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Terrain characterization from bathymetry data at various resolutions in European waters – experiences and recommendations.	
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Geomorphic terrain features relevant for habitat mapping have been reviewed and described in case studies from Denmark, Ireland and Belgium. The report proposes standardized scales and methods for mapping of ecologically relevant geomorphic features, and also recommends that future development of EUNIS should include formal integration of geomorphological features.	
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Executive Summary

This report reviews how bathymetric data may be used to characterize seabed terrain with a view to benthic habitat mapping. This study was led by the Geological Survey of Norway with contributions from the Geological Survey of Denmark and Greenland, The Geological Survey of Ireland and the Royal Belgian Institute of Natural Sciences.

The report starts with a review of the geomorphic structures relevant to habitat mapping, also considering the extent to which geomorphology has been included in various legislative and habitat classification systems. Methods for terrain characterisation are then reviewed, showing how bathymetric data can play an important role in delimiting geomorphic features and benthic habitats, and how geomorphic structures are used in different habitat classification systems.

Case studies have been included from Denmark, Belgium and Ireland, in order to illustrate the wide spread in physiographic settings which can be found in European waters and provide examples of data at different spatial resolutions.

The report gives a summary and recommendations for the formats and resolution of bathymetrical data to be used for ecosystem based management of European waters, and proposes recommendations for future development of the EUNIS habitat classification system.

Content

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 to develop new products and services, and 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 for data management include the Geo-Seas e-infrastructure, EMODNET and the upcoming WISE-MARINE data and information management system.

Bathymetry is one of the data sets handled by EMODNET, and the purpose of this report is to investigate and document how the bathymetric data may be used to provide ecologically relevant knowledge about benthic ecosystems, and how that data must be delivered to the users in order to be useful. Bathymetry is expensive to collect, and it is important to find out how detailed it needs to be, in order to be able to define what kind of resolution is needed for different purposes.

Traditionally, the primary use of bathymetry has been safe navigation. However, in recent decades, it has become clear that it is also an important source of information for the marine ecosystems. Many habitats can be wholly or partly characterized by geomorphic features. The scale of these geomorphic features ranges from meters to several tens of kilometers.

This study is a cooperation between several institutes – the Geological Survey of Norway, The Geological Survey of Denmark and Greenland, The Geological Survey of Ireland and the Royal Belgian Institute of Natural Sciences. Case studies have been included from Denmark, Belgium and Ireland, in order to illustrate the wide spread in physiographic settings which can be found in European waters. The study starts (Section 2) with a review of the geomorphic structures relevant to habitat mapping, also considering the extent to which geomorphology has been included in various legislative and habitat classification systems. Methods for terrain characterisation are reviewed in Section 3, showing how bathymetric data can play an important role delimiting geomorphic features and benthic habitats, and how geomorphic structures are used in different habitat classification systems.

Case studies from Denmark, Ireland and Belgium are described in Section 4. The last section gives a summary and recommendations for the formats and resolution of bathymetrical data to be used for ecosystem based management of European waters, and recommendations for future development of the EUNIS system.

2 Geomorphic structures relevant for habitat mapping

2.1 Introduction

The distribution of benthic habitats is often linked to changes in the geomorphology of the seabed, and this is reflected across a vast range of spatial scales. At the broadest scale, continental shelf habitats differ from those found on deep sea plains, whilst different communities again are found on the continental slope and in canyons or on seamounts. Characterisation of geomorphic features even at this broad scale therefore offers an important high level view of the likely distribution of habitats. On a more local scale, for example, the benthic communities found on rocky reef are quite distinct from those found on the surrounding, relatively flat seabed. The distribution of benthic fauna and vegetation most commonly responds to changes in the topography. Animals or plants find their particular spatial niche in relation to the topography that best suits their mode of living: for example where they find access to food, shelter and suitable substrate. The geological history causing the particular topographic features to occur at the seafloor is not necessarily directly important to the benthic fauna, however, there are many documented cases where species show a preference for geomorphic features with a particular geological origin (e.g. raised tectonic features off Alaska show a strong link to rockfish habitat [1]. By understanding the geological history and processes we can gain greater insight into benthic habitats than by merely identifying highs and lows in the seafloor. Changes in geomorphology *may* coincide with changes in the surficial geology but this is not always the case, depending on the geological and associated environmental processes operating in the area and the timescales over which they operate. For this reason geomorphology should be considered as a separate layer of information to surficial geology, although both are important components in structuring benthic habitat.

Marine benthic habitats tend to be structured by their two or three dimensional geomorphological characteristics coupled with overlying hydrographic parameters [2]. This makes them more challenging to map using remote sensing than their terrestrial counterparts. Some structures however, such as biogenic structures (e.g. coral reefs, sponge reefs, mussel beds) or shallow water habitats dominated by vegetation (e.g. kelp forests, sea grass beds) can be identified more directly by remote means [2]. In most cases however, biological information comes from separate sampling by using physical or visual methods and geomorphology can suggest likely targets for those species or communities which associate with particular bathymetric features. High resolution seabed mapping techniques such as multibeam, LIDAR, laser line scan provide the baseline data for much of today's work on marine habitat mapping, and together with GIS analysis have revolutionised marine benthic habitat mapping. On a regional or global scale however much can also be done with lower resolution surveys, not least a classification of global marine geomorphology [3, 4].

The newly published book, 'Geomorphology as Benthic Habitat. GeoHAB Atlas of Seafloor Geomorphic Features and Benthic Habitats' [5] contains a timely review of geomorphology in relation to benthic habitat together with case studies from around the world from many leading research groups and national agencies involved in the field of benthic habitat mapping. The very fact that this book was produced is testament to the importance of geomorphology in relation to benthic habitat mapping. Chapter 6 of the book provides a thorough review of geomorphology in coastal, shelf and abyssal regions and we refer the reader to this publication rather than repeating details here. In preparation of the book the editors made a particular effort to standardize the terminology used to describe geomorphic features between the various case studies. This is an important step since the literature reflects the fact that geomorphic features are described using a vast array of terminology, perhaps compounded by the fact that non-geomorphologists now have access to the data that allows them to put a name to structures they identify in the bathymetry data. By using the IHO list of geomorphic features [6] as a basis, the book has largely achieved this goal, and additionally incorporated several features that were not present in the IHO list. Whether or not the benthic habitat mapping community continues to follow this trend of standard nomenclature, remains to be seen.

The diverse range of geomorphic features described in the 57 case studies contained in the book reflects the fact that nearly any geomorphic feature is important for benthic habitat. Listing the features covered by the case studies in the book, in order of the number of times they were cited as a major focus for the study we have: sandwave/sandbank, coral reef, canyon, glaciated shelf, seamount-guyot, plateau, shelf valley, temperate rocky reef, seagrass, ridge, fjord, trough-trench, hydrothermal vents, escarpment, pinnacle, estuary, peak, channel, cold seep, holes, platform, barrier island, tidal inlet, embayment, sill, terrace, mound. The editors note that estuaries and deltas were perhaps under-represented in the cases studies, as were deep ocean (abyssal/hadal) environments. Rather than reflecting the fact that these are less important for habitats, the editors suggest it is more likely that the lack of case studies in shallow coastal areas reflect difficulties in accessing appropriate technology to map these very shallow environments. In the deep sea they suggest that the high cost of surveys, location in high seas outside national jurisdiction/responsibility and perception of these environments as remote from human activities have all led to a lack of focus on marine habitat mapping to date in these areas. Gaps in the areas of study presented may also somewhat reflect the focus of the marine Geological and Biological Habitat mapping (GeoHab) community who contributed to the book, though measures were to taken to overcome any such bias by directly inviting case studies where geographical/geomorphic gaps were present in the original submissions.

It is clear from the scientific literature that there is general agreement among the marine habitat mapping community that geomorphology is important for benthic habitat mapping. At least to a certain extent, or at certain spatial scales, geomorphology can serve as a proxy to some of the factors directly influencing the distribution of benthic species and communities. The extent to which it can do so is often dependent on how unique the geomorphic features are with respect to the surrounding seabed. For example Greene et al. [1] found that demersal shelf rockfish show distinct affinity for habitats associated with geomorphic features formed by a variety of geological processes, but all resulting in high relief rugged or rugose seafloor features that generally interrupt the flat seafloor. The authors suggest that the rockfish find shelter in this type of morphology and also benefit from concentrated nutrients which are a result of turbulence in the current flow caused by the seabed features.

Whilst benthic fauna may directly respond to factors including temperature, salinity, oxygen concentration, light availability, and sediment composition it has frequently been observed that species generally show preferences for certain depths and topographic conditions [2] so by analysing bathymetric data to delineate geomorphic features and/or derive quantitative descriptors of the terrain, such as slope, we can obtain crucial input data for the process of habitat mapping. The United States Coastal and Marine Ecological Classification System CMECS (see section 2.3.4) summarises the ecological relevance of geomorphic features (geoforms) which are one component of the full ecological description with the following succinct statement:

“Geoform units provide structure, channel energy flows, and regulate bioenergetics. They also control such processes as water exchange rates and water turnover times; hydrologic and energy cycling; shelter and exposure to energy inputs; and migration and spawning. Because of these diverse interactions, it is impossible to fully understand a biotic community without also considering the geological context in which the organisms are found” [7]

The term geomorphology instantly brings to mind natural features of the seabed, and the habitat community to date has largely focussed on mapping habitats associated with such natural features. With modern technology, however, we are equally well able to map many man-made features of the seabed which have a topographic expression. These are particularly relevant to marine habitats in the coastal zone where coastal protection structures, piers, harbours, marinas, etc. are common features. Other anthropogenic structures influencing habitat may include artificial reefs, shipwrecks, windfarms, pipelines, offshore dumping sites, mining sites, etc. and all of these may be resolved with multibeam surveys, depending on the resolution, and therefore are recognisable either visually or detectable through the use of terrain analysis. Such man-made geomorphology is important to consider, especially as more and more scientists are using automated geomorphic classifications and modelling techniques in the process of habitat mapping. It is important to remember the origin of the geomorphic features to help explain the habitat associated with them, and provide the correct information for informed management of the marine environment.

Among the benthic habitat mapping literature quite a high proportion of studies have presented 'habitat' maps based primarily on geomorphology/surficial geology; however, it is important to remember that geomorphology *per se* is not habitat. Classified geomorphic features are merely one layer of abiotic information that may be used together with biological and other data to make a true habitat map.

'Broad scale maps of abiotic features are not habitat maps, and only become so with the addition of biological data.' [2].

The concept of 'habitat' is confused somewhat by several of the habitat classification schemes in common use, particularly hierarchical schemes, which are abiotic at the higher levels and only introduce a biological component at the lower levels (section 2.3). The various terminologies in use are discussed further by Costello [8] and Brown [2]. In this review, since we need to address all geomorphic structures and methods characterizing terrain in use by the habitat mapping community, including those at marine landscape/seascape level, we must adopt a less restricted definition of habitat in order to provide information relevant to those making habitat maps at an abiotic or full biotic level. This inclusive approach is in keeping with the compiled work reported by Harris and Baker [5] which aims, among other things, to advance our understanding of the different habitats associated with particular geomorphic features.

