	**0.278**	**0.241**	**0.210**	**0.189**
		0.216	0.992	0.089	0.070	0.024	0.012	0.006	0.080	0.060	0.052	0.046	0.041

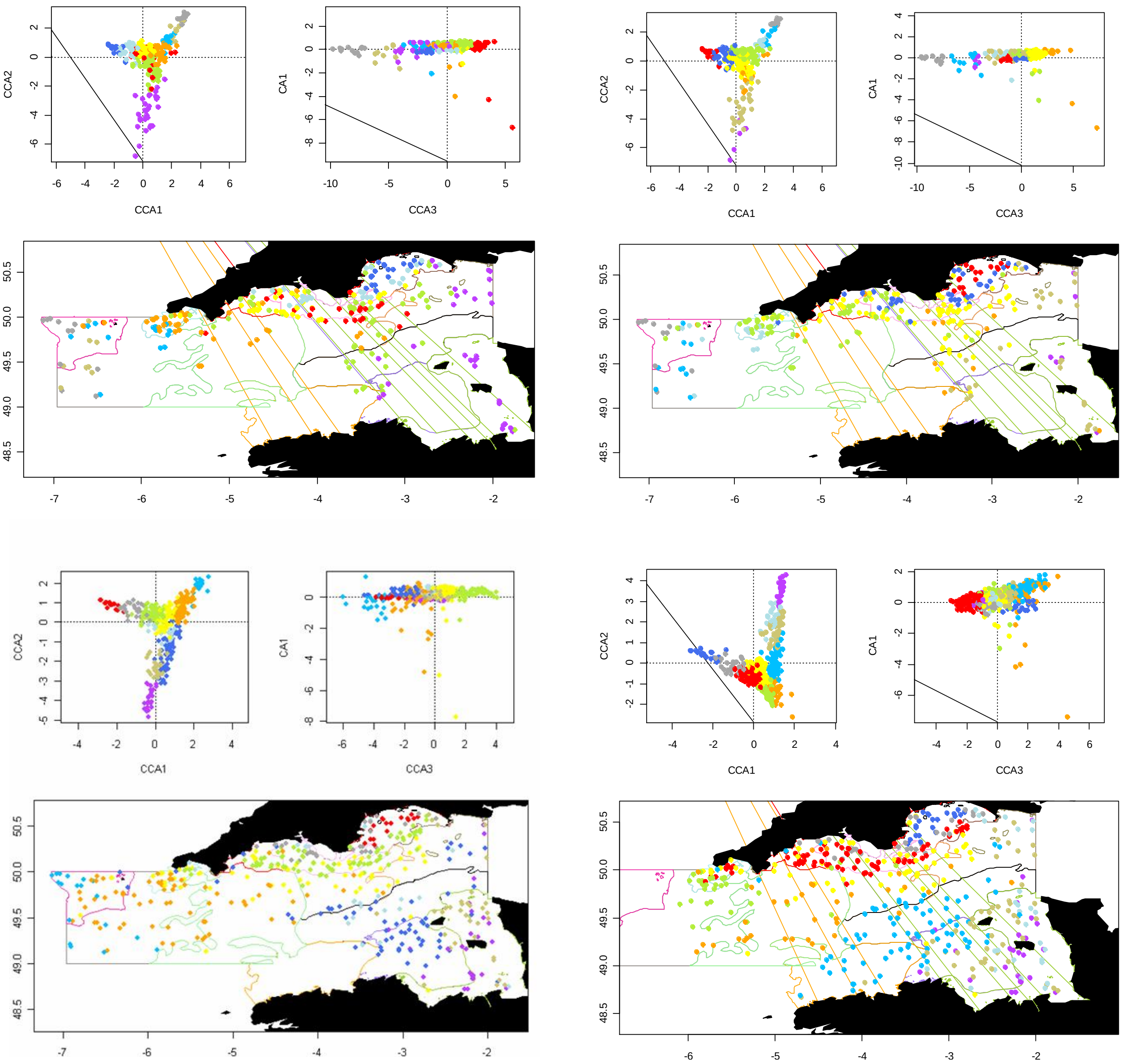


Figure C2-14: Canonical ordination and spatial plots of canonical clusters based on various levels of sediment aggregation, fine resolution (top left), medium resolution (top right), Folk (bottom left) and EUNIS (bottom right). A comparable spatial plot for the coarse resolution is shown in the previous figure (Figure C2-13).

Clustering in ordination space, using the first three canonical axes, enabled us to classify the species composition in terms of the available sediment information and these clusters are plotted spatially in Figure C2-14. The first two sediment classification schemes (fine and medium resolutions) have fewer samples as detailed granulometric analysis was not available for many data sets. Despite this it is obvious by inspection that all the classification schemes produce similar spatial patterns, the main differences being a consequence of where samples representing a continuous multivariate or spatial gradient are split into separate clusters.

Figure C2-15 compares the ability of each of the raw sediment classification systems to correctly classify the species composition of catches on the basis of the classification of the sediment data (top row), with the ability of the canonical ordination to do the same (bottom row). If a bar is of a uniform colour it indicates that all the samples belonging to one of the ten species clusters (Figure C2-3) were associated with a single cluster in either the sediment or canonical analyses. If the same colour appears in a number of bars this suggests that the corresponding cluster based on species composition is split amongst a number of the canonical clusters. Samples are significantly more ordered in the lower plots than in the upper plots suggesting that there is greater spatial correspondence between catch composition and the clusters determined by canonical correspondence analysis than with clusters based on 'raw sediment classification' alone (Figure C2-13).

Discussion

Many studies on the correlation between sediment type and the distribution of a species have been conducted. Unsurprisingly, for benthic species the results have been significant, leading to the use of sediment information in habitat maps. However there is a difference between the realized (where a species occurs) and the fundamental (where a species is able to occur) niche. Habitat maps based on single species information tend to best describe the realized niche only, so that as its abundance changes the spatial extent of its distribution is not expected to alter dramatically. In contrast habitat maps based on the information from many species are more indicative of the fundamental niche as it relates to the ecosystem interactions. It should therefore be much better at predicting the spatial extent of the distribution with changing abundance of a specific species and will be much more useful in marine spatial planning than the single species approach.

The results suggest that sediment data at a site can provide a significant amount of information on the likely catch composition at a given trawl station of a stratified random beam trawl survey. Furthermore it can do so irrespective of the precise system used to classify sediments and tends to explain about 15% of the total variance in canonical ordination. However the first unconstrained axis was roughly twice as important as the first constrained axes suggesting that there are important components in the species distribution that as yet remain unexplained. Given the importance of sediment type, several avenues of investigation were developed to ascertain where the variance components, sediment and catch data were coming from and determining the most efficient method to utilize the sediment information.

Ordination on the sediment data alone suggested that the largest variance components were located in the small number of samples representing the coarsest sediments. The reason for this lies with the finite sampling volume approach necessary for sediment sampling. Unlike the species composition data, sediment sample volume is fixed so that the proportion of one size fraction ultimately influences the proportion of the other size fractions. The effect is largest for the combination of small sample volumes, large particle sizes and higher resolution sediment classes. This effect is much less marked for the coarse resolution sediment information having just five classes.

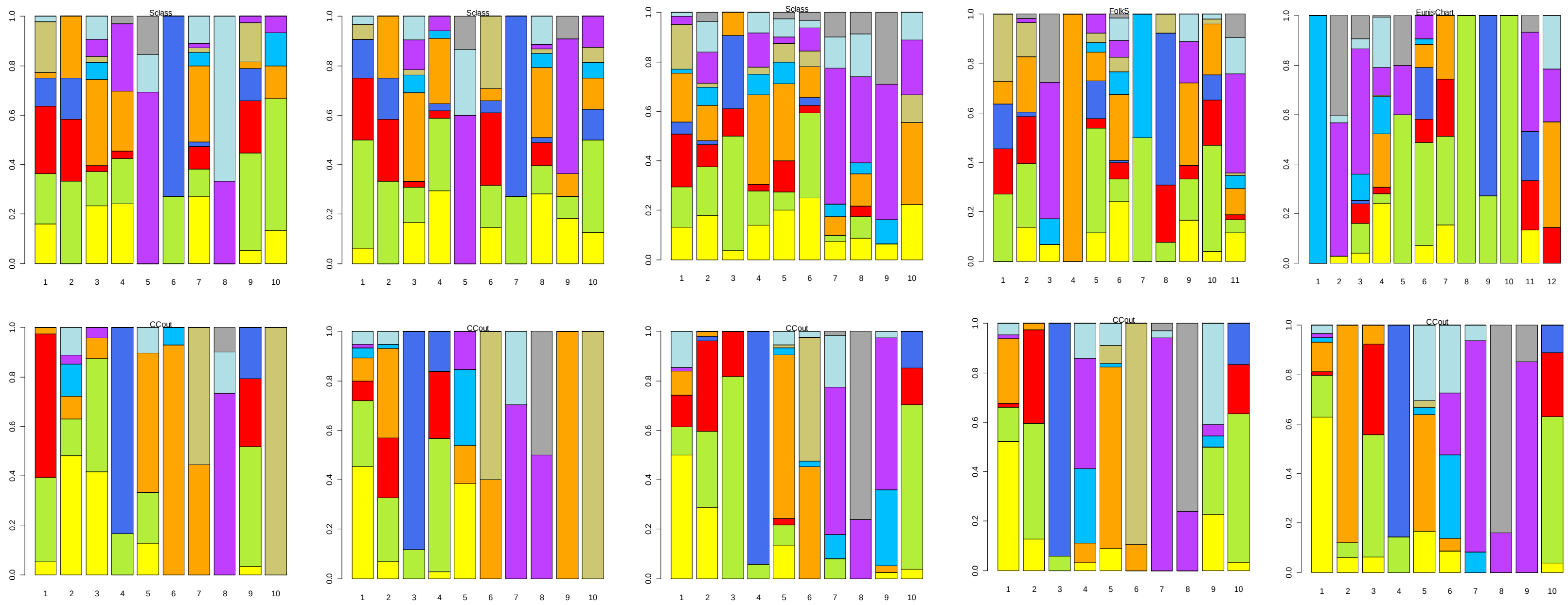


Figure C2-15: Plots of Percentage cross-tabulation, showing agreement between the sediment classification and the species composition classification for decreasing levels of sediment resolution data (left to right). Top row shows results using sediment data alone. Bottom row shows results using canonical ordination. Samples are significantly more ordered in the lower plots indicating that the spatial overlap in sediment clusters with those based on species follows different lines of division based on differences in the variance gradients. Cluster numbering (colour) is not comparable across analyses (either top to bottom, ore left to right). The figure is designed to show how consistently a cluster is species composition can be identified on the basis of the sediment information). If all colours were to appear in all columns it would indicate a random distribution suggesting there was no link between the species composition and the sediment information. If each column were characterised by a single colour and each column had a different colour sediment information could be directly linked to species composition. The greater the degree of ordering the better the ability to predict the appropriate species cluster assignment on the basis of the sediment cluster.

The pie plots of species composition (Figure C2-2) indicate both inshore-offshore (north-south) as well as east-west gradients consistently observed over the time series of available data. Species composition follows much smoother gradients in ordination than the fine resolution sediment data (compare

Figure C2-5 and Figure C2-7). Clustering of species data shows a high degree of spatial consistency within clusters, with the major split running from the eastern tip of Brittany to Portland on the UK coast.

Clustering of the sediment information is equally spatially coherent as was the species composition in terms of the degree to which samples are clumped spatially at the level of 10 clusters (Figure C2-6). However, at lower levels of clustering, spatial conservatism is poorer, particularly for the fine resolution sediment data. It is then not highly surprising, given the relative differences in variance at different points in the gradients that clusters based on sediments do not very well match those based on species despite the spatially conservative nature of both. Using canonical correspondence analysis to explore the shared components and developing clusters based on the site scores on the first three canonical axes provides clusters consistent with both the sediment and species information. Because of the influence on variance of the coarse sediment in the fine resolution sediment classification systems the clusters are not always intuitive. For example the canonical clustering based on the fine resolution sediment information determines the samples taken at the extremes of the east west gradient as more similar than those samples taken more proximally. Lower resolution sediment classification or adoption of a-priori classes (eg. Folk or EUNIS) performs better, but it is not reasonable to exclude the possibility that this is an artefact of sampling effort, as greater sample numbers were available for the analysis using the low resolution and pre-classified information.

The misclassification rate of species samples based on the information from sediment data is relatively high, especially when using the fine resolution sediment classes. For simpler sediment classifications the canonical analysis does retain the majority of the species information, but clusters appear to overlap spatially with those examined for the species composition alone, suggesting that the variance components are different along the ordination gradients in the separate species and sediment analyses. The coarse sediment classification based on the canonical analysis is highly accurate at the level of four clusters, but deteriorates at higher levels. Nevertheless clustering at wider spatial levels is still useful for stratification purposes, since in reality the species composition indicates continuous gradients so that the cut off points along these gradients are relatively arbitrary.

For the purposes of spatial prediction of the abundance of a single species the canonical clusters may or may not be useful dependent on the niche breadth with respect to the proportion of the ordination gradient covered by a specific cluster. This suggests that the species ordination axes are likely to be better predictors than the sediment information. In other words, where community information exists this is likely to be a better predictor of the likely abundance of a species at a site because the community structure integrates over all environmental variables, not just sediment. However, sediment information does play a role so that the ability to predict species composition on the basis of sediment information should be investigated using independent data, i.e. data not used in the development of the model. Unfortunately at this point there were insufficient samples to allow for such an approach.

A major concern prior to this study regarding the efficacy of this analysis was the difference in the scale of sampling between the sediment data (scale of metres) and catches (scale of miles). The worry was that the likely variance in sediments over a two mile beam trawl tow might be bigger than the variation between tows so that a single sample along the tow was never likely to be well correlated to the catch. Indeed clustering does indicate that some sediment samples taken at the sub-tow scale are associated with different clusters. However, this flipping between clusters appears to be happening mainly between adjacent clusters which can then be explained by much smaller levels of variation along the sediment ordination gradient. This suggests that sediments in the western English Channel are spatially highly ordered at scales in excess of 2 miles, the scale at which fish sampling occurs. This indicates that generally a sediment sample, covering less than a metre square, can usually be seen to be representative of the sediment encountered over the entire trawl track for course resolution sediment data. At higher grain size resolutions samples tend to show larger levels of variation along a trawl track particularly with respect to the larger sediments.

Looking at the coarse sediment classification quite strong spatial patterns emerge. Some of these are highly consistent with the species distribution, but unfortunately some also appear to be consistent with the sediment sampling methodology. The majority of French samples have been collected by dredge and these samples are found in the most eastern part of the survey grid. In addition UK samples have employed a variety of sampling gears including grabs and corers, the success of actually obtaining a sample by using the latter being particularly susceptible to the inclusion of gravelly sediments. There may therefore be some correlation between the gear used and the sediment sample taken. Further analysis should be conducted to see if the gear component can be isolated from the analysis to make data combined across gears more universally useful.

Conclusions

- Rather than trying to provide habitat maps on single species distributions based on sediment data an attempt was made to characterize whole community distributions. Different resolutions of classification of the sediment data were employed to determine the level of detail necessary to describe the preferences of fish and commercial species.
- Expectedly sediment data was found to be an important driver of the species composition of demersal fish communities, but sediment type was also correlated to depth in the western channel largely because currents, themselves affected by depth, are the main drivers of sediment distribution in the area. Nevertheless sediment data provided additional explanatory power.
- Clustering species composition and sediment samples within 12 miles of trawl stations suggested a poor definition of species composition based on sediment types. However, conducting correspondence analysis of the data suggested that both sets of data displayed continuous gradients in sediment and species rather than distinct subpopulations. The main reasons for misclassification were that the ordination gradients were split into clusters at different locations in n-dimensional space as well as in spatial plots of the information.
- Canonical correspondence analysis (CCA) using the sediment ordination axes as explanatory variables for the composition data indicated that sediment could explain around 15% of the variance (mainly on the first and secondary canonical axes) in species composition irrespective of the sediment classification system used. Classification systems with greater resolution (more sediment classes) did not provide improvements in the ability to predict fish communities.
- Developing clusters on the basis of the first two canonical axes in the CCA using Euclidian distance as a measure of dissimilarity allowed more consistent classification at least separating the major types of communities. Finer scale community definition proved difficult as the sediment data was only partially responsible for structuring demersal fish communities.
- However knowing that both sediment and species data present continua, rather than discrete clusters suggests that the information is still sufficient to determine likely species composition on the basis of sediment type in the western English Channel.

This hypothesis is supported by the fact that when the canonical clusters are plotted spatially they represent reasonably well separated spatial clusters.

- Future research should attempt to predict species composition on the basis of sediment samples and compare these with independent collections of fish communities. It was also noted during this analysis that the sediment sampling methodology is not consistent across time and space and further investigations will be required to determine if this causes bias / artefacts in the CCA. For this analysis it is not possible to determine the effects as the distribution of different gears has a very strong spatial correlation consistent with the spatial distribution of species. In part this is because different gears are employed on different habitats but this does not preclude further effects.

Case Study 3: Seabed characterization in shallow waters using multibeam backscatter data

Example of intermediate to fine-scale sediment mapping

Xavier Monteys, Gill Scott, David Hardy, and INFOMAR team members

Geological Survey of Ireland

Abstract

Multibeam sonar is the most widely used seabed mapping technique for all water depths. Many multibeam systems are capable of recording acoustic backscatter, and these datasets, when fully geo-referenced and together with bathymetric information, are suitable for seabed-type characterisation. In shallow waters, multibeam data density, spatial resolution and wavelength parameters allow for full coverage and meter-scale mapping. The physical interplay between backscattered sound and seabed properties is complex, but is known to correlate. We present a number of case studies for which we have explored and extended this well-established correlation, using backscatter data as a grain size proxy for production of distribution maps. The results identified variability in backscatter behaviour depending on seabed type. Soft, fine-grained sediments exhibit strong linear correlations that can be used with confidence when mapping seafloor grain size properties. In hard substrates the backscatter data signatures are more incoherent, dependent upon the general hardness and textural seafloor parameters of the seafloor.

Introduction

Multibeam sonar systems have become the most widely used for seabed mapping in surveys worldwide, with the result that large volumes of multibeam data are now held in numerous databases for use in a variety of marine disciplines.

Most multibeam systems simultaneously log two types of datasets: water depth and the amplitude of backscatter returns from the seabed. Backscatter is the incoherent echo of an acoustic pulse transmitted through the water column and reflected from a finite area of seafloor. It is, partially, a function of radiometric and geometric parameters for which corrections can be applied so that the refined signal is primarily influenced by seabed surface and shallow sub-surface scattering processes.

Acoustic seabed processes are governed by complex multivariate functions and direct inversion models attempting to deal with the large number of parameters involved face the challenge of resolving the many unknowns. Fortunately, generalisation of the mathematical models employed is appropriate for certain seabed conditions. In these simplified scenarios, a number of seabed properties can be quantitatively estimated together with their associated error and confidence values.

Information derived from backscatter in this manner has potential applications in a range of marine disciplines including geotechnical mapping, environmental monitoring and, not least, marine habitat mapping which was the main driver for this study.

This paper explores the applicability of a generalised backscatter-sediment grain size model for a range of seabed scenarios by using illustrative case studies from shallow waters. It employs simple and robust statistical assumptions, and attempts to draw general guidelines for using and interpreting backscatter data, particularly in the benthic habitat mapping context. It also briefly discusses model limitations, and potential error sources.

Methods

This section describes the methods used in this analysis and the rationale employed when extracting statistical parameters from multibeam backscatter data; sediment textural parameters from seabed samples; and when deriving, empirically, the statistical relationships.

Multibeam backscatter data

While there are a limited number of manufacturers of multibeam echosounder systems (MBES), each model has its own particular specifications with respect to beam width, wavelength, swath acquisition settings, gains, bottom detection algorithms and recorded data types. As a result there can be slight variations in the backscatter signature produced for the same patch of seabed by different systems and even by the same system used at different settings. However, though they are generally un-calibrated, different systems produce similar backscatter responses in terms of range and amplitude variations.

Backscatter data can be acquired as amplitude values, similar to sidescan sonar, or by as area-normalized backscatter strength. The system employed in this study was the Kongsberg-Simrad MBES EM1002S (95 kHz) which recorded backscatter strength. Strength datagrams are recorded in Decibels (dB) which is a logarithmic unit, and in two formats: Beam Amplitude backscatter for which a single value is recorded for each returned acoustic beam and intensity correlates directly with depth; Time Series where multiple backscatter amplitude values are recorded for each beam by sampling the individual reflectivity time series. The un-calibrated backscatter recorded ranged from +0 dB to – 60 dB [80].

The system-specific acquisition software, together with the MBES hardware, applied a series of corrections for source level and receiver sensitivity, attenuation, spherical spreading in the water column and grazing angle effects [81].

To minimize angular beam artefacts the backscatter datasets used in the statistical analyses were limited to returns from the 45° incident angle.

Prediction maps were subsequently generated from the results of these analyses but were applied to the full-coverage, compensated imagery data generated by IVS Geocoder [82].

Geo-acoustic scattering

Only a fraction of acoustic energy is backscattered and logged and it is the surface and subsurface properties of the seabed that are largely responsible for the amplitude of the received echoes.

A number of parameters are needed to model the complex acoustic scattering process and these can be grouped under three main headings: acoustic impedance water/seabed; surface roughness; and volume reverberation [83].

The parameters involved vary considerably depending on seabed type and composition; for hard seafloor (rock or very coarse gravel) water/seabed interface impedance and surface roughness parameters dominate, with negligible input from volume scattering, while for soft sediments, the volume backscatter contribution becomes significant.

Sonar angular domains must be factored when modelling the acoustic response as backscattered energy varies as a function of the incidence angle. Beyond the critical angle (>60°) the input of volume scattering is almost negligible, while at lower incident angles (between10°-60°) the volume contribution is variable.