The importance of geomorphology in relation to benthic habitats means it has been used directly (although still as a proxy) in applied management of the marine environment such as marine reserve design [9], marine protected areas [10-12] or integrated coastal zone management [13, 14]. With the rise in predictive modelling of benthic habitats over the last few years we have also seen the applied use of geomorphic classifications as an environmental predictor variable in several studies, e.g. cold water corals [15] and rockfish [16]. Numerous other studies have used terrain variables derived from bathymetry data in the prediction and classification of the potential habitat distribution for particular species e.g. cold water corals [17-19], lobsters [20] or communities/assemblages [21-23] over a wide range of spatial scales.

In the following sections we examine how geomorphology has been included (or omitted) in various legislation surrounding habitats relevant for Europe, and then see to what extent it is included in some commonly used habitat classification systems. Finally we look at some examples of geomorphology related to habitats for single species which have been reported in the scientific literature.

2.2 Geomorphic structures in legislation

2.2.1 European Union Directives

The Marine Strategy Framework Directive (MFSD) [24] outlines a framework for an ecosystem-based management of human activities which supports the sustainable use of marine goods and services. The goal of the framework is to achieve 'good environmental status' by 2020. Eleven qualitative descriptors offer a basis for assessing environmental quality, however the MFSD does not directly address geomorphology. Potentially, geomorphic characterisation could contribute to assessment of some of the descriptors, in particular descriptor 6 (Sea floor integrity) and descriptor 7 (Alteration of hydrographical conditions), however there is no requirement that geomorphology is considered in such assessment.

The MFSD is complementary to and provides the overarching framework for other directives relevant to the marine environment including the Habitats and Water Framework Directive. The EU Habitats Directive [25] requires member states to take measures to maintain or restore certain natural habitats. Among the list of marine habitats to be addressed nearly half of them are either geomorphic features or features that can be identified through geomorphic analysis. Marine habitats listed in the directive that are directly identifiable by geomorphology (with appropriate supporting information) include sandbanks, seagrass (*Posidonia*) beds, estuaries, large shallow inlets and bays, reefs, submarine structures made by leaking gases, mudflats/sandflats, and coastal lagoons.

The EU Water Framework Directive [26] is also important for the marine environment particularly in coastal areas where it applies to estuaries and waters up to 1 mile from the low-water line. The directive does not specifically address geomorphology, but geomorphic (natural or anthropogenic) features can be important in influencing the passage of water and it is geomorphic analysis that will allow the delineation of features such as estuaries.

2.2.2 The Convention for the Protection of the Marine Environment of the North East Atlantic (the OSPAR Convention)

The OSPAR list of threatened and/or declining species and habitats (www.ospar.com) includes several habitats which are either geomorphic features, or which potential occurrences may be identified from suitable data through geomorphometric analysis. In addition, the list includes threatened species many of which may have habitats that are associated with particular geomorphic features, at least at some stage in their life cycle.

The OSPAR listed habitats with a geomorphic signature include: carbonate mounds, seamounts, and *Lophelia pertusa* reefs. Deep sea sponge aggregations are also listed, which may have a topographic signature, but it could be argued whether or not they are really geomorphic features. Both reefs and sponge aggregations would be dependent on bathymetric data of sufficiently high resolution to resolve a topographic signature indicating potential occurrence.

2.3 Geomorphic structures in marine habitat classification systems

In this section we review the extent to which geomorphic features are specified in some of the most widely adopted marine habitat classification systems that have been reported in the marine habitat mapping literature to date.

2.3.1 EUNIS

EUNIS is a broad classification spanning terrestrial and marine environments and has been widely applied, particularly within the EU, but also elsewhere in the world. Despite attempts to harmonize the classification, and significant improvements over the years, EUNIS has evolved in a somewhat ad-hoc manner with classifications being developed targeted to specific habitats, and with varying levels of detail. EUNIS has no specific focus on terrain characterisation or geomorphology. It is a hierarchical classification (levels 1-6) which, for the marine environment at its upper 3 levels is determined by biological zone (littoral, circa littoral etc.), energy (wave/tidal) and seabed substrate (Fig. 1). A related deep sea classification system was proposed by Howell [27] and is included in the summary illustrated in Figure 2 from the UK Seamap project [28]

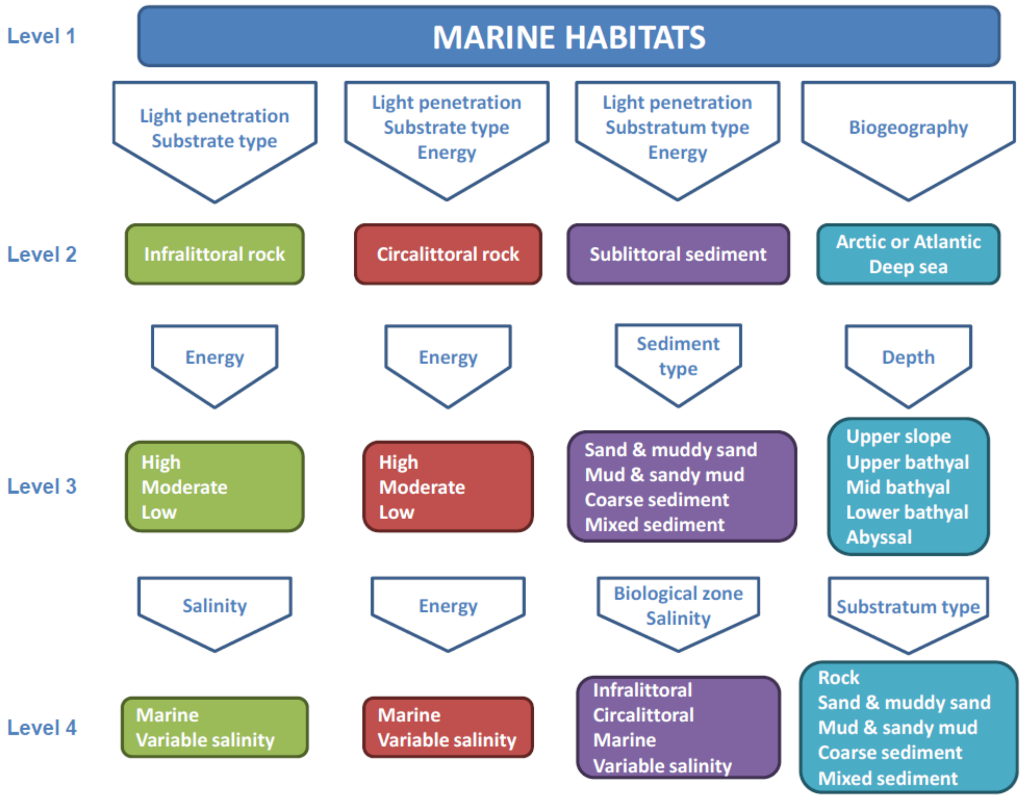


Figure 1. Diagram of the physical data layers (blue arrows) used to predict habitat at different levels of the EUNIS and deep-sea classifications. From [28].

More detailed classifications beyond level 3 become more and more specifically related to benthic fauna. Broad-scale predictive maps of EUNIS habitat classes at level 3 or 4 have been produced (e.g. [28, 29], however at this level they are not *true* habitat maps since they lack biological data. The absence of terrain information or geomorphology as an input to the EUNIS marine habitat classification could seem to be a major weakness. However, recent work (e.g. [30, 31]) has demonstrated how bathymetry data (of various resolutions) and associated terrain characterisation (e.g. benthic position index, slope) can be used to identify certain habitats e.g. rocky reefs, and therefore make a major contribution to habitat mapping to EUNIS level 3 and 4. Terrain characterisation can also make a valuable contribution to a sediment (grain size) map which is an essential part of the EUNIS classification. Such use of data is further supported by MESH (Fig. 2). We must therefore conclude that EUNIS is *able* to use terrain characterisation in an indirect manner; however, since it is not directly part of the classification, whether or not terrain characterisation is used is determined entirely by those scientists applying EUNIS and making the habitat map.

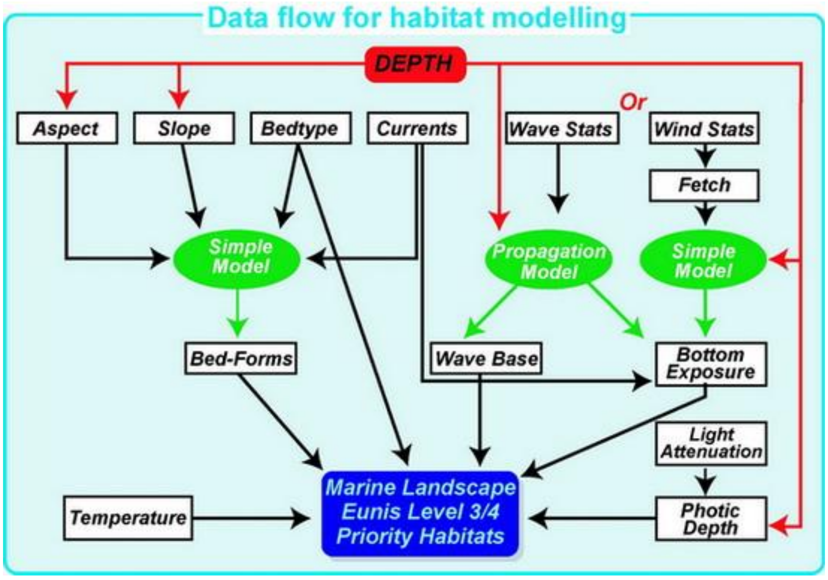


Figure 2. Ways of combining environmental data for habitat modelling. Depending on the resolution of the data layers, the final product may be a 'Marine Landscape', a EUNIS level 3 or 4, or focused on a priority habitat. From http://www.searchmesh.net/default.aspx?page=1761

In devising the deep water habitat classification, Howell [27] examined the potential inclusion of geomorphic features; however in the final proposal geomorphology is omitted. The reasons for this are discussed by Howell but are based on the lack of clear relationships between geomorphology and biology across all scales relevant in the deep sea.

2.3.2 Seascape/Marine Landscape classification *sensu* Roff and Taylor [32], Roff, Taylor and Laughren [33]

This is a rule-based classification which applies abiotic information to categorize pelagic and benthic environments. The top levels (1-4) are at global scale and are based on oceanographic factors. At level 5, as the classification moves to regional scale (hundreds to thousands of kilometres), the marine environment is split into pelagic and benthic with successive divisions of the benthic realm over the remaining levels (6-8) which focus on a more local scale (tens to hundreds of kilometres), based on photic depth, bottom temperature and finally topographic and geological attributes. Level 7 includes a very broad scale classification of slopes which may be classified as high (>2°) or low (<2°). Level 8 is reserved for classification of surficial sediment type. There is no specifically geomorphic component to the classification. The marine landscape/seascape classification, or modifications of this approach, have been quite widely adopted, particularly where there is no dedicated seabed mapping programme but there is a strong demand for information at a management level [28, 34-38] as this approach provides a good framework by which to categorize naturally different areas of the marine environment without the need for detailed data. We note however that whilst the upper 7 levels of the classification are quite easy to apply from global datasets (oceanography and bathymetry) it would be difficult to apply level 8 – sediment classification without a large historical inventory of geological sampling, or limited sediment sampling, plus geophysical data which are prerequisites for a reasonable sediment map to be constructed. Roff et al. [33] discuss the biological relevance of the classification and its limitations. The authors conclude that the seascape approach, while based on abiotic information, can allow identification of representative habitats containing representative community types. It is one approach that can offer a sound basis for classification particularly relevant for marine conservation and planning of marine protected areas. It is also an approach that can, in part at least, be guided by automated classification e.g. Lucieer and Lucieer [39].

2.3.3 Greene et al. [40, 41] Classification Scheme for Deepwater Habitats

Geomorphic features are an integral part of the benthic habitat classification scheme proposed by Greene et al. [40] across all scales. In contrast to EUNIS and Roff et al. [37], the scheme developed by Greene et al. [40] is only benthic, and therefore directly relevant to benthic habitat mapping. The Greene et al. [40] classification was updated by Greene et al. [41] and classifications based on this approach have been quite widely adopted, especially in the U.S.. Most of the structures described by Greene et al. have since been included in CMECS (Section 2.3.4), and since this has now become a wider and more overarching standard, it is perhaps more appropriate to follow CMECS now, whilst acknowledging the original contributions of Greene et al. [40, 41].

2.3.4 US Coastal and Marine Ecological Classification Standard (CMECS)

The Coastal and Marine Ecological Classification Standard (CMECS) [7] is an ecological classification which provides a structured way to organise information pertaining to the geological, hydrological and biological character of marine, estuarine or lacustrine systems. CMECS version 4 published in January 2012 represents the culmination of over a decade of development work on CMECS and the incorporation of precursor classifications including Allee et al. [42]. CMECS has been developed specifically for the U.S. coastal and marine environments, but the principles could be applied to other regions and trials have already been conducted outside the U.S. as part of the development process.

CMECS divides the ecological system into 5 components (Fig. 3) which provide a structured way to organise information and offer a standard terminology for describing them. Each component can be identified and mapped independently or combined as required - section 12.6.2 (Federal Geographic Data Committee 2012). For example for benthic habitat mapping the Benthic Biotic Component, Substrate Component may be combined to produce a habitat map e.g. Figure 12.5 (Federal Geographic Data Committee 2012). The Geoform Component may also be incorporated to provide a habitat map which fully integrates geomorphology [43].

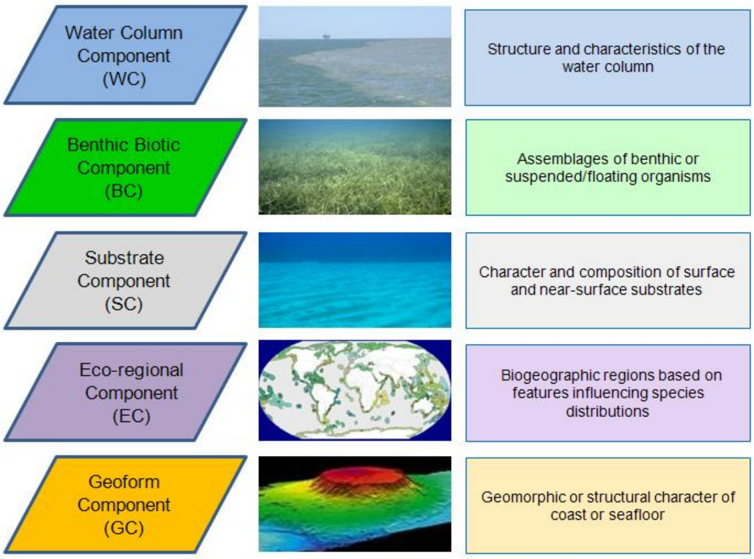


Figure 3. The five CMECS components including the Geoform Component describing geomorphology. http://www.csc.noaa.gov/benthic/cmecs/

CMECS has incorporated geomorphic structures primarily as part of the Geoform Component (GC) (although small features may appear as part of the Substrate Component). Under the GC CMECS offers a systematic way to describe the major geomorphic and structural characteristics of the seafloor across a variety of spatial scales. Five aspects of the coastal and seafloor morphology are described under the GC: tectonic setting, physiographic setting, geoform origin, geoform, and geoform type (Table 1)

The GC has four subcomponents each relevant to particular spatial scales from mega through to microscale (*sensu* Greene et al. [40]). Tectonic setting and physiographic setting describe large megahabitat scale or global features. Level 1 and 2 geoform subcomponents describe smaller features through meso- and microscale. CMECS acknowledges that while geoform subcomponents may have a general scale range associated with them, features in this category will naturally overlap each other. Since CMECS is an ecological classification, and not a mapping standard, there has been a conscious decision not to dictate mapping scales, or tie CMECS to specific mapping technologies. Some scale ranges are given for some of the geoforms to assist with delineation, but otherwise the classification is quite flexible with regard to scale (R. Allee, personal communication).

CMECS divides geoforms into coastal or marine. The CMECS classification further lists subforms (level below a geoform e.g. head of a canyon) and anthropogenic geoforms, e.g. artificial reefs, jetty, harbour, aquaculture installations. In addition CMECS offers the concept of modifiers for each geoform which includes the direct use of terrain variables such as slope, rugosity. CMECS incorporates most of the geormorphic structures described by Greene et al. [41] together with others, including estuarine features. The features listed are too numerous to reproduce here but an extract from the list is given in Table 1 below. While the list is quite comprehensive the authors note also it may be subject to modification as the CMECS standard is applied over time.

Table 1: Extract from CMECS table D1 to illustrate the type of geomorphic features represented. Note the full table is available in CMECS version 4 Appendix D (Normative): CMECS Geoform Component [7].

Table D1 Geoform Component: Tectonic and Physiographic Settings, Geoform Origin, Geoform and Geoform Types.

Tectonic Setting	Physiographic Setting	Geoform Origin	Level 1 Geoform	Level 1 Geoform Type	Level 2 Geoform	Level 2 Geoform Type
Abyssal plain	Abyssal/Submarine Fan	Geologic	Apron			
Convergent Active Continental Margin	Barrier Reef		Bank/Shoal			
Divergent Active Continental Margin	Bight		Bar	Bay Mouth Bar	Bar	Point Bar
Fracture Zone	Borderland			Longshore Bar		Relict Longshore Bar
Spreading Center	Continental/Island Rise		Basin			
Mid-Ocean Ridge	Continental/Island Shelf		Beach	Barrier Beach	Beach	Barrier Beach
Passive Continental Margin	Continental/Island Shore Complex			Mainland Beach		Mainland Beach
Transform Continental Margin	Continental/Island Slope			Tide Modified		Tide Modified
Trench	Embayment/Bay			Tide Dominated		Tide Dominated
	Fjord			Wave Dominated Beach		Wave Dominated Beach
	Inland/Enclosed Sea					Pocket Beach
	Lagoonal Estuary		Beach Berm		Beach Berm	
	Major River Delta		Boulder Field			
	Marine Basin Floor				Cave	
	Ocean Bank/Plateau		Channel	Tidal Channel	Channel	Tidal Channel/Creek
	Riverine Estuary			Slough		Pass/Lagoon Channel
	Shelf Basin					Sand Channel
	Shelf Break		Cone		Cone	
	Sound		Cove	Barrier Cove	Cove	Barrier Cove
	Submarine Canyon			Mainland Cove		Mainland Cove
	Trench		Delta	Levee Delta	Delta	Levee Delta
				Glacial (Kame) Delta		Ebb Tidal Delta
						Flood Tidal Delta
						Flood Tidal Delta Slope
			Delta Plain			
					Depression	Scour depression
			Diapir	Salt Dome	Diapir	Salt Dome
			Drumlin Field		Drumlin	
			Dune Field		Dune	
			Fan	Washover Fan	Fan	Washover Fan
				Alluvial Fan		
				Basin Floor Fan		

CMECS does not prescribe the data to be used in delineation of geoforms. Since, by definition, geomorphic features have a topographic signature most of which should be readily identifiable from bathymetric data at suitable a resolution, although Shumchenia and

King [43], in applying CMECs classification, have used acoustic backscatter and interpreted depositional environment to determine geoform.

2.3.5 **Integrated Australian Classification Scheme**

The Australian hierarchical framework for classification of biodiversity and for bio-regionalisation, marine resource planning and management [44] is a mixture of the other classification schemes described in the previous sections.

Geomorphological units are specifically addressed and are included at level 3. Units are typically 100 km or greater in extent. Terrain characterisation and smaller geomorphic features may also contribute to primary and secondary biotopes (levels 4 and 5). Last et al. [44] emphasise the importance of the upper levels 1. Biogeographic province, and 2. Bathome (bathymetric boundaries) in influencing the biological communities and biodiversity actually associated with a particular geomorphic unit. The classification system provides a mechanism to divide a geomorphic feature, e.g. a large canyon which extends through several bathomes, into several sections – canyon upper slope, etc. The authors also point out that surrogate relationships are well documented for some geomorphic units e.g. estuaries but are still largely unvalidated for others, particularly those in the deep sea (>200m) (e.g. Heap and Harris [45]). This topic is addressed in further detail by Althaus et al. [45] who examined the extent to which certain geomorphic features [47] can act as surrogates for benthic biodiversity on Australia's western continental margin. The authors conclude that some geomorphic features have high potential to act as surrogates for biodiversity at intermediate spatial scales, but that a hierarchical context is necessary to define and validate them within a larger, biogeographical context. Some features e.g. peaks [47] are effective surrogates, whilst others e.g. shelves [45,47] are simply too large to be effective surrogates and they add little information to that already identified at higher levels of bathomes and provinces [44, 48].

No comprehensive list of geomorphic features is given by Last et al. [44] but the following typical units are given, split by bathome:

Coastal: fringing reefs, beaches, estuaries, tidal flats, mudflats, drowned river valleys, and marine embayments

Continental shelves: coral cays, glaciation structures, sand banks, deltaic bottoms, and rocky banks

Continental slopes and the abyssal sea floor: submarine canyons, seamounts, escarpments, plains and valleys.

These are typically those geomorphic features identified by Harris [10] and Heap and Harris [45] and other authors cited by Last et al. [44].