Sonar power and wavelength (frequency) are important system parameters influencing backscatter strength and the amount of penetration in soft sediments. Spatial resolution (beam footprint) and data density must also be considered for accurate prediction of sediment properties at appropriate mapping scales.

Data quality

Backscatter data quality is sometimes neglected but it is essential to assess its suitability for seabed characterisation as, while some data may be of sufficient quality for bathymetric profiling, it may not reach the standard required for seabed mapping. Ship motion dynamics and sea conditions due to adverse weather are the main factors affecting data quality. Simple weather filtering can be performed using the ship's motion sensors indices; however, these sometimes involve extensive deletion.

Water column artefacts can impinge on data quality. Changes in bottom detection settings can also cause unusual backscatter signatures (system artefacts), generally appearing as segments in the ship trackline mosaics.

In this study, we have removed poor quality data by filtering out areas where the weather or system settings where detrimental.

Seabed sediment textural properties

In this study ground-truthing refers, primarily, to sediment samples but also to underwater video data. Over 500 seabed samples and more than 30 video transects were examined. Sediment samples were obtained using a variety of grab samplers and a small box corer. In some sites several samples were taken to assess consistency.

The multi-beam footprint ranged from 1-5 m while the seabed surface area physically sampled was approximately 25 x 25 cm.

Sediment properties considered were principally limited to those concerning grain size and texture though apparent conductivity was also studied in Case C. Geotechnical parameters, while important, were not used in the statistical analyses due to lack of data. Nonetheless, grain size descriptors are the most widely used to categorize seabed sediment and for benthic mapping. In addition, multibeam backscatter data is known to correlate to sediment grain size parameters, e.g. [84] [85]. However, it is important to take into consideration non-lithogenic elements, such as shell fragments, which can confound the backscatter/sediment grain size relationship. Though they are integral to the sediment matrix and are included in the particle size analysis, shell fragments can alter the normal grain size-backscatter pattern. Other biogenic deposits such as maerl, can completely mask the underlying sediments, as can gassy sediments and groundwater discharge.

Statistical Analyses

While the scientific literature details complex statistical analyses used to investigate the relationship between backscatter and grain size parameters [86] [87], a simple, linear, least squares regression model was used in this study. We adopted this approach when extending this well-established correlation for the robustness of the technique and for its ease of interpretation. Complementary data such as sample descriptions, video and bathymetry, were used to identify trends in this relationship and to explain the non-conformity of outliers.

The models developed were used to predict grain size parameters, develop maps of the same, and to produce error and confidence values.

Results

Results are presented as three regional case studies, each illustrating the relationship between multibeam backscatter data and seabed properties in contrasting, shallow water, seabed environments (see summary table below). From these, a set of general guidelines has been attempted. However, given the complexity of the acoustic response and the nature of seabed geology, predictions and guidelines should be interpreted with caution.

Table C3-1. Overview of the case studies.

	Case 1	Case 2	Case 3
Overview			
Area	Bantry and Dunmanus Bays	Western Irish Sea	Malin Sea
Description	Shallow-water embayments	Shallow, open water	Mid Shelf
Water Depth	20 – 80 m	50 – 100 m	160 - 180 m
Sediment type	Soft, silts - gravelly sand, low biogenic content	Soft, fine sands – sandy gravel, mixed biogenic content	Very soft sillts with sand
Ship /system	R.V. Celtic Voyager EM1002 S	R.V. Celtic Voyager EM1002 S	R.V. Celtic Voyager EM1002 S
Methods			
Geophysical data used in analyses	Backscatter at 45^0 incident angle and 10 x10m grid (IVS Geocoder)	Backscatter at 45^0 incident angle and 10 x10m grid (IVS Geocoder)	Swath backscatter parameters extracted usign Geocoder IVS 7. EM electrical resisitivty methods (WHOI)
Ground-truth samples	112 samples of which 79 used for statistical analyses	210 samples of which 175 used for statistical analyses	10 samples used to constrain the sediment properties
Sampler	Day-Grab, Reineck mini-box corer	Day-Grab, Shipeck grab	Day-Grab
Grain size analysis	Combination of malvern laser particle sizer and sieving	Combination of malvern laser particle sizer and sieving	Malvern laser particle sizer and sieving
Under water video	5 video lines	10 video lines	2 video lines

Case Studies

Case Study One: Bantry and Dunmanus Bays, SW Ireland

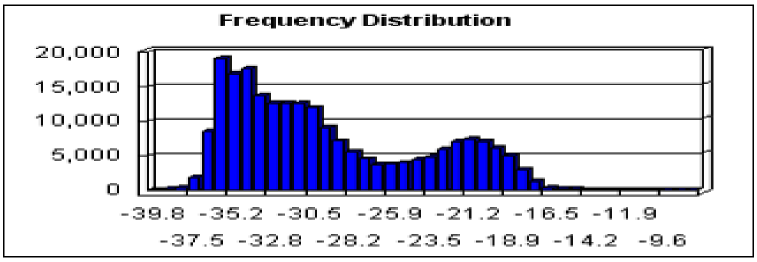
Bantry and Dunmanus Bays were chosen for investigation of the relationship between backscatter and fine-grained, soft sediments. They are located in the southwest of Ireland and comprise a shallow-water area of approximately 600 km^2. The seafloor is generally smooth and flat, with occasional disruption by rock outcrops, and is characterised by unconsolidated, soft, fine-grained sediments with low biogenic content ranging from silts to gravelly sands.

Descriptions and images of the 112 seabed samples collected were recorded onboard ship. Of these, 79 were fine-grained (< 1% gravel). Five short video lines were also recorded.

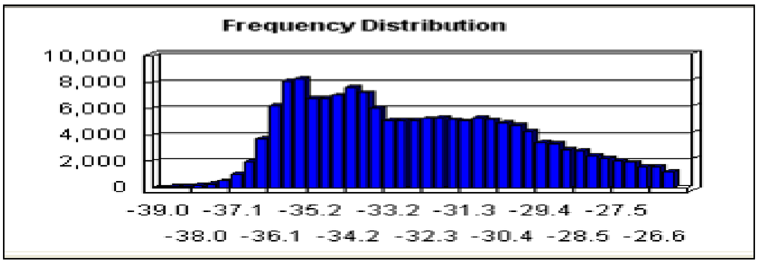
For the statistical analyses, time series backscatter from the 45° incident angle was extracted from the raw multibeam data.

A 10 X 10 m backscatter-compensated mosaic was then created in preparation for the prediction stage of the analysis.

Basic backscatter statistics were calculated for the entire study area, which included some hard substrates, and for zoned areas around the 79, finer-grained seabed samples. For the wider study area backscatter exhibited a bimodal distribution with values ranging from -7 to -40 dB. For the sample sites, the histogram shows a slightly negatively skewed near-normal distribution and a narrower range of -26 to -40 dB (see below).



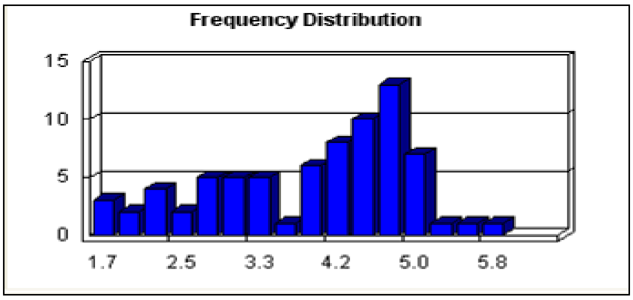
Statistics	
Minimum	-39.8
Maximum	-7.3
Range	32.5
Mean	-29.34
Standard Deviation	5.64



Statistics	
Minimum	-40.0
Maximum	-26.0
Range	14.0
Mean	-32.44
Standard Deviation	2.72

Figure C3-1. Histogram distribution plots for backscatter. Top panel: comprises backscatter records from the entire study area which included boths soft and hard substrates. The histogram exhibits a bimodal distribution. Bottom panel: backscatter data histogram from the 79 finer-grained sampling sites. The histogram exhibits a, negatively skewed, near-normal distribution characterised by a moderate to low standard deviation.

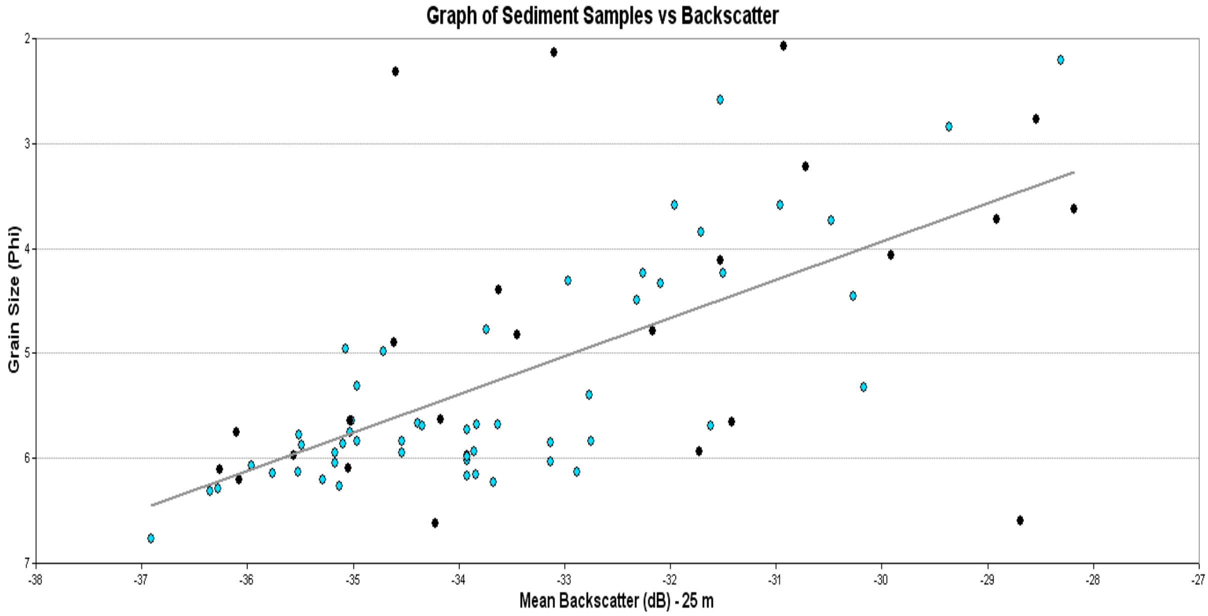
For the 79 sediment samples, mean particle size ranged from 1 Φ (medium sand) to 6 Φ (silt) with the majority falling within the silt-sand interval (Wentworth scale and Krumbein Φ scale).



Statistics	
Count	74
Minimum	1.7
Maximum	5.9
Mean	4.02
Standard Deviation	1.04

Figure C3-2. Mean grain size (Φ) histogram. Mean Φ is 4 (very fine sand). Standard deviation is low (σ =1).

Ordinary least squares regression analysis was performed to explore the relationship between backscatter and sediment grain size. The results are shown below.