2.4 **Summary**

In addition to the review offered in this chapter, we have attempted to summarize the use of geomorphic classifications under the various habitat classification systems and legislation documentation which actually specify geomorphic features into a composite table (Table 2). In addition we include the features listed in Harris and Baker [5] as a summary of features described in the case studies presented in the book. Compilation of this table has been difficult due to the use of different terminology, differing levels of specification, and/or adoption of composite geomorphic features (including more than one feature), or listing of only example features in the literature. The list however, does give an overview of the most documented features.

It is clear from the summary in Table 2 that classification of geomorphic features, and the adoption of such classifications within existing habitat classification systems, is focussed at larger features, on a regional to global scale. There is also a great variation in how specific the geomorphic features are and what scale they cover, such that some 'composite' geomorphic features may or may not include smaller geomorphic features which are equally or more relevant to the biology. This variety in size and typical nature of geomorphic features will have an impact on their biological relevance, as observed by Althaus et al. [46].

The geomorphic features present will of course depend on dominant processes affecting the morphology of the seabed. This will vary depending on the region considered, for example a glaciated shelf is likely to include smaller features such as moraine ridges, drumlins, glacial lineations, iceberg plough marks – which, dependent on other factors, and processes operating, may have a link to the distribution of fauna. The degree to which these smaller geomorphic features are important will depend to a certain extent on the scale of the study, and the type of biological data available. Away from glaciated margins, different features will be found in areas of the seabed dominated by tectonic, hydrographic, or seep-driven processes but in each case we expect smaller geomorphic features that will affect benthic communities. Such smaller features may not have a particular geomorphic 'name', and therefore a place in the IHO list [6], but are very important especially in fine scale mapping which is typically the level at which biological information is included.

Table 2. Summary of geomorphic features specified in selected classification schemes, literature and legislation. Features shown in bold appear in at least 3 classifications, some additional features were listed only in IHO [6] and have been omitted from the list as it is not specifically targeted toward habitat mapping. Note that the list is indicative only as some classification systems only list example features.

	Greene et al [41]	CMECS [7]	Last et al. [44]	Harris and Baker [5]	EU Directive [25]	OSPAR	IHO [6]
abyssal plain	x	x	x				x
abyssal/submarine fan	x	x					
apron	x						x
atoll	x						
barrier island				x			
beach, relic	x						
bight		x					
borderland	x	x					x
canyon	x	x	x	x			x
carbonate (coral) reef	x	x	x	x		x	
channel/gully	x			x			
cold seep				x	x		x
continental/island rise	x	x	x				x
continental/island shelf	x	x	x				x
(continental margin)		x					x
continental/island shore complex		x					
continental/island slope	x	x	x				x
deep sea sponge aggregations						x	
deformed, tilted and folded bedrock	x						
delta, fan	x	x	x				x
embayment		x	x	x			
escarpment			x	x			x
estuary	x	x	x	x	x		
exposure bedrock	x						
fjord	x	x		x			
flats/floors	x						
fracture zone	x	x					x
glaciated shelf	x		x	x			
hill/abyssal hill							x
holes				x			x
hydrothermal vent				x			
inland/enclosed sea	x	x					
inlet	x			x	x		
karst, solution pit, sink	x						
lagoon/lagoonal estuary	x	x			x		
landslide	x						
marine basin floor/basin	x	x					x
mid ocean ridge		x					x
mound	x			x		x	
mudflat/sandflat			x		x		
overbank deposit (levee)	x						x
peak				x			x
pinnacle, cone	x			x			x

plateau/ bank	x	x		x			x
platform				x			
ridge	x			x			x
rill	x						
rocky reef				x	x		x
sandwave/sediment wave, sandbank	x		x	x	x		
scarp, cliff, fault or slump scar	x						
seagrass				x	x		
seamount/guyot	x			x		x	x
shelf break		x					x
sill				x			
sound		x					
terrace	x			x			x
trough/trench		x	x	x			x
valley			x	x			x

Rigorous analysis of biological – geomorphic relationships remains a priority for the habitat mapping community. However, due to the number of different processes operating and differences in oceanographic conditions and benthic communities found on similar geomorphic features around the world it is unrealistic to think that geomorphic features can be a surrogate for biological assemblages on a global scale. On a regional or local scale, within a particular oceanographic setting however, this becomes more realistic. In these situations it is important that the relationships are investigated further as data become available. In some areas the links are clear (e.g. Greene et al. [1]), whilst in other areas other properties of the seabed may be more important than geomorphology in influencing the distribution of fauna. The lack of a clear one-to-one relationship between geomorphic feature type and fauna is perhaps the main reason why geomorphic features per se do not feature in all the habitat classification systems. If not treated properly, geomorphic classifications could be misleading as a surrogate for benthic habitat; this was noted by Howell [27] in concluding that geomorphology should not currently be a part of the deep water habitat classification. There is still some debate in the literature about just how biologically relevant classification [27]or management [48-50] based on geomorphology is, so the habitat mapping community and managers should be wary of over- or mis-applying geomorphology (e.g. for MPA design) when relationships to biology are not well known.

Recently developed habitat classification systems that have emerged beyond the level of specific case studies, and not in an *ad hoc* manner e.g. CMECS [7], Last et al. [44] provide mechanisms to include regional and oceanographic settings, and even surficial sediment discrimination to enable geomorphic features to be set in their proper environmental context. Taken in the correct context within these classification systems, geomorphic units have the potential to act as better surrogates for the distribution of benthic fauna, that is, if the dominant fauna respond to the processes and environmental conditions associated with the geomorphic feature.

Geomorphic classifications are also included in other classification systems not detailed above due to a lack of published literature in English. For example the Norwegian Nature Type classification system (NiN) [51 (*in Norwegian*)] which, like EUNIS, covers both terrestrial and marine environments is a hierarchical system which includes geomorphology at a regional and local scale as part of the 'Landscape' level classification. Landscape in the NiN context differs from that of Roff et al. [33] in that it applies purely to landscape-scale geomorphology, and NiN differs from the likes of EUNIS in that it has its foundation in basic ecological principles, rather than adding ad-hoc classes. NiN provides the mechanism to classify the geomorphology of the seafloor into landscape classes at a regional scale [52-54] and also at the next level in the hierarchy to specify landforms at a more local scale e.g. pockmarks, glacial lineations, moraine ridges. NiN is currently being tested in the marine environment within Norway and will be developed further over the next few years, including documentation in English, after which it may be of more interest to a wider user community. A brief introduction to NiN in English is included in Thorsnes et al. [52].

3 Methods for terrain characterisation of ecologically relevant geomorphic structures

With the availability of multibeam bathymetric data, or high density single beam echosounder data e.g. Olex [55-57] the morphology of the seabed has become visible to all in unprecedented detail. Even global bathymetric datasets, e.g. GEBCO [58], combining satellite derived bathymetry and shipborne data, where available, and compiled European datasets (e.g. EMODnet hydrography portal http://www.emodnet-hydrography.eu/) have become an impressive resource. Bathymetry data are often presented as shaded relief maps which give the user an innate sense of the geomorphology of the seabed. Many geomorphic features can be further delineated and/or highlighted visually by the use of terrain indices, such as slope, and these indices can also help to automate classification of geomorphic structures. The various approaches to characterising the terrain to identify geomorphic structures will be discussed in turn.

3.1 Expert interpretation of geomorphology using bathymetry data

In the past, interpretation of undersea features would have been made from nautical charts or contour maps generated from bathymetric soundings. Now that full coverage data is more widely available the most common method for visualisation of bathymetric data is through the use of shaded relief maps. These may be combined with colour shaded maps representing depth to give an overall picture of the seabed terrain (Fig. 4).

Whilst colour shaded relief is popular as an end product, many experts prefer to use simple grey-scale shaded relief for interpretation of features. Shading may be achieved through the application of a variety of algorithms implemented in desktop mapping software, which provide either a single, multiple or moveable light source (Fig. 4). Evans [59] (referring to terrestrial mapping) points out that visual interpretation of elongate features from a hill-shade map is biased by the direction of illumination used, this is supported by a detailed study by Smith and Wise [60] who studied landform identification from digital elevation models (DEMs) and satellite imagery. The influence of light source should be equally true for bathymetric data, though is more difficult to test in the same manner as Smith and Wise since, except in very shallow clear water, we do not have access to independent datasets like the satellite image, and must rely solely on remotely sensed bathymetry.

The type of light source employed, and whether or not the bathymetry is vertically exaggerated is a matter of personal choice for the interpreter, will depend to a certain extent on the dataset being considered. Software offering a three dimensional view of the data, with the opportunity to ‘fly’ around the seabed is also employed by some scientists for interpretation of geomorphology. Traditionally geomorphology has been interpreted by geologists with regard for the processes affecting the geomorphic features created, and there is a whole scientific sub-discipline of geomorphology within the terrestrial realm. However, in the marine realm we have not yet seen any real specialism in this direction and marine scientists, whilst having a background in one of the traditional sciences, tend to be more multi-disciplinary. Since the advent of desktop GIS and related technologies, shaded relief maps can easily be viewed and, to a certain extent at least, interpreted/classified by scientists from all disciplines who are interested in benthic habitat. Seeing such data has certainly helped the biological community set a spatial context to their observations and has raised awareness among biologists and geologists alike that geomorphology is intrinsically linked to habitat. Interpretation of geomorphology by non-specialists, without full understanding of geological/geomorphic processes, however, can have its drawbacks. The overgeneralization of geomorphic features is one such potential risk; another is the misapplication of terminology.

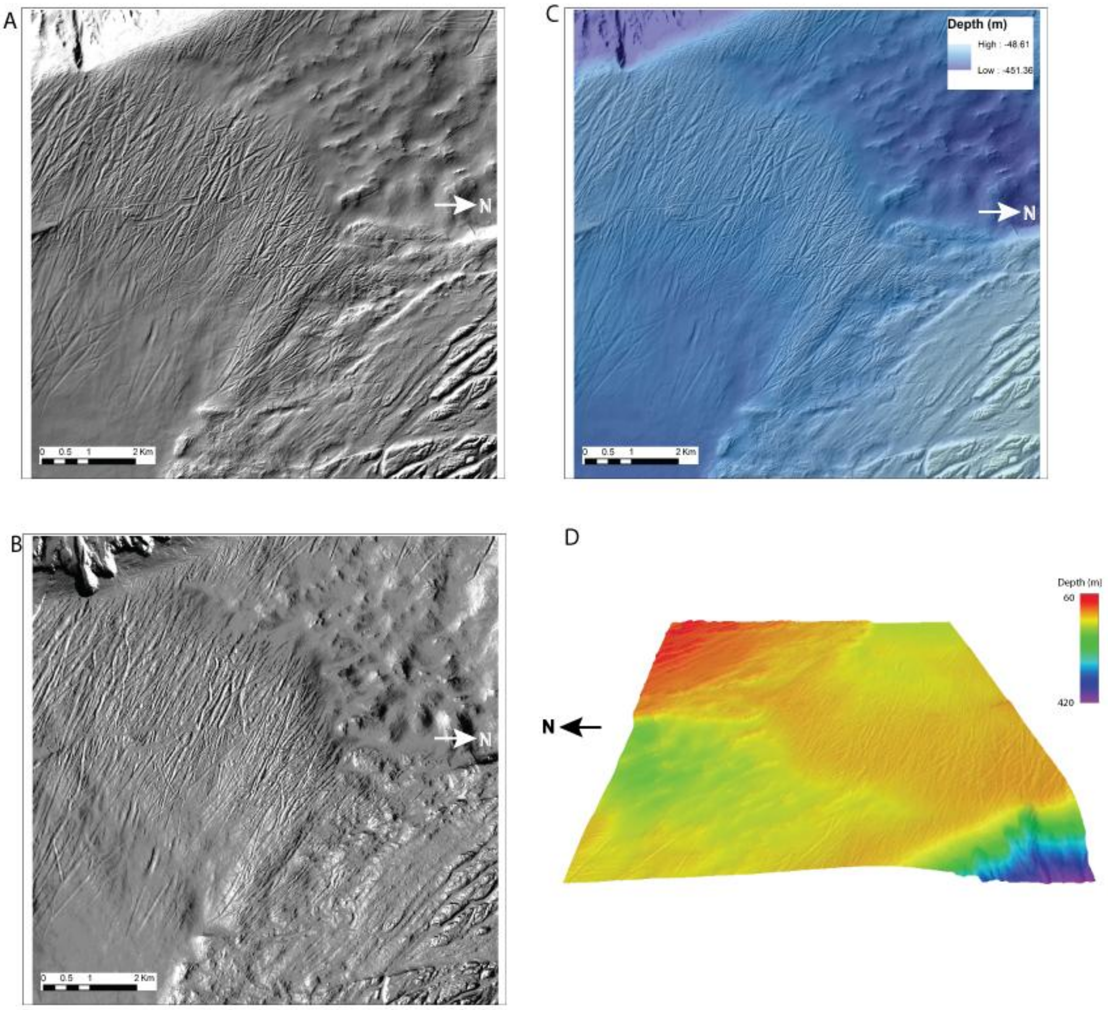


Figure 4. Examples of 5 m resolution bathymetry as shaded relief (hillshade) (a) ArcGIS® grey-scale shaded relief with default parameters (single light source) (b) Jenness multi-directional grey-scale shaded relief (c) ArcGIS® colour-shaded relief (d) Fledermaus 3D colour shaded bathymetry – note orientation reversed to highlight bathymetric features. Figure M. Dolan. Data MAREANO - www.mareano.no.

3.2 **Use of terrain variables derived from bathymetric data**

There is a long term stream of literature related to terrain analysis of digital elevation models (DEMs) in terrestrial applications, particularly in connection with soil science. Summaries focussed on terrestrial terrain analysis and morphometric classification are available (e.g. [61-63]) and all offer quite detailed insights into the computation methods involved and the key issues, including scale. Bathymetric data have more recently become widely available as raster data or digital terrain models (DTMs) which is equivalent to the terrestrial DEM. Bathymetric data, particularly full coverage multibeam data, offers tremendous potential for the generation of terrain variables that can be derived, and these data are now available at comparable resolutions to terrestrial DEMs, depending on the survey equipment used. Many desktop Geographic Information System (GIS) software packages offer tools to readily compute at least some quantitative terrain variables from bathymetry data e.g. slope. These derived variables can be useful in describing, interpreting and classifying geomorphology in the marine environment, similar to practices for land data. They can also be of further use in geological interpretation and habitat mapping/modelling.

Calculation of terrain variables requires some method for mathematically representing the topographic surface and then using this to calculate the required terrain parameter. Surface representation is typically achieved by either using neighbourhood analysis of raster pixels, or by fitting a polynomial expression to describe the surface, or digital terrain model. A review of terrain variables was provided by Wilson et al [64,65] in the context of marine benthic habitat mapping. Wilson et al. [64,65] grouped the terrain variables into 4 main types describing different properties of the terrain – slope, orientation, curvature/relative position, terrain variability (Fig. 5) and we follow this template, providing a summary of the calculable variables in Table 3. Further details on many of the algorithms available for the computation of variables are also provided in the literature cited in the table. Brown et al. [2] offer a useful summary of the extent to which many of these various terrain variables have been employed within published habitat mapping studies in the period 2000 to 2011.

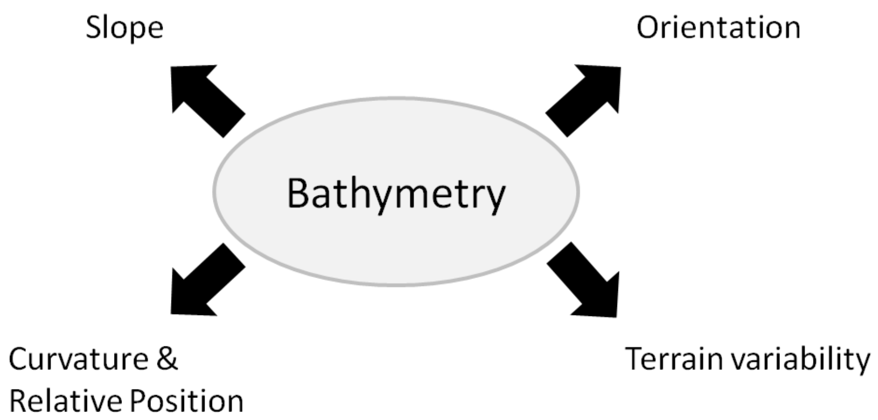


Figure 5. Summary of the types of terrain variables that can be derived from bathymetry data. Simplified from Wilson et al. [64,65] – additional details of the specific terrain variables within each type are given in Table 3, and their geomorphic and ecological relevance is summarised in Table 4.

*Table 3. Summary of derived terrain variables that can be used to quantitatively describe bathymetry data. *We have adopted the terminology in use by ESRI for plan and profile curvature, since these are more widely used than curvature calculations offered by Jenness (2011). The methods used by some commonly used commercial software for basic slope, aspect and curvature are listed for information.*

Terrain variable		**Computation**
Slope		
Basic slope	Computes the slope angle (degrees or percentage) in the direction of steepest slope.	Standard in desktop GIS ArcGIS® - 3x3 window (Horn [66]) Fledermaus® – several options including Horn [66] ENVI® – multiple window sizes Wood [67] = Evans [68] IDRISI® - 4 cell method
Directional slope	Calculates the slope in specific compass directions.	Specialist e.g. (Jenness [69]), Fledermaus®.
Orientation		
Aspect	Computes the orientation of the seabed i.e. which direction it is facing. Values are generally given in degrees but can be converted to radians if required.	Standard in desktop GIS. Manual conversion to radians within GIS if required. ArcGIS® - 3x3 window (Horn [66]) ENVI® – multiple window sizes Wood [67] = Evans [68] IDRISI® - 4 cell method
Northness	Northness is the cosine of aspect (radians). Values range from +1 to -1 where positive values indicate north-facing and negative values indicate south-facing orientation. Northness is used where orientation is required as continuous data making aspect unusable because 0° is seen as remote from 359°.	Specialist. Manual calculation from aspect in GIS
Eastness	Eastness is the sine of aspect (radians). Values range from +1 to -1 where positive values indicate east-facing and negative values indicate west-facing orientation. Eastness is used where orientation is required as continuous data making aspect unusable because 0° is seen as remote from 359°.	Specialist. Manual calculation from aspect in GIS
Curvature and Relative Position		
Curvature from surface geometry		
Curvature	Equivalent to general curvature (Jenness [70]). Units radians per linear unit (sometimes multiplied by 100), as in ArcGIS®. Positive values for concave, negative for concave (this can vary in other software). It is also possible to calculate maximum curvature (convexity) and minimum curvature (concavity) [67]	Standard in desktop GIS or specialist (e.g., Wood [67], Jenness [70]) ArcGIS® – (Zevenbergen and Thorne [71]) ENVI® – (Wood [72]) = Evans [68] IDRISI - (Pellegrini [73])
Curvature dependent on slope (gravity) i.e. having some reference direction/plane		
*Profile Curvature	Calculates the curvature parallel to the direction of maximum slope. This equivalent to longitudinal curvature (Jenness [70]). Positive values for concave, negative for concave.	Standard in desktop GIS ArcGIS® (Zevenbergen and Thorne [71]) Also e.g. Wood [67], Jenness [70]

*Plan curvature	Calculates the curvature perpendicular to the direction of maximum slope. Equivalent to cross sectional curvature (Jenness [70]). Positive values for concave, negative for concave.	Standard in desktop GIS ArcGIS® (Zevenbergen and Thorne [71]) Also e.g. Wood [67], Jenness [70]
Other measures of curvature	See e.g. (Jenness [70]), and others listed in (Shary et al. [61], Schmidt et al. [62]).	Specialist.
Bathymetric position index (BPI)	BPI value provides an indication of whether any particular pixel forms part of a positive (positive BPI value) or negative feature (negative BPI value) with respect to the surrounding terrain. BPI can be calculated at local and/or broad scales set by the user by setting the size of the neighbourhood to be analysed (circle, annulus or rectangle). A rectangular window can also be used e.g. (Dolan et al. [21]). BPI is adapted for bathymetry data from the Topographic Position Index (TPI) used in terrestrial studies but is also referred to as TPI in some marine studies e.g. (Whitmire et al. [74], Harris [75]). No units.	Specialist. Manual calculation in desktop GIS, or included in BTM toolset for ArcGIS® (Wright et al. [76])
Terrain Variability		
Rugosity	Rugosity measures the ratio of surface area to planar area. A flat, non rugose area will have a surface area of 1. Higher values indicate more variable terrain.	Specialist. e.g. (Jenness [70]), BTM toolset for ArcGIS® (Wright et al. [76]), Fledermaus®. All based on Jenness [77]
Terrain ruggedness index	TRI is calculated by comparing a central pixel with its neighbours, taking the absolute values of the differences, and averaging the result.	Specialist. e.g. (Valentine et al. [78], Wilson et al. [65], Marsh and Brown [79])
Bathymetric roughness	Measure of maximum variability in bathymetry within a user defined analysis window. At larger analysis window sizes the calculation becomes sensitive to artefacts from the analysis window (Wilson [64])	Specialist. Manual calculation in desktop GIS. (Dartnell [80], Whitmire [81], Wilson [64])
Relative relief	Relative relief is measure of the change in relief over a standard area e.g. 1 km^2	Specialist. Manual calculation in desktop GIS, e.g. using the 'Range' algorithm in ArcGIS® Spatial Analyst (Thorsnes et al. [52])
Fractal dimension	The fractal dimension is a measure of surface complexity. Values range between 2 (flat) and 3 (rugged, space-filling terrain)	Specialist e.g. (Wood [67]), IDRISI®
Total curvature	A total measure of curvature that does not consider whether the topography is concave or convex.	Specialist. (Jenness [70])
Rate of change of slope	Second derivative of bathymetry. Similar to total curvature but values differ due to calculation methods and units. Has also been called 'complexity' e.g. (Rattray et al. [22])	Specialist. Manual calculation in desktop GIS.
Standard deviation of slope	The standard deviation of slope, i.e. variation in slope over a certain distance (analysis window). Standard deviation of multiscale slope can also provide a good alternative measure of variability (Dolan, [82]).	Specialist. Manual calculation in desktop GIS. Multiscale e.g. Wood, 2009. Recently reported for terrestrial as most stable method (Grohmann, Smith and Riccomini [83])

Table 4. Geomorphic and ecological relevance of different types of terrain parameters.