Statistics	
Slope (β)	-0.340669
Students t (β)	-7.39447
Std Error (β)	0.046071
p-value (β)	0
Y intercept	-7.436066
Correlation (R)	-0.644392
Students t (R)	-7.39447
p-value (R)	0
R-squared	0.415241
Std Error of XY	0.873423
No. of Observations	79

*Figure C3-3. Scatter plot showing mean backscatter strength vs. mean sample grain size (**Φ**). Linear correlation (Pearson coefficient) is 0.64. Black dots show samples with a significant presence of shell fraction in the sample (>25%), which coincide with the majority of outliers.*

The results indicate that fine-grained sediments (silts-fine sands) are associated with levels in the lowest quartile of the full backscatter range. There is a strong linear correlation between coarser samples and higher backscatter values.

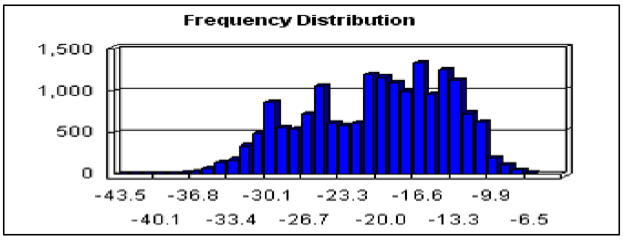
It was observed that shell content influenced the backscatter returns. However, the limited number of samples precluded constraining this relationship. The presence of gravel is associated with backscatter values > -27 dB.

Case Study Two: Western Irish Sea

The second study area was chosen to explore the relationship between backscatter and sediment grain size parameters in soft, mixed sediments and, in particular, to investigate the effects of gravel.

The Western Irish Sea is a shallow (50-100 m) open sea and covers an area of circa 850 km². The seafloor is generally smooth with occasional bedforms and other seabed features. It is characterised by soft, unconsolidated, mixed sediments with variable biogenic content, ranging from fine sands to sandy gravel. Seabed sample descriptions and images were logged onboard and descriptions of seabed facies recorded for the video lines were subsequently transcribed.

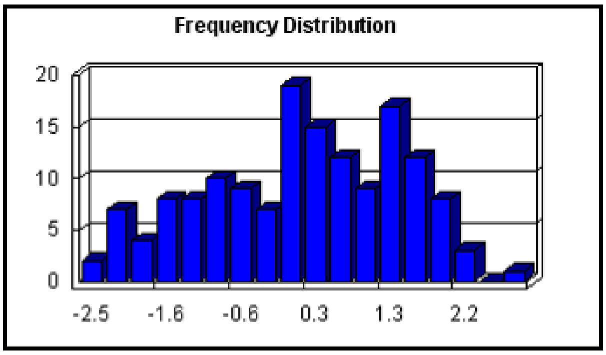
Backscatter from the 45° incident angle exhibited a bimodal distribution with values ranging from -6 to -44 dB.



Statistics	
Count	17602
Minimum	-43.5
Maximum	-6
Sum	-351215
Mean	-19.95313
Standard Deviation	6.389845

Figure C3-4. Backscatter Histogram distribution. Backscatter, was recorded at the 45° incident angle from across the study area including soft and hard substrates. Values range from -6 dB to -44 dB. The histogram exhibits a bimodal distribution.

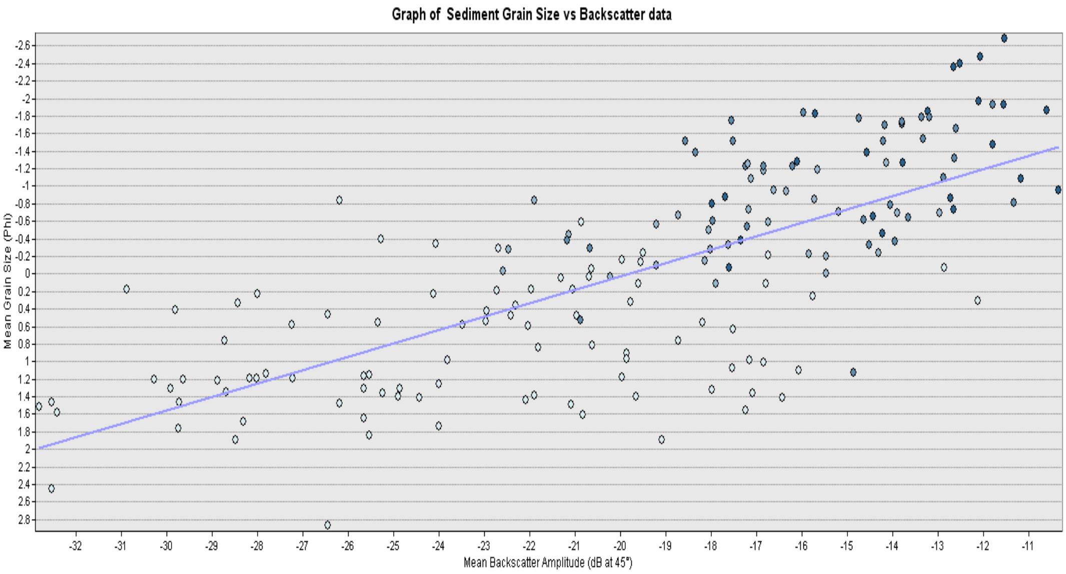
Of the 210 sediment samples, 175 were selected for statistical analysis as the balance were inconsistent with the seabed scenario under scrutiny. Mean particle size (Φ) ranged from -3 (fine gravel) to +3 (fine sand) with the majority of samples in the sand-gravel interval (see diagram below).



Statistics	
Count	151
Minimum	-2.499918
Maximum	-3.070143
Sum	44.669807
Mean	0.295827
Standard Deviation	1.22675

Figure C3-5. Mean grain size (Φ) histogram for the Western Irish Sea. Mean Φ is 0.3.

Ordinary least squares regression analysis was performed to explore the relationship between backscatter and sediment grain size and the result are shown below.



Statistics	
Slope (β)	-3.460079
Students t (β)	-13.956005
Std Error (β)	0.247928
p-value (β)	0
Y intercept	-19.729193
Correlation (R)	-0.727734
Students t (R)	-13.956005
p-value (R)	0
R-squared	0.529597
Std Error of XY	3.795109
No. of Observations	175

Figure C3-6. Plot showing mean backscatter strength vs. sediment grain size (Φ) Linear correlation (Pearson coefficient) is 0.73.

The study area comprised mixed sediments ranging from sand to sandy-gravel, producing backscatter values between -32 dB to -10 dB. In general the relationship between grain size and backscatter exhibits a strong linear correlation. As expected, and as for Case 1, the coarser sediments result in higher backscatter.

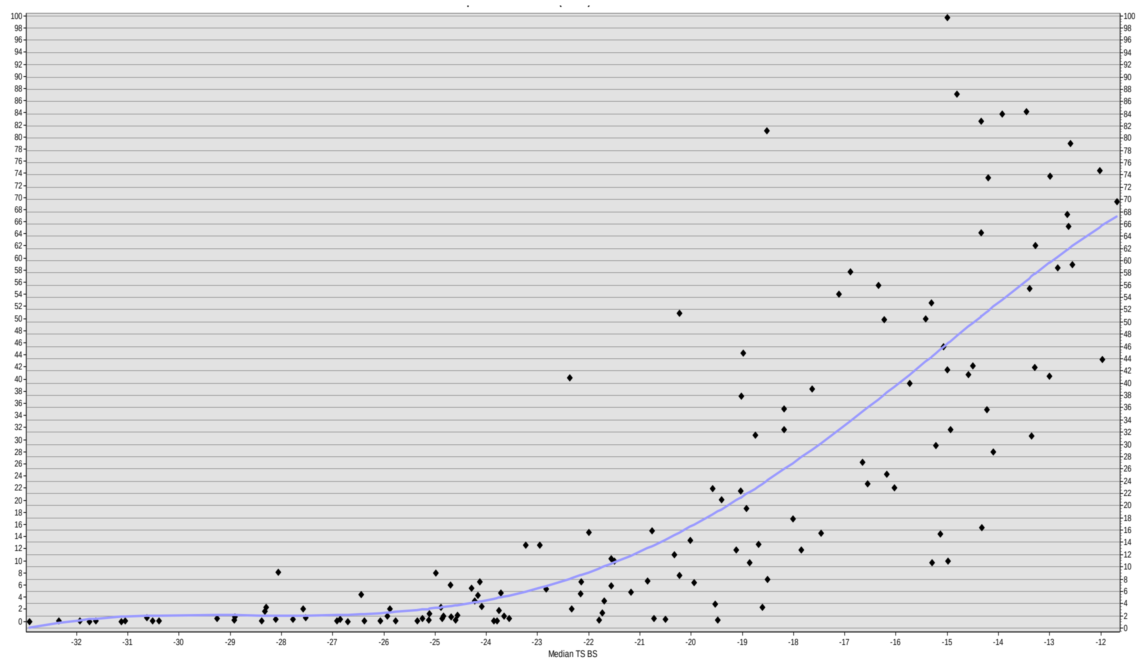


Figure C3-7. Plot showing mean backscatter strength vs. % gravel fraction

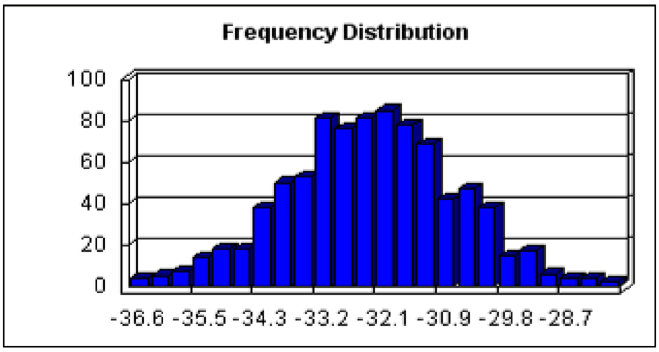
Case Study Three: Malin Sea

The third study area was chosen to explore the relationship between backscatter and sediment properties in very soft, fine-grained sediments and, in particular, the transition between very fine sand and silt.

The Malin shelf is located off NW Ireland in depths of between 50-180 m. The study area lies in the deepest part of the Malin Basin (160-170 m). Here, the seafloor is smooth, flat and consists of homogenous, fine sediments, ranging in size from silt to very fine sand [88].

Backscatter parameters were extracted from a short-line of multibeam data using IVS Geocoder. These included mean total, mean near-range and mean far-range backscatter derived from the averaged swath. This data was then compared with electro-magnetic (EM) geophysical data from the same location. The EM system used (WHOI) consists of a ~40 m - long array which is towed at low speeds and in contact with the seafloor. The system's transmitter generates harmonic EM fields over a range of frequencies (~200 Hz–200 kHz), and the returns are collected by three receivers towed at fixed distances behind (4 m, 12.6 m and 40 m). For this exercise, amplitude data from one of the frequencies (20.1 kHz) on the 12.6 m receiver was converted to apparent conductivity [89].

Backscatter from the 45° incident angle exhibited a normal distribution with values ranging from -28 to -37 dB (see below).



Statistics	
Minimum	-36.6
Maximum	-27.77
Range	8.83
Mean	-32.18
Standard Deviation	1.55

Figure C3-8. Histogram distribution of backscatter records along the studied line. Values range from -28 dB to -37 dB. The histogram exhibits a bimodal distribution.

Historical geology maps and a small number (10) of seabed samples, taken in the vicinity of the line, were used to constrain the seabed geology and aid interpretation of the results. The sediment samples comprised homogenous, very fine-grained sediments, ranging in mean grain size from 4 to 6 Φ (fine sand to silt).

A number of regressions were performed, each comparing a different backscatter parameters against conductivity (see below).

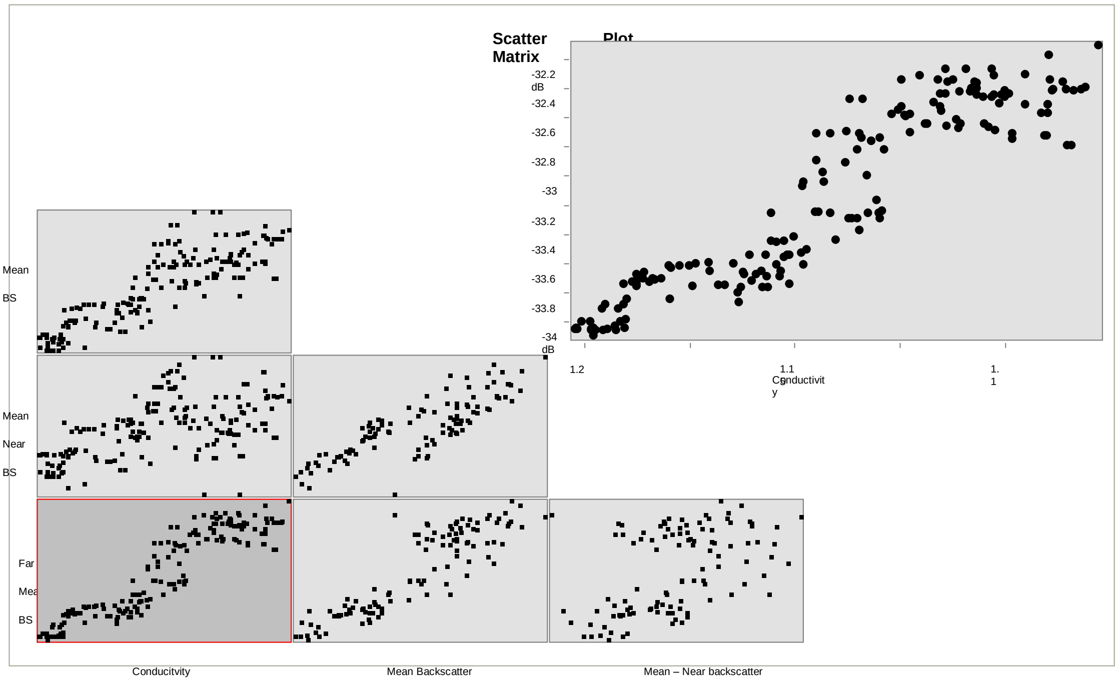


Figure C3-9. Matrix scatter plot comparing swath backscatter parameters, extracted using IVS™ Geocoder, with apparent conductivity. These include mean total backscatter, mean near-range backscatter and mean far-range backscatter. Apparent conductivity was derived from amplitude data. Correlation coefficients: Mean far range vs Conductivity (enlarged top-right),– R = 0.92. Mean total range vs Conductivity, R = 0.86; Mean near range vs Conductivity, R 0.54.

The along-line spatial variations from the same line interval were also explored (see below).

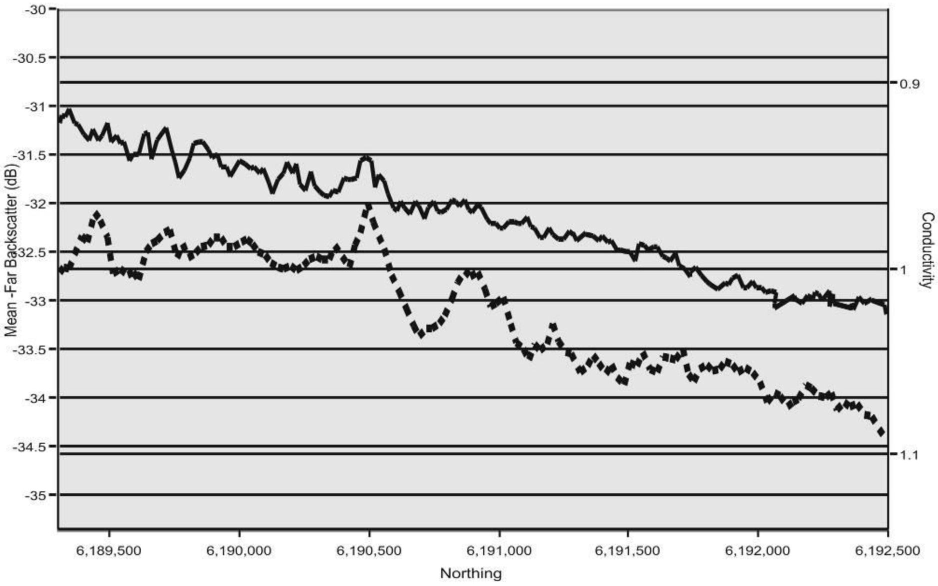


Figure C3-10. Composite plot capturing variations in mean far-range backscatter (dashed) and apparent conductivity (continuous) along the line (3 km) Grain sizes range from very fine sand in the south to very fine sand-silt in the north.

Backscatter for this fine-grained area, falls entirely within the lower backscatter range. The matrix scatter plots (Figure C3-9) show strong, linear correlations between mean backscatter parameters and apparent conductivity. This correlation is particularly strong for mean far-range backscatter (R = 0.92) and the relationship is also captured by the composite plot (Figure C3-10)

Far-range backscatter is calculated as the beam average backscatter of the far-range angular sector over a number of swaths (30). In the standard geo-acoustic model this angular sector is primarily influenced by amplitude returns from the seabed surface.

Case Study Three illustrates two things: The importance of the angular sector when considering backscatter and the high degree of correlation between seabed surface backscatter and apparent conductivity within this grain size range.

Prediction Mapping

The regression equations derived from the statistical models can be applied to the backscatter datasets from which they were derived to produce prediction maps.

This process was performed for the compensated, gridded backscatter values of Case 1: Bantry and Dunmanus, generating a database of predicted, sediment information that can be mapped, such as mean grain size and percentage distribution of the different fractions and including information on statistical error indicators and confidence values.

Summary

In many scenarios, including those outlined in this study, multibeam backscatter-seabed type models can be used to accurately predict a number of key seabed indices. The linear regression model used was empirically derived from large, marine-acoustic databases and hundreds of seabed samples. The model chosen has proven robust and uncomplicated, potentially offering, to the wider marine community, a reliable yet simple template for seabed classification using multibeam backscatter.

The primary focus of this study, as detailed in the affiliated benthic habitat mapping chapters, is on the relationship between sediment grain size parameters and backscatter characteristics. The proposed model indicates a consistent, strong, linear relationship between mean grain size and backscatter, particularly for the finer-grained sediments (Silt to gravelly sand range). It also outlines the confounding effect of shell fragments on this relationship.

For gravel-dominated seabed facies, the results suggest that predicting mean grain size using such a model may be problematic. Indeed, unpublished GSI studies failed to find a simple correlation pattern between backscatter data and sediments with large clast sizes. This seems consistent with theoretical expectations which contend that backscatter returns at this wavelength and in this type of seafloor, are dominated by surface roughness parameters. Similarly, rock outcrops are difficult to differentiate using backscatter alone; bathymetric textural parameters may provide better discrimination of rock types.

Sonar system specifications, acquisition settings and calibration issues often result in across-platform inconsistencies in backscatter datasets, therefore the empirically derived models presented here should be used for guidance only, particularly when considering seabed scenarios which differ from our case studies.

Acknowledgements

The authors wish to acknowledge the Geological Survey of Ireland and the Irish marine Insitute for the use of INFOMAR datasets. The authors would like to thank Xavier Garica (UTM-CSIC) and Rob Evans (WHOI) for facilitating the EM results.

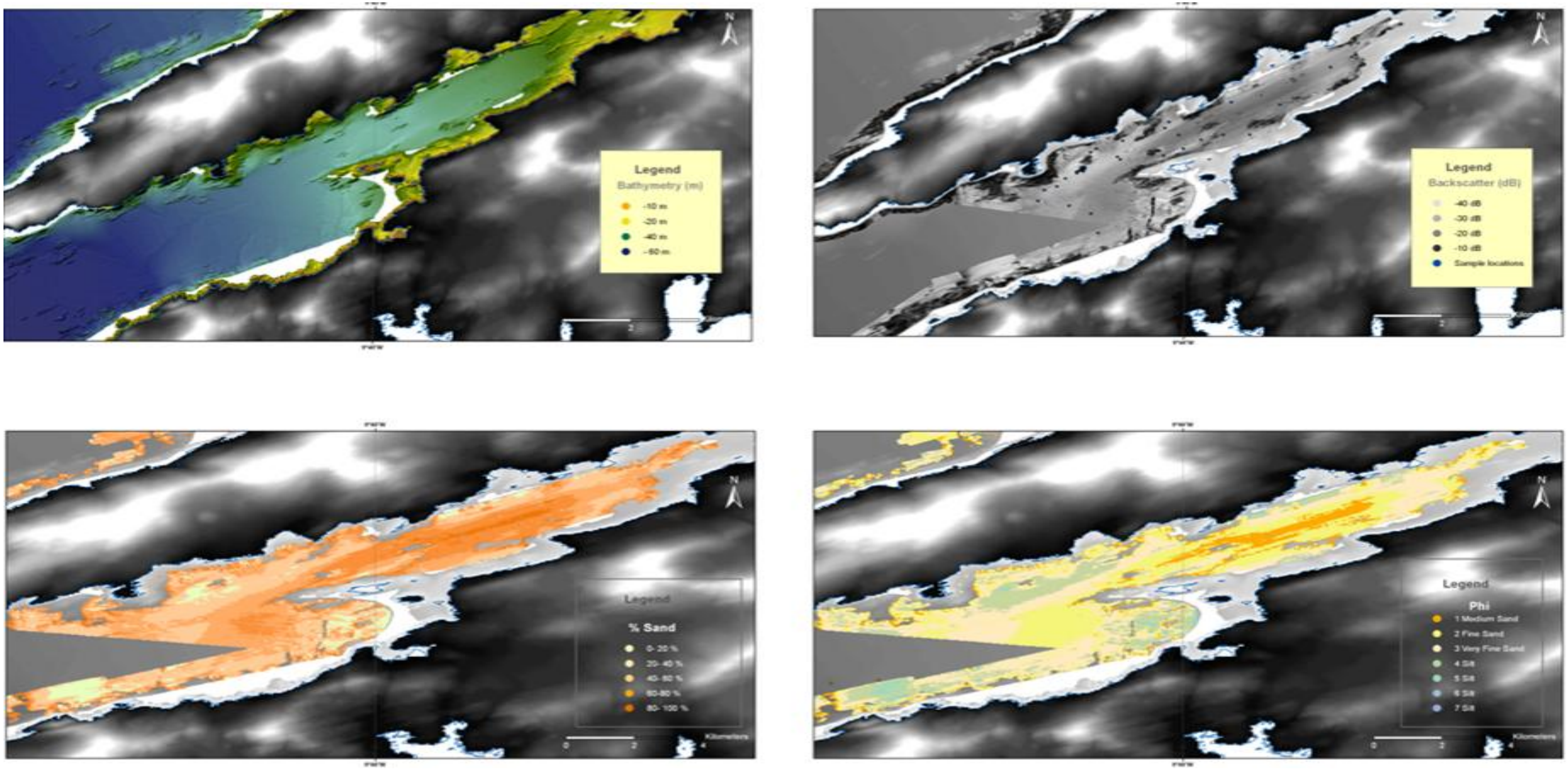


Figure C3-11. Dunmanus Bay, SW Ireland. Linear regression model. Bathymetry, backscatter and estimated grain parameter maps developed by applying linear regression equations to gridded backscatter values. The areas mapped are limited to the backscatter range of the model (low). Results are stored in integrated GIS databases and include other statistical indices.