	Slope	**Orientation**	**Curvature and Relative Position**	**Terrain Variability**
Ecological relevance	Stability of sediments (ability to live in/on sediments) Local acceleration of currents (food supply, exposure, etc.).	Exposure to dominant and/or local currents from a particular direction (food supply, larval dispersion etc.)	Index of exposure/shelter e.g. on a peak or in a hollow (food supply, predators etc.)	Index of degree of habitat structure, shelter from exposure/predators (link to life stages). Structural diversity linked to biodiversity
Geomorphological relevance	Stability of sediments (grain size). Local acceleration of currents (erosion, movement of sediments, creation of bedforms).	Relation to direction of dominant geomorphic processes.	Flow, channelling of sediments/currents, hydrological and glacial processes. Useful in the classification of landforms.	Terrain variability and structures present reflect dominant geomorphic processes.

From Table 3, we can see that there are a number of methods available to calculate the various types of marine parameters. Whilst slope and aspect seem relatively straightforward with limited options, there are still a number of algorithms that can be used (Dunn and Hickey [84], Jones [85,86], Shary et al. [61], García Rodríguez and Giménez Suárez [87], Dolan [82]). However, the array of names and algorithms for various measures for calculation of curvature can be particularly confusing, not least because the terminology has been applied differently by the developers of the algorithms, and their implementation in software (Schmidt et al. [62], Jenness [70]). For example profile curvature as given by Zevenbergen and Thorne [71] and implemented in ArcGIS® has also been called horizontal curvature (Shary [88], Florinsky [89]) and is equivalent to longitudinal curvature (Jenness [70]). Each of these terms refer to some type of downslope curvature and are relevant with respect to gravity driven processes. Shary et al. [61] and Schmidt et al. [62] offer good summaries of the methods available for curvature calculation. This is helpful on an academic level, but on a practical one the situation could be helped with better documentation of implementation algorithms by the commercial software, as the user is too often left unaware of what calculation they are actually performing.

Each of these terrain parameters has been used in habitat mapping with a view that to a certain extent it can act as a surrogate for some parameter, or suite of parameters which directly affect the distribution of biological communities and species. Depth alone, for example, can be a surrogate for many things (temperature, salinity, light etc.) and is often the dominant variable in habitat modelling studies (Dolan et al. [21]). The other terrain indices, derived from bathymetry data are relevant for benthic habitat and geomorphology for the reasons summarised in Table 4. Their performance as surrogates for some or all of these influences is clear by the wide adoption of these indices in modern habitat mapping. There is a strong push for better use of surrogates based on such readily mapable variables which help bridging the gap between sparser biological sampling and the desire for full coverage habitat maps. The degree to which any terrain variable can be a successful surrogate will also depend on the study area, data resolution and analysis scale. A detailed review of the issues associated with surrogacy is beyond the scope of this report and the reader is referred to Harris [75] for a good review of the topic in relation to habitat mapping. In this report we focus on the methods for calculation of terrain variables and issues of scale.

The scale dependence of these parameters is a '*basic problem in geomorphology'* [61] which has long been recognised in terrestrial geomorphology [90]. Shary et al. [61] point out the motivation for finding 'scale free' morphometric variables (terrain variables) and provide several demonstrations of the changing values of variables with data resolution. The problem is no different when it comes to bathymetric data (Dolan [82]). The values for all the terrain variables in Table 3 are dependent on the resolution of the raster bathymetric data. Using standard desktop GIS (ArcGIS®) the variables are calculated using a 3x3 analysis window around each pixel in turn. Using slope as an example, since it is perhaps the most used and intuitive variable, we see that for a 5 m raster bathymetry grid, the distance over which slope is measured, for instance, would be 15 m x 15 m (3 x 5 m cells). Using a 50 m grid the slope would be measured over a distance of 150 m x 150 m, and using a 500 m grid this increases to 1500 m.

Due to the different length scales considered, plus the level of detail of the bathymetric data, slope values for a particular location, based on each of these different datasets, will give very different results [82]. An example is given in Figures 5 and 6 showing slope values for different sizes and types of geomorphic features. Further details on the study area, together with additional slope calculations are given by Dolan [82]. Figure 7 shows profiles across the points shown in Figure 6 indicating the extent of the analysis window for each scale of computation. With the advent of easily generated slope values in desktop GIS it is all too easy to take the values generated by GIS slope calculation tools without thinking about what they really represent, and over which length scales. Another factor to be aware of is edge effects in the calculations. Some GIS software removes all edge cells that cannot be analysed with a full *n* x *n* rectangular analysis window (or other analysis window, e.g. circle, annulus). Other GIS software (including ArcGIS®) creates temporary cells based on neighbouring cells at the edge of the raster dataset and uses these values in computation of terrain parameters within the specified analysis window. This approach induces edge effects in the data i.e. the values of calculated terrain variables may not be reliable in the outermost cells.

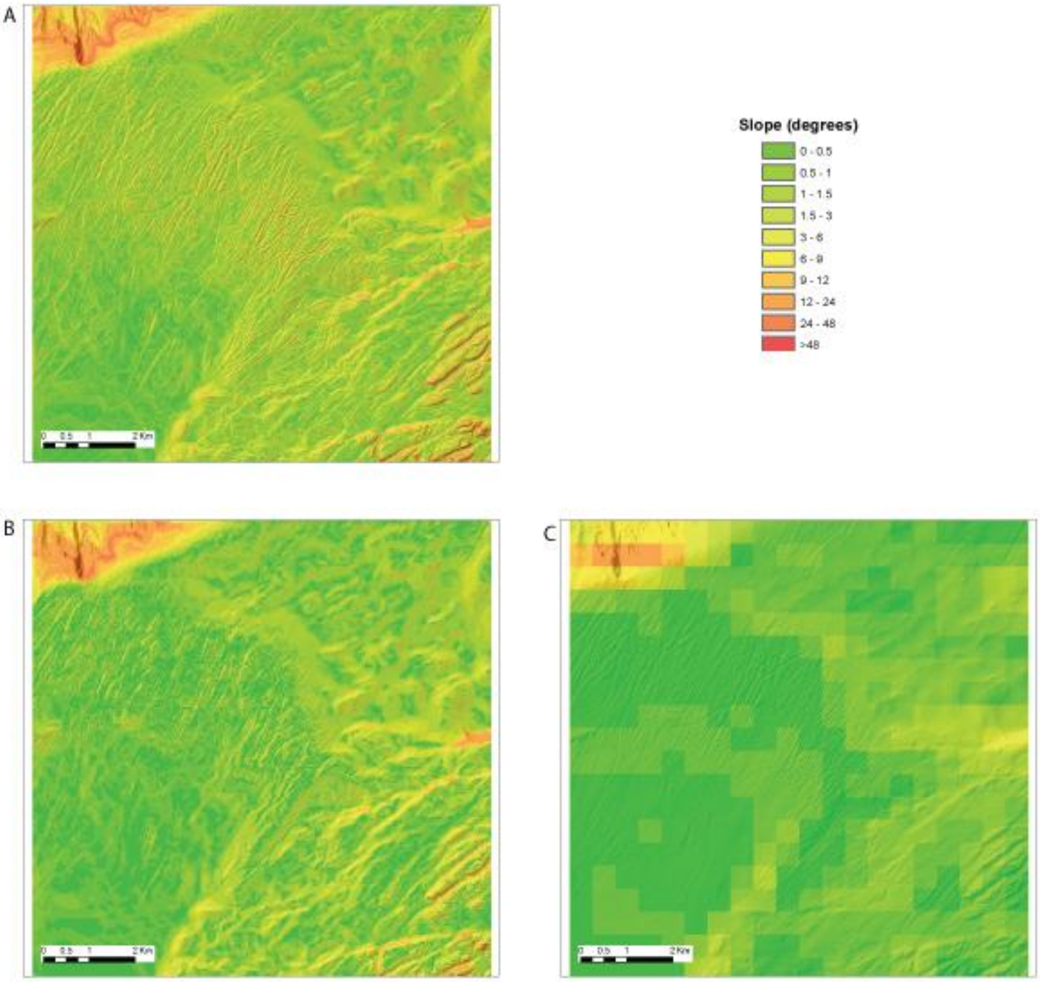


Figure 6. Example of single-scale (3x3 analysis window) slope at three different cell sizes (a) 5 m, (b) 50 m, (c) 500 m. The same colour scale is used for slope values across each cell size. From Dolan [82].

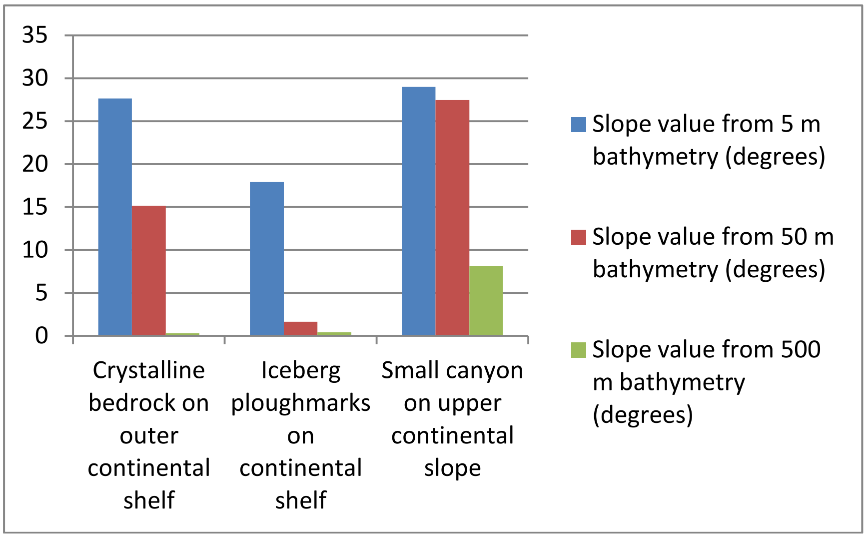


Figure 7. Variation in slope values calculated for 3 points from 5 m, 50 m, and 500 m bathymetry data. Calculations performed in ArcGIS® Spatial Analyst (3x3 cell analysis window). From Dolan [82].