Table C3-2. Summary guideline for using multibeam acoustic backscatter as surrogate for sediment mapping.

Seabed Hardness	Sediment Type	Textural Categories (Folk's)	Acoustic Scattering	Backscatter Levels	Statistical Relationship backscatter / grain size	Notes
Soft	Unconsolidated, fine grained sediments	Mud to sand (unimodal to multimodal grain size distribution)	Interface and volume (subsurface penetration)	Low	Strong, linear correlation between backscatter and grain size parameters	Case A Case C
	Unconsolidated, mixed sediments (fine dominated)	Gravelly-sand ***/*** gravelly-mud (bimodal grain size distribution)	Interface and volume (subsurface penetration)	Moderate	Strong, linear correlation between backscatter and grain size parameters	Case B
Hard	Unconsolidated, coarse dominated sediments	Sandy, muddy-gravel or gravel (unimodal to multimodal grain size distribution)	Interface (negligible suburface penetration)	Moderate -High	Gravel fraction dominates backscatter. Weak correlation between sandy fraction and the backscatter	Case B
	Rock or hardgrounds	Bedrock, hardgrounds, carbonate crusts and other hard surfaces	Interface (no subsurface penetration)	High	No consistent relationship between rock type and backscatter parameters	Unpublished GSI data

Case Study 4: Revisiting the spatial distribution of EUNIS Level 3 North Sea habitats in view of Europe's Marine Strategy Framework Directive

Example of broad to fine-scale sediment mapping

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Introduction

European legislation with relevance to seabed management has become increasingly complex. Overall, there is a demand to move towards a functional and ecosystem-based approach to management. This cannot be achieved by merely integrating present-day monitoring activities calling for alternative approaches. Adaptive and risk-based monitoring are promising new concepts that will keep monitoring manageable and time- and cost-efficient.

The Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC), adopted in June 2008, is the environmental pillar of the EU's Integrated Maritime Policy. It aims at achieving healthy marine waters by 2020, applying an integrated approach to ecosystems and striving to contain the collective pressure of human activities within sustainable levels. The MSFD prescribes broad-based marine monitoring related to 11 descriptors. Monitoring results are a key element in assessing environmental status, and in determining and evaluating any action needed or taken. The MSFD includes a requirement to adopt specific and standardised methods for monitoring and assessment. Such standardisation ensures internal data consistency so that the development toward good environmental status throughout European seas can be compared and evaluated in an integrated, transnational way. The MSFD includes a requirement for the assessment of marine habitat types (not directly required within the Water Framework Directive), with the additional stipulation that monitoring methods and indices of change be habitat specific [89].

Generally, there is a need to modify and extend the present monitoring practices and to move from 'station-oriented monitoring' to 'basin or system-oriented monitoring', in combination with specific 'cause–effect' studies for the highly dynamic marine systems [90]. A change in monitoring strategy is also needed in habitat studies, because habitat area, extent, condition and status are critical elements within the MSFD.

On a broad-scale and within a European perspective, sediment type has been used as a surrogate of EUNIS Level 3 habitats (e.g. EMODnet-Geology [48] and EUSeaMap [3]. The spatial distribution of seabed-sediment types reflects the interplay of near-surface geology, hydrodynamics and large-scale sediment transport. Towards finer scales, sediment type may be a direct indicator of the actual sediment processes that drive habitat changes, both naturally and anthropogenically steered. Geological system knowledge helps in understanding the distribution of sediment types, and in refining distribution predictions.

With regard to the descriptors biodiversity, food webs, and seafloor integrity, some countries suggest that no changes should occur in the distribution and area of habitat types, distinguished at EUNIS Level 3, as indicator of good environmental status. Additionally, it may also be desired to maintain the extent of biogenic substrates and gravel beds. This implies that reference situations are known, as also their degree of natural variability. However, ranges of uncertainty are hitherto not addressed.

In this case study the spatial distribution of EUNIS Level 3 habitats is revisited, evaluating uncertainty and confidence aspects related to the distribution of the habitat types and suggesting methods for the assessment of change. A plea is made for mapping at a scale of 1:10.000. This fine-scale mapping could be achieved by extending the coverage of very-high-resolution multibeam data, but also by making more and better use of existing sediment databases. When sediment data are digitally available, and harmonised to common classification systems, it is possible to query these databases in a flexible way.

Methodology

To illustrate the concept of flexible sediment parameter mapping, full-distribution-curve data were compiled for the Belgian part of the North Sea (sediCURVE@SEA database [69] and for the Dutch part of the North Sea up to 52° latitude (database Geological Survey of the Netherlands).

First, the merged grain-size database was used to generate two ArcGIS layers of sediment-type distribution, one with only a few classes (simplified Folk classification as used in the EMODnet-Geology sediment map [48]) and the other more differentiated (original Folk classes). Mapping to the original Folk classes was done using the USGS sediment tool (http://woodshole.er.usgs.gov/pubs/of2007-1186/OFR2007-1186.pdf). As an extension in ArcGIS, it allows annotating Folk classes in a feature table. From interpolated grids of the percentages gravel, sand, silt and clay, it produces a Folk grid. Here, for a first exploration, inverse weighted distance power 2 was used to interpolate.

Secondly, the full range of sediment data was explored by calculating various percentiles of the sediment distribution (e.g. d10, d35, d50 and d90), as well as the Folk parameters mean, sorting, skewness and kurtosis. Parameters were calculated on the full data (including mud and gravel) and on the sand fraction separately. This narrowing of the grain-size range can be useful when studying temporal sediment changes that are easily overprinted by a few coarse clasts, or a too fine tail of the sediment distribution.

Finally, some sample-based results were compared to information obtained from fine-scale very-high-resolution multibeam bathymetry and backscatter.

Results

Figure C4-1 shows the simplified Folk sediment map for parts of the Belgian and Dutch sectors of the North Sea. Each colour represents one of four EUNIS Level 3 habitats in the sublittoral: sandy mud to mud (A5.3), muddy sands to sands (A5.2), coarse sediments (A5.1) and mixed sediments (A5.4; not discussed here). It is based on the percentages of gravel, sand, silt and clay as measured in seabed-sediment samples.

The same dataset was also plotted to show the original Folk classes (Figure C4-2), adding detail that lacks on the simplified Folk map. The biggest differences between the two maps concern the sandy mud to mud class.

As one example of the possibilities of the flexible sediment parameter mapping, Figure C4-3 shows the sorting of the sediments. Compared to Figures C4-1 and C4-2, seabed types are now more differentiated. Generally, the seabed sediments of the shoals and sandbanks are better sorted than those occupying the intervening gullies. The poor sorting in the gullies is mostly associated with the presence of gravel. In the near-coastal area with the highest diversity in Folk classes (Figure C4-2), sediments are mostly very poorly sorted, mostly due to the silt-clay-rich substrate. However, in areas where sand predominated, sorting has become worse in time. Van Lancker et al. [91] hypothesised that this poorer sorting is the result from long-term anthropogenic activity, including the disposal of sediment dredged from harbours and waterways. If and how this impacts on seafloor integrity is yet to be explored.

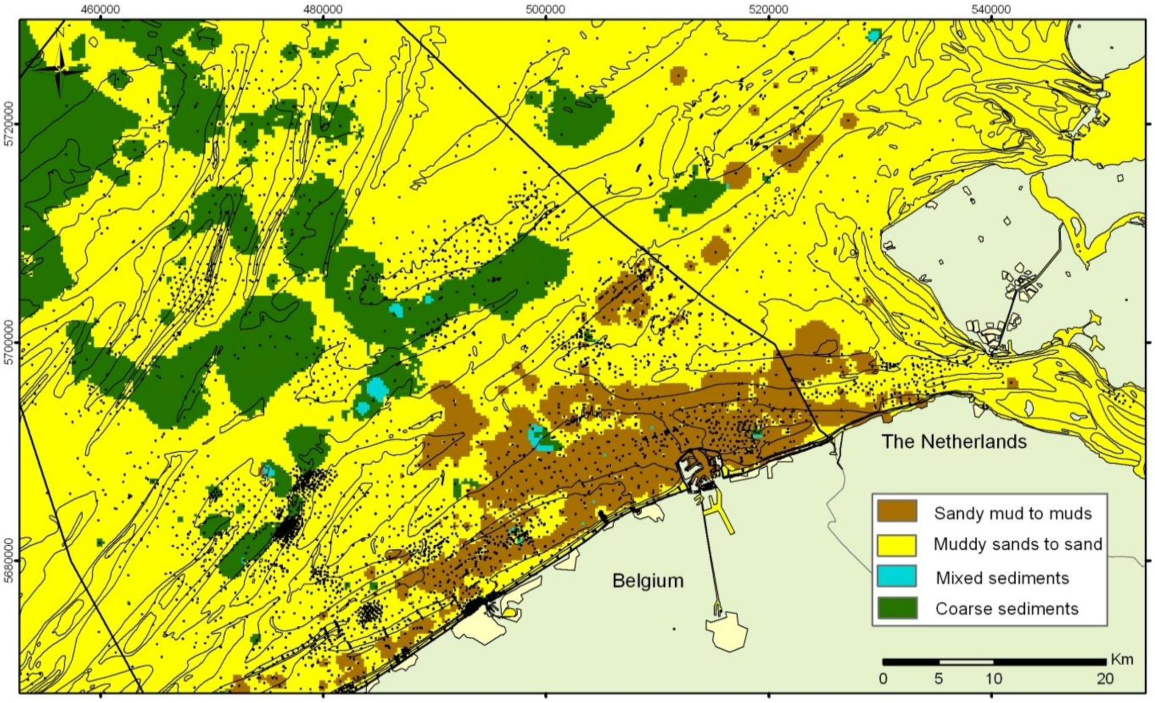

Figure C4-1. Simplified Folk sediment map, representative of EUNIS Level 3 habitats: sandy mud to mud, muddy sands to sands, coarse sediments and mixed sediments. The distribution reflects the percentages of gravel, sand, silt and clay from sample data (black dots). The sample density per polygon is a rough indicator of the confidence of the map.

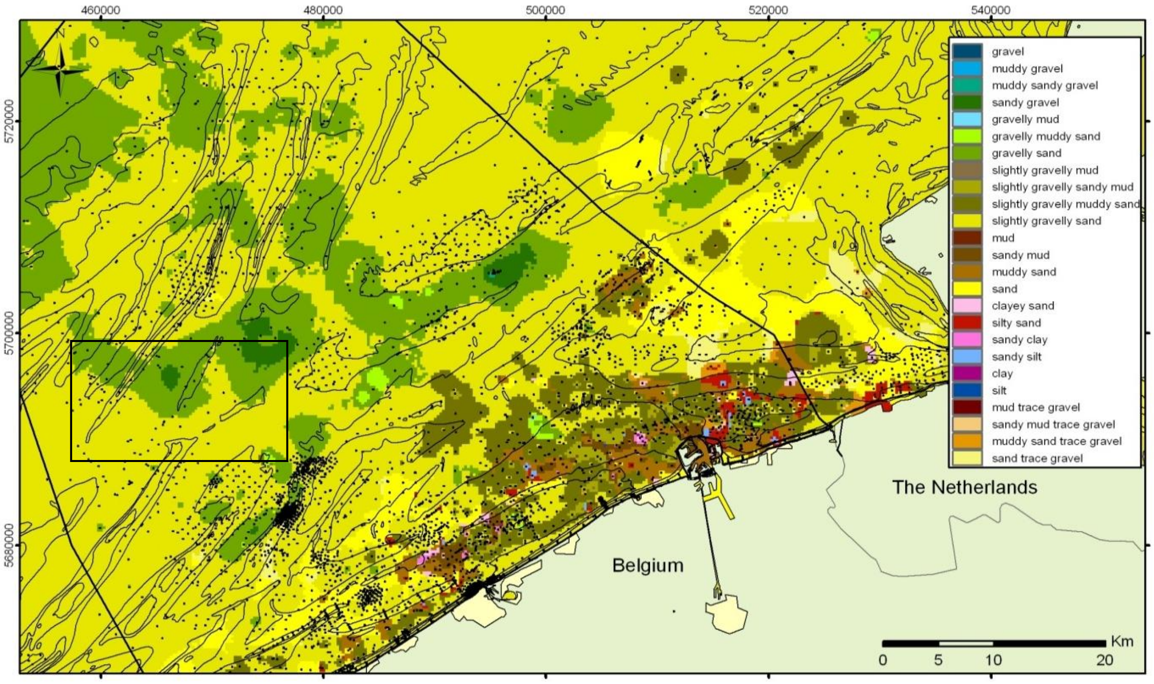

Figure C4-2. Original Folk classes providing detailed information on the distribution of sediment types. Many of the smaller polygons are characterized by only a few data points, suggesting low confidence for those areas, which can be remedied only by additional field observations. The rectangle on the left shows the location of fine-scale very-high-resolution multibeam data.

Evaluation and discussion

Evaluation of the distribution of sandy muds to muds

The complex distribution pattern of the fine classes in the Belgian-Dutch coastal zone is due to the combined effects of lithologically variable Holocene tidal deposits, a diverse and fluctuating hydrodynamic regime governed in part by water depth and seabed morphology, and long-term human activities (e.g. harbour infrastructure works, disposal of dredged material). Under storm conditions, wave action may scour the seabed to below the top of the older Holocene silts and clays. When eroded, these fine-grained sediments add to the complexity of the overall sediment distribution [91]. The patchy distribution of the fine sediment classes is probably very sensitive to temporal changes in governing factors such as near-surface geology and hydrodynamic regime. The muddy nature of the seabed and the high temporal variability of local sediment processes, that these fine-scale areas have in common, would explain why the habitat is rather poor. It is strongly dominated by the *Macoma balthica* macrobenthic community [59]. Species occurrence and diversity is likely very patchy and variable.

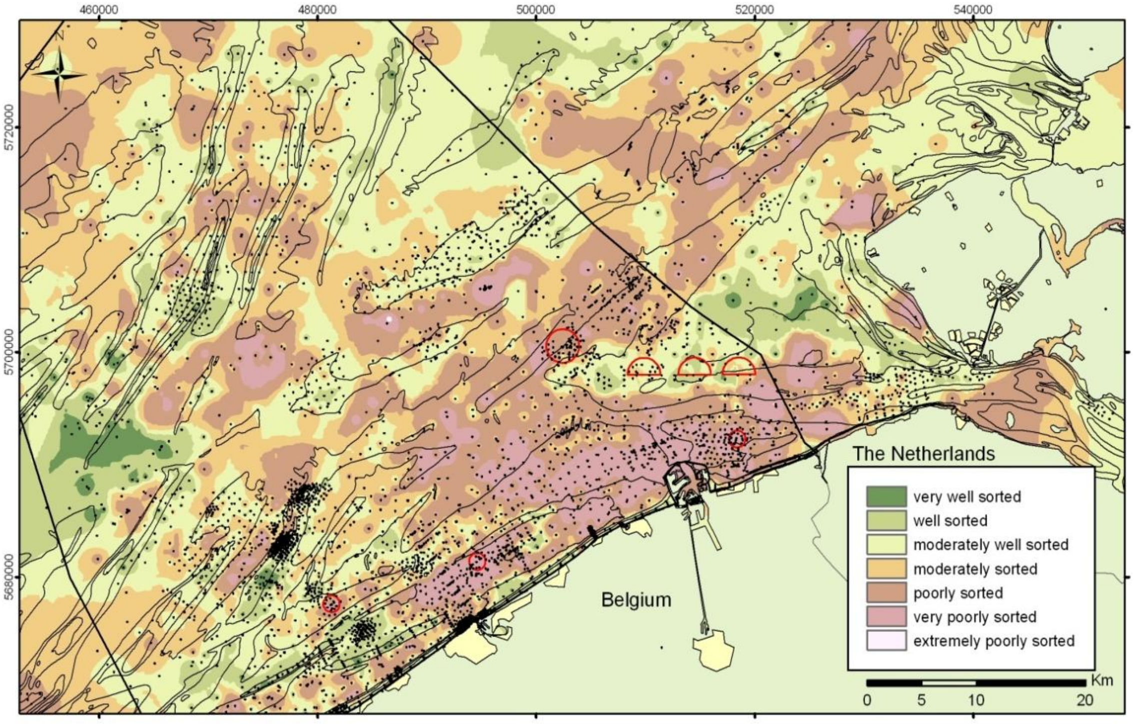

Figure C4-3. Spatial distribution of sediment sorting, here calculated over the full range of the sediment distribution. Red polygons demarcate present-day disposal grounds for dredged material.

Noteworthy are the patches of fine, poorly sorted sediment outside the coastal zone (Figures C4-2 and C4-3). Van Lancker et al. [91] hypothesised a relationship with the long-term (30 years) disposal of dredged material on the ebb-tidal delta of the Westerschelde estuary. It is further hypothesised that the resulting morphological changes have led to a permanent alteration of hydrographical conditions, resulting in more active sedimentation of fines in this area. These modifications have resulted in changes in the habitat and species distribution. Very-high-resolution multibeam bathymetry and backscatter, in combination with sample analyses, showed dense aggregations of mud-loving species as well as opportunistic species in these areas [91].

Evaluation of the distribution of muddy sands to sands

When applying the simplified Folk classification, the tidal-ridge system of the Belgian-Dutch sector of the North Sea falls mostly within the muddy sands to sands category (Figure C4-1). In the original Folk rendition (Figure C4-2), much of this area is labelled as slightly gravelly sand. Here, muddy sand and sand *sensu stricto* take up relatively small areas, with the sand being characterized by its very good sorting (Figure C4-3). In relation to habitat, the composition and vertical distribution of the small gravel fraction could be further explored when determining the indicative meaning of the maps.

Considering the dominance of slightly sandy gravel, which has a mud content of less than 10%, enrichment of fines due to marine aggregate extraction or near- and far-field effects of dredge-spoil dumping can only impact on the distribution of the classes of the simplified Folk map (and therefore on EUNIS Level 3) when the resulting concentrations exceed the 20% used as a boundary value in separating sandy muds from muds and muddy sands from sands. Changes from 2 to 18% mud, for example, will not be apparent. On an overall habitat level, this may not be problematic, but it limits the use of time series of simplified Folk maps as a monitoring tool for environmental change.

Evaluation of the distribution of coarse sediments

On the seabed, the transition from sandy to gravelly areas is not a simple spatial gradient that can be expressed easily on a map. Rather, it is marked by patchiness that is not static, but changes quickly as conditions on the seabed change. The following issues arise in the mapping of coarse sediments, especially if gravel is concerned:

- Underestimation of gravel content and distribution if sample data have been collected with Van Veen grabs that are unsuitable for taking representative samples of gravelly seabed sediments.
- Shells and shell hash add to the percentage of gravel, but should be considered separately from siliciclastic gravel. Visual sediment descriptions are needed to differentiate these two elements used in the calculation of the gravel percentage.
- The distribution of coarse sediments may be derived also from acoustic depth and backscatter information, but this method has its limitations as well (see Monteys et al., Case Study 3). The strong backscatter is caused mainly by the landscape morphology of typical gravel areas, though gravel itself may not be present (Figure C4-4). Areas of coarse-grained sediments distilled from backscatter analysis are far larger than expected on the basis of sample data.

High-quality observations show that gravel beds are mostly covered with sands of varying thickness, adding to the complexity of detecting and monitoring their limits of occurrence. Typically, video imagery shows a mostly sandy seabed with patches of gravel covered on and off by thin veneers of sand (Figure C4-4). Fluctuations in gravel content at the surface and in the upper decimetres of the seabed may occur. It is not yet clear how areas of surficial gravel may shrink and grow as natural conditions vary, both locally and on broader scales, making it difficult to define a T_0 reference as part of an initial assessment.

In light of this fact, suggesting thresholds to the spatial distribution of coarse sediments, and especially of gravel beds, as an indicator of good environmental status and to ensure the sustainability of aggregate extraction, dredge-spoil dumping and other human activities is not straightforward. Proposed maximum changes in the distribution of EUNIS Level 3 habitat types, although seemingly attractive for their clarity as an objective, must be considered in relation to the uncertainty and natural variability of the reference situation used. When such uncertainty or natural variability is greater than the maximum acceptable change in areal extent of sediment types, alternative indicators must be defined.

The influence of uncertainty and natural variability in the initial assessment of EUNIS Level 3 distribution has not yet been quantified. Aside from increasing efforts to monitor, understand (by generating system knowledge) and model natural variability as one measure of uncertainty (limitations in sampling, sample analyses and data interpolation being others), a way forward in the short term would be to select representative seabed types at key locations and monitor their change, and to determine how such observations can be up-scaled to larger areas. An example would be to follow-up the distribution of sand cover and epifauna in gravel areas in the near and far field of extraction sites.