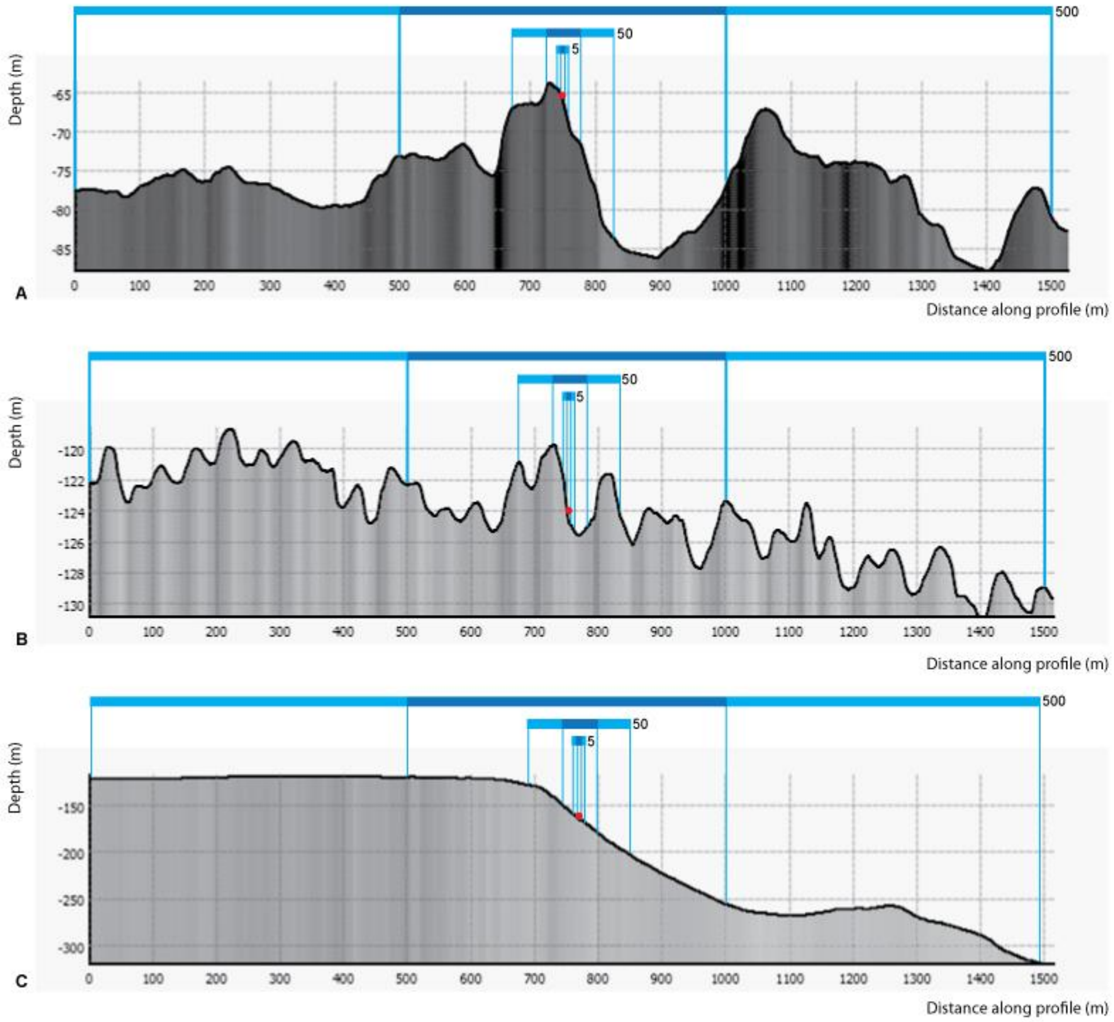


Figure 8. Profile view of 5 m resolution bathymetry showing detailed vertical variation in terrain and indicating approximate length scale (blue bars) over which a 3 x 3 cell analysis window for the computation of terrain variables operates about a point (red dot) for different data resolutions (5 m, 50 m, 500 m). The length scales for calculation based on a 5 m bathymetric dataset are indicated in the lowest blue bar with darker blue indicating the central pixel. Length scales corresponding to calculations based on 50 m and 500 m bathymetry data are shown in the overlying blue bars. The location of the red dot roughly corresponds to the point used to extract slope values in Figure 7. Three examples are given to show the effect of the window size across varying types of terrain (a) crystalline bedrock on outer continental shelf (b) iceberg ploughmarks on continental shelf (c) small canyon on upper continental slope. From Dolan [82].

It is important to be mindful of the differences in bathymetric data resolution with regard to all terrain computations, but equally it is important to be wary of setting strict numbers on the value of slope (or other variable) in classification schemes (habitat or geomorphic). A number of classification schemes including Greene et al. [40], CMECS [7] list particular slope values among the criteria for identifying or classifying certain geoform features. Taken in correct geological sense, slope values should be the slope measured along a profile across the feature of interest. Greene et al. [41] specify that the slope should be an *in situ* assessment estimated from video, still photos or direct observations. CMECS do not specify the method to be used in geoform characterisation but do refer back to Greene et al. [41] in presenting slope as a geoform modifier.

Over small length scales, calculations are also sensitive to noise and artefacts in the bathymetric data [91] which give rise to misleading values in the derived variables, and may persist even following advanced processing of the data. One way to overcome noise and artefacts is by simply lowering the resolution of the data, which has the effect of averaging out problem data - for example convert a noisy 5 m grid to a 50 m grid. Whether or not this is a suitable approach will depend on the individual dataset and required end product. In many cases it may be necessary to keep a high resolution grid, but employ other methods to identify and remove artefacts in derived terrain analysis/morphometric classification [92]. Improvements in multibeam systems and associated motion sensors together with advances in processing have meant that over the past ten years or so the general quality of multibeam data has improved significantly. Nevertheless using old, or composite datasets from several surveys over a period of time (often employing different equipment), noise is typical in seabed mapping so we should always be mindful of problems associated with this and other artefacts.

As discussed by Wilson et al [65], multiscale methods for computation of terrain variables allow an alternative method by which noise and artefacts can be overcome in terrain analysis, whilst retaining the original resolution of the bathymetric data.

There are five main approaches to obtaining terrain indices at different scales which are summarised in Table 5:

Table 5: The five main approaches to obtaining terrain indices at different scales. Adapted from Dolan [82].

#	Approach
1	Change Resolution (resampling) then calculate terrain variable
2	Average depth over n x n windows then calculate terrain variable
3	Calculate terrain variable then average result over *n* x *n* window
4	Calculate terrain variable at multiple scales using selected *n* x *n* analysis windows
5	Multiscale analysis[1] of terrain variable

Additional methods have been tested in terrestrial geomorphology (e.g. Dragut and Blaschke [93]) but are not yet in use in seabed mapping, nor have they become standard in terrestrial mapping. Each of these methods is explored further with regard to slope derived from bathymetry data by Dolan [82].

Multiple scale analysis allows computation over larger window sizes than the 3x3 window offered in standard GIS analysis e.g. Wood [67], ENVI®, IDRISI®. Each terrain variable can be generated over larger window sizes providing a measure of the variable value for each cell over longer length scales. Depending on the bathymetric data resolution this may be more appropriate to the features of interest than the 3x3 analysis window. It is often the case that a combination of fine-scale and broad-scale variables offers the best descriptors or predictors of physical habitat. This fact arose from the widespread application of BPI calculations at fine- and broad-scales. BPI computations at these scales have been made ‘easy’ by tools such as BTM modeller, it is possible that the lack of adoption of multi-scale

[1] Note that Wilson et al. [65] used the term multi-scale analysis for all types of analysis beyond the 3x3 standard analysis window. For clarity we now adopt the term *multiple scale* analysis to refer to analysis at successive analysis window, while reserving the term *multi-scale* analysis for analysis which runs concurrently at multiple scales and reports the mean value and standard deviation over all analysis scales considered. *n* x *n* refers to the size of the analysis window in raster grid cells where n = 3, 9, etc.

approaches for calculation of the other types of terrain variables (Table 3) among the scientific community is just as related to ease of calculation as it is to ecological relevance. It seems that there is insufficient literature to prove or disprove the ecological relevance of the multi-scale approach. Some studies that have employed multi-scale variables for calculation of other variables have found that a combination of analysis scales are relevant for quantitatively describing and predicting the habitat in which a particular species or community is found [17, 65] while others have concluded that a particular analysis scale is preferable [20]. This is likely dependent on the size and variation in bathymetric features within the study area, plus the habitat preferences of the species in question.

In addition to computing terrain variables at individually selected analysis scales it is possible to generate a true multi-scale variable describing quantitatively the extent to which a particular location is part of a slope, for instance, across a range of analysis scales. This concept is discussed in a terrestrial context by Landserf [67] and was investigated in a marine context by Lucieer [94].

3.3 **Automated and semi-automated morphometric classification of bathymetric data.**

Terrain indices, particularly curvature, have been used further to classify landforms and geomorphic features, providing an automatic classification by morphometric feature, or at least a classification which can act as a first-pass result that be taken further by experts to produce a true geomorphic classification. Figure 3.5 shows how different types of surfaces that are described by second order polynomials e.g. Wood [72] can be used to identify six morphometric feature classes – peak, pit, ridge, channel, plane, and pass.

The motivation for using this type of approach is often to help remove some of the subjectivity from the classification of geomorphic features, plus to use the power of GIS to highlight the major features and ease of the laborious process of digitisation. The automated classification of landforms has grown up and been applied mainly in terrestrial applications (Wood [72], Fisher, Wood and Cheng [95], Dragut and Blaschke [93], Dragut et al. [96], Dragut and Eisank [97], Evans [59]). Similar approaches have also been applied in seabed mapping, but the approach has not become as widespread as the use of basic terrain indices. For example Lucieer and Pederson [98] used the classifications of Wood [72] to identify ridges, crests etc. in relation to lobster habitat; the structure of coral reefs was investigated using the same basic approach by Zieger et al. [92]. These studies use Wood's multiple and multi-scale scale methods to examine the morphology and classification across several scales. Resulting classifications can be hard, or with fuzzy boundaries e.g. marking the degree to which a location belongs to a certain feature class across different scales [72].