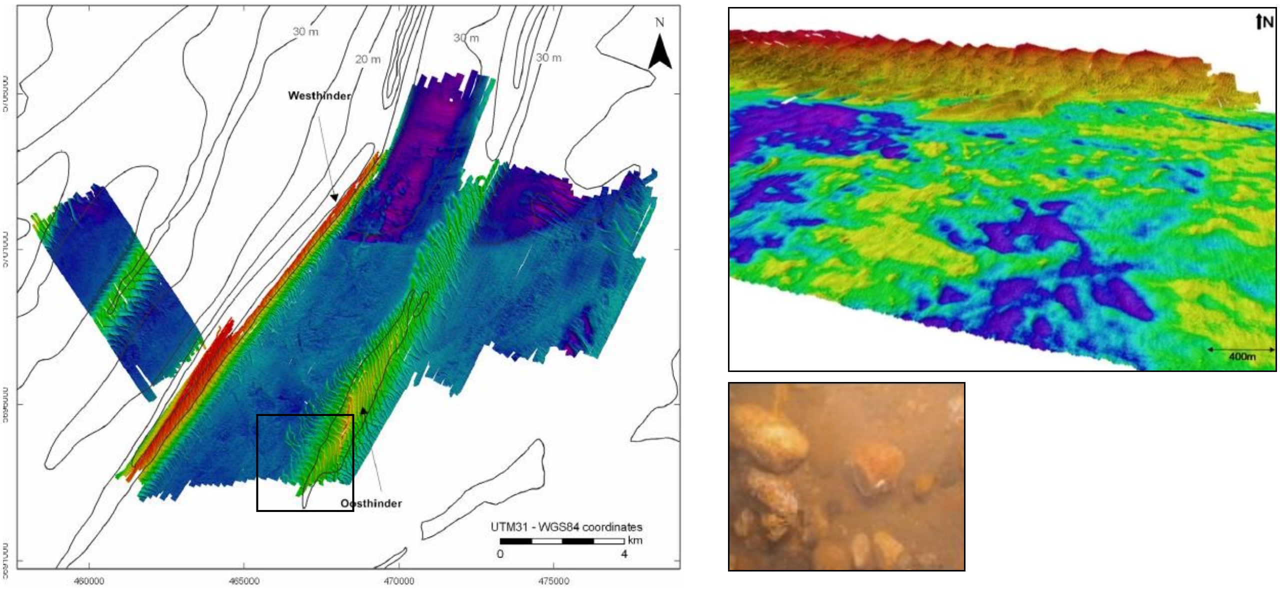

Figure C4-4. Multibeam bathymetry of an area in between the Westhinder and Oosthinder tidal ridges (Belgian part of the North Sea) where coarse sediments prevail (for location, see Figure C4-2). The box denotes the area shown in detail in Figure C4-5. At the foot of the Oosthinder, barchan dunes occur; these are typical for coarse substrates. The gravel beds are associated with variable small-scale morphology: localised pits of 2 to 5m in depth are common, occurring in zones of more than 500m across (upper right). Backscatter images show high reflectivity and a coarse to rough texture [92].

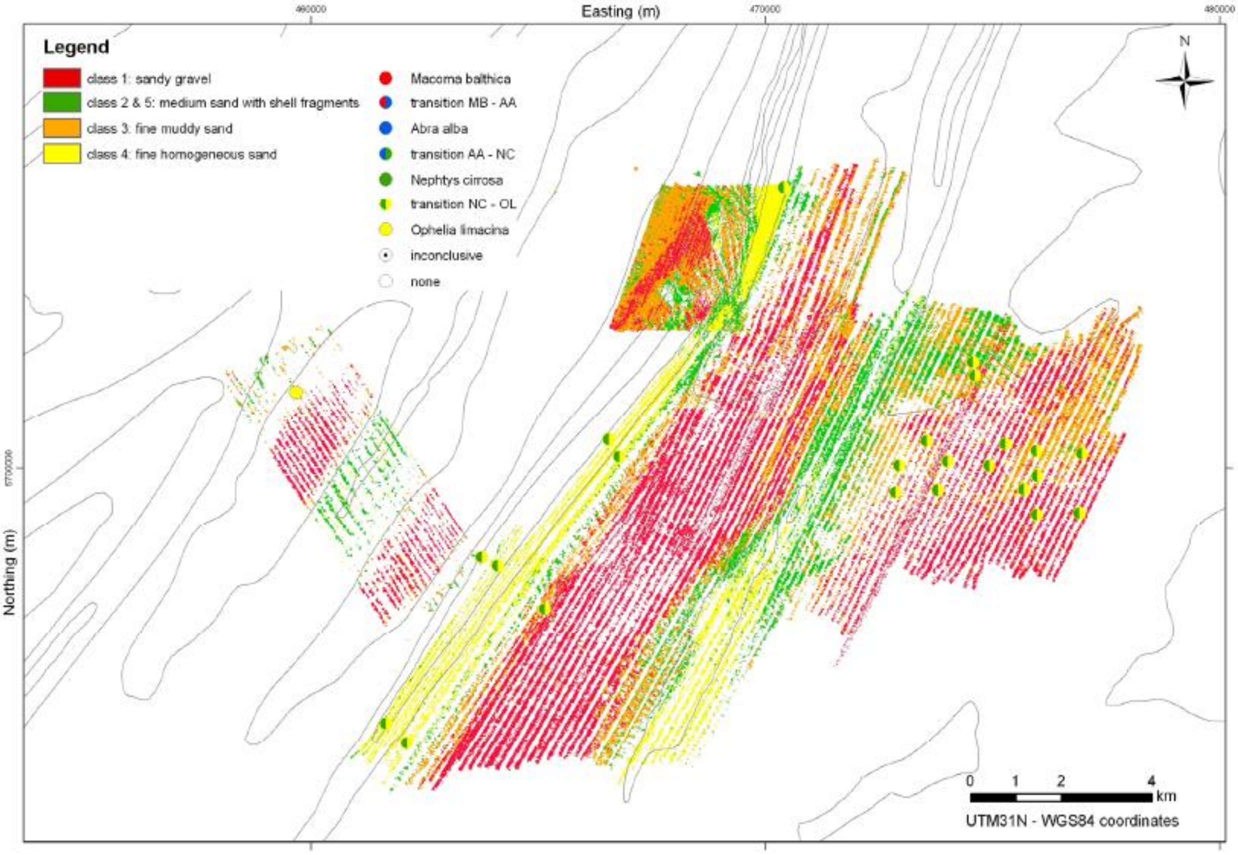

Figure C4-5. Acoustic seabed classification of the tidal-ridge area marked by the box in Figure C4-4. Sediment on the ridges clearly differs from surficial sediment in the intervening gullies, where sand included gravel admixtures. Superimposed on the seabed image are biological sample locations, annotated with the associated macrobenthic community. All of the samples are assigned to the Ophelia limacina community. They are representative of the sand occurring on top of the gravel, and bear little or no relationship with the gravel underneath [92].

Conclusions and recommendations

As indicator of good environmental status (European Marine Strategy Framework Directive), some countries propose to maintain, within natural limits, the distribution and area of EUNIS Level 3 habitats. For southern North Sea habitats, this criterion relates mainly to the distribution of sandy muds to muds, muddy sands to sands, and coarse sediments.

In this case study, the areal distribution of those habitat types is evaluated and some causes of their temporal variability are flagged.

Some recommendations:

- It should be remembered that a map is a cartographic representation of the best available data, collected over many years using a variety of sampling and other observation techniques. Given the complexity (e.g. patchiness) and dynamic nature of the seabed, no map can be produced that is 100% correct, 100% of the time;
- Typical surface-sediment maps provide insight into the spatial variability of seabed properties and are a direct but imperfect surrogate for habitat distribution;
- Through flexible sediment-parameter querying and mapping, and combining parameters, spatial variability can be further explored in function of process and system knowledge. Such exercises help in the optimisation of monitoring programmes and with the formulation of hypotheses on seabed changes within an

MSFD context (e.g. seafloor integrity). Gradients of disturbance or degradation can be more easily identified and validated;

- Sediment maps need confidence assessments, based on accurate metadata of the underlying datasets (e.g. related to sampling methods and condition, remote observation, analytical techniques, and the map-making process (including interpolation));
- If quantitative evaluations of habitat change are to be made, each of the habitat types should be sufficiently sampled and natural variability quantified as part of an initial assessment. Sufficient sample density is especially critical for the characterisation of a heterogeneous seabed (e.g. muddy and coarse sediments); statistical significance of the results should be tested in this case;
- The most appropriate locations, spatial scales and resolution of initial assessments and follow-up monitoring should be specified;
- Seabed heterogeneity and patchiness can best be resolved from full-coverage data, as provided by very-high-resolution multibeam depth and backscatter data;
- More experience is needed on how to quantify sediment gradients from multibeam data in an monitoring context (e.g. transition from one habitat type to another);
- When detecting changes in an assessment context, it is recommended to:
    - Only perform assessments where sufficient validated seabed data are available with vintage annotation;
    - Study the processes underlying the change to understand the causes and driving forces;
    - Increase the knowledge on the relation between sediment changes and deterioration of benthic fauna and flora (e.g. thresholds). Flexible sediment mapping and easy parameter delivery, targeting critical thresholds, will facilitate the exploration of sediment variability against benthic data.

Annex A. **References**

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Annex C. **Terminology**

Term	Description
Abiotic	Non-living chemical and physical factors in the environment which affect ecosystems.
ArcGIS	Esri's ArcGIS is an industry standard geographic information system (GIS) for working with maps and geographic information.
BALANCE	Baltic Sea Management – Nature Conservation and Sustainable Development of the Ecosystem through Spatial Planning (http://www.balance-eu.org).
Beam trawl	Fisheries related term. A cone-shaped body ending in a bag or codend, which retains the fish catch.
BIO-ENV	A software procedure within PRIMER (www.primer-e.com) that uses all available environmental variables to find the combination that 'best explains' patterns in biological data.
dbSEABED parser	An Information Processing System for Marine Substrates (INSTAAR). Through the parser, outputs are produced that are compatible with Geographic Information Systems (GIS), relational databases, and several other highly useful formats. The outputs can be used in many end-user software applications.
EMODnet	European Marine Observation and Data Network (EU-DG MARE).
EUNIS	The European Environment Agency classification scheme for habitats (European Nature Information System) for managing species, site and habitat information. It is a pan-European classification of terrestrial, freshwater and marine habitats.
EUSeaMap	EUSeaMap (EMODnet) is a broad-scale modelled habitat map that covers over 2 million square Km of European seabed.
GeoSciML	Geosciences mark-up language. Global standard for geosciences data exchange.
INTERREG	An initiative that aims to stimulate cooperation between EU regions.
MESH	Development of a framework for Mapping European Seabed Habitats (http://www.searchmesh.net).
Multibeam backscatter	Backscatter is the amount of acoustic energy received by multibeam sonar after complex interaction with the seafloor.
OneGeology	An international initiative of the geological surveys of the world to create dynamic geological map data of the world, available to everyone via the web (http://www.onegeology.org).
Sediment classification systems	Methods for classifying sediment type, e.g. based on gravel, sand, mud or clay content.
Side-scan sonar	Sonar device that emits conical or fan-shaped pulses down toward the seafloor across a wide angle to obtain high quality imagery.