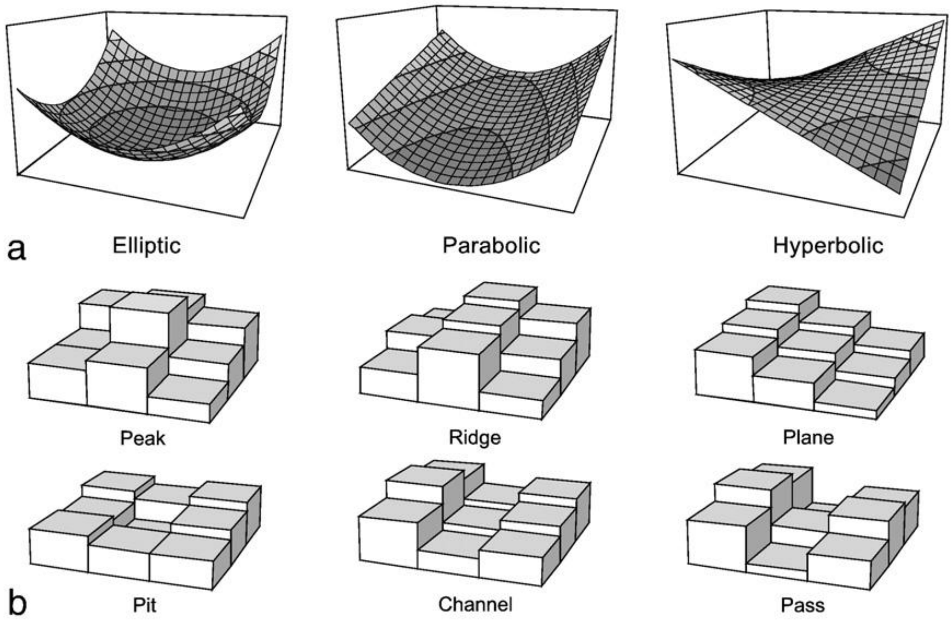


Figure 9: From Zieger et al. (2009). Second-degree polynomials (a), are applicable to derive six morphometric feature classes (b), simplified by a 3×3 cell raster. Adapted from Wood [72].

Curvature dominates the classification of landforms, particularly in terrestrial applications. Several marine studies have used other terrain indices to produce a geomorphic classification of the seabed, particularly BPI which, like curvature indicates relative position. This was the approach taken by Lundblad et al. [99] and Lanier, Romsos and Goldfinger [100] and further implemented by Lundblad and colleagues in the BTM modeller [76] tool which has seen quite widespread adoption in the marine habitat mapping sector. This approach uses BPI as the primary morphometric discriminator, but also includes slope and rugosity (small scale variations) to further categorise the seabed. Whilst the slope and rugosity indices in BTM modeller are only calculated at a local scale (3x3 window) the overall approach incorporates different scales, since BPI can be calculated at local and broad scales. The inclusion of this multiple scale component assists in the characterisation of features. Use of the BTM approach can be combined with further terrain analysis, and acoustic backscatter. For example Erdey-Heydorn [101] used surface texture analysis, and sidescan sonar data to reach an automated classification following the Greene et al. [40] habitat classification scheme. Surface texture has also been used in other studies (e.g. Cutter, Rzhanov and Mayer [102]) and the combination of topographic indices with backscatter (e.g. Marsh and Brown [79]) is also practical for seabed habitat mapping, particularly if the aim is to classify physically different habitats, rather than simply geomorphic features. Terrain indices can also be combined with other physical variables e.g. bottom currents, chlorophyll, turbidity etc. to produce a classification that permits the delimitation of ecologically relevant zones [103].

The above approaches are all based on a pixel by pixel approach to classification. Recently object-based methods, often called object-based image analysis (OBIA), have been adopted in both terrestrial (e.g. Dragut and Blaschke [93], Anders, Seijmonsbergen and Bouten [104]) and marine studies (Lucieer [105], Lucieer and Lamarche [106]). The object based approach overcomes some of the difficulties with pixel-based classification, not least that it is inherently multi-scale. Instead of considering the information in each pixel, OBIA is based on information from a set of similar pixels – image objects which have similar properties e.g. statistics of pixel values, object shape, object texture etc. [106]. Multiple segmentations are typically run with different parameter settings, and OBIA is generally used as a supervised classification technique whereby classification is based on several training objects that are then used to classify the rest of the data. Image based approaches seem to offer a very promising method for classification in the future, especially in relation to seabed habitat mapping. That said, pixel based methods are likely to remain in widespread use due to their relative ease of use. At present OBIA requires specialist software [106, 107] and specialist knowledge. Tools for OBIA linked to desktop GIS would go a long way toward placing the object based methods in the hands of the wider habitat mapping community. More research is also required to prove the value of OBIA, particularly in relation to marine habitat mapping. If such studies are positive then it is likely that further adoption of OBIA methods will naturally follow.

3.4 **Summary**

This section began with a review of how geomorphology is traditionally interpreted from bathymetry data by experts. Hill shading and software allowing three dimensional visualisation of the seabed have become common practice in such analysis. Further, it allows visualisation of the data that makes them accessible to all. Visual analysis is likely to always have its place in geomorphic interpretation, since it really gives the interpreter a ‘feel’ for the data. One drawback to using this approach in isolation, however, is that of subjectivity, which is particularly important with regard to scale. Methods that can help to make classification more objective are in demand, and it is these that form the focus of the rest of this chapter. We provided a summary of the most common terrain indices that can be derived from bathymetric data. It is clear from the range of indices to describe various aspects of the terrain, and the numerous algorithms available for their calculation, that such analysis be carried out in an informed manner with regard for computation algorithms and data resolution (scale). If data are to be harmonised for neighbouring areas of the seabed it is essential that harmonised methods, and scales are used. As more and more of the seabed is mapped using modern methods these issues become more important as we begin to fit the maps, and not just work with isolated case studies.

Scale (data resolution and analysis neighbourhood) is a central theme in relation to terrain variables. It is important to calculate terrain variables at the appropriate scale with respect for the geomorphic features/habitats of interest. Unless we are only interested in one size of feature it makes sense that a multi-scale approach would be more successful. Scale is a crucial element of terrain characterisation that must be borne in mind both when computing, and when reporting terrain analysis. Reporting a maximum slope value of say, 3° for a particular seabed geomorphic feature, or habitat type, will be no use when mapping the neighbouring area, without knowing over what distance the slope was calculated, and with what level of detail in the bathymetric data. It is therefore essential, in efforts towards harmonisation of datasets that the data resolution the slope was calculated from is reported, and what algorithm (software) and analysis neighbourhood was used (if not implicit in software). Any information on multiple scale calculation should also be given, depending on the approach taken (Table 5 – summary approaches). Standardisation of the data resolutions employed at fine, intermediate and broad scale – as per case studies in this chapter, would also help to standardise the computation of terrain variables, by removing one source of scale-associated variation. This is one way that variables could become more consistent on a European-wide basis. A further measure towards standardisation would be to work, following cartographic rules, towards producing maps at fixed mapping scales e.g. 1:10.000 (local map series), 1:100,000 (national map series), 1:1.000.000 (e.g. European map series) when digitising geomorphic, and habitat classifications. It is likely that local case studies will persist with other data resolutions and map scales, and these are valuable in their own right. However it is important to keep data harmonisation in mind as more and more of the seabed becomes mapped and classified.

Finally we looked at a few methods that have been used to apply terrain analysis to geomorphic classification. This step towards automated classification allows scientists to reap the practical benefits of GIS analysis, and remove some of the subjectivity from the traditional methods for geomorphological analysis. It is not certain whether a raised area of the seabed formed by glacial processes (e.g. moraine ridge) is different, in ecological terms, from a similar sized elevation formed by other processes. However, removing the expert entirely from the interpretation process leaves greater potential for erroneous, or incomplete geomorphic classification. Geomorphologists typically use not just the morphological feature itself, but also its context, or setting in relation to other structures/processes to determine geomorphic classification. This aspect of interpretation will be difficult to replace with automated methods. Best practice will most likely be achieved if experts remain involved in terrain characterisation and the classification of geomorphology, but utilise terrain variables and/or morphometric classification to assist in the process.

4 Multiple scale terrain characterization – case studies

4.1 Case study overview

Case studies based on examples from the North Sea and Celtic Sea are presented. These case studies demonstrate the complementary usefulness of bathymetry at a wide range of scales – from highly detailed studies with 5 metre or finer grid cell sizes from multibeam bathymetry, to low detail studies using bathymetric data available through the EMODnet Hydrography project. The study, using a 500 metre data set, has been done by the Geological Survey of Denmark, with J. Leth as the lead author, with contributions from Z. Alhamdani. The Geological Survey of Ireland has led the study using a 50 meter data set, with Janine Guinan as the lead author with contributions from the INFOMAR team at the GSI. The study on shallow sandbanks using a 5 meter set has been led by Vera Van Lancker from MUMM.

4.2 Case study from the North Sea – using 500 metre resolution

4.2.1 Introduction

This case study demonstrates to what extent large scale (500m) terrain characterization can provide information on geomorphic features for the use in seabed habitat mapping. A study area has been selected covering the NE North Sea and the Skagerrak as well as the northern part of Kattegat comprising Danish, Norwegian and Swedish waters (Fig. 10). Apart from being a cross-border region the study area provides a wide range of well-known broad-scale geomorphic features such as trenches, flats and slopes.

The bathymetric data base used for this 500m scale terrain characterization case study is the EMODNET Hydrography data portal which provides data for selected maritime basins in Europe. Bathymetry data (grid size 0.25 x 0.25 minutes, roughly corresponding 500 x 500m) has been extracted for the North Sea, the Skagerrak and for the Kattegat to make up the background data for the analysis.

To classify the diverse range of geomorphic features in the study area we followed the list of terms and definitions of undersea feature names published by IHO [6]

4.2.2 Modelling benthic geomorphologic features

Automatic classification and modelling of benthic morphological features is a function of three main parameters:

1. The bathymetry map accuracy and resolution
2. The sediment map resolution and confidence.
3. The modelling algorithm

The bathymetry map (Fig. 10) chosen for this work was downloaded from EMODnet-Hydrography Portal (http://portal.emodnet-hydrography.eu/EmodnetPortal/index.jsf#). The bathymetry DTM data set has 0.25 x 0.25minute grid cell size (~500m) and was determined from 3 data sources: High resolution single or multibeam survey data, DTM data provided by Hydrographic Offices from their internal databases, and GEBCO 30´´ gridded data. The accuracy and precision of the gridded data will vary from one basin to another. QA and QC were applied to the datasets before merging them in the DTM according to a set of predefined guidelines (EMODNET, [108]).

The sediment map was acquired from EMODNET Geology group (http://www.emodnet-geology.eu/), they produced a seabed geology map of 1:1million scale (Fig. 13) using different data sources which were harmonised into a single seamless map though some boundaries discrepancies can be noticed. The EMODNET map is a polygon vector dataset which was rasterised in this work and snipped to the bathymetry map with the same grid size of 500m.

The Benthic Terrain Modeller (BTM) developed by Lundblad et al. [99] was the algorithm adopted in this work for benthic features classification. The related ArcGIS® tool [76] was developed in 2005 to facilitate the mapping and characterization of benthic morphological features. These features are sometimes associated with some kinds of marine species. Rockfish for example, is commonly found on or near hard complex structures, sand eel is normally associated with sand banks.

The BTM modeller contains a set of tools that allow users to create grids of slope, bathymetry positioning index (BPI), and rugosity from an input bathymetry dataset.

The BPI together with slope and depth forms a classification dictionary that can be trained according to the area under investigation to create a new grid depicting various benthic terrain features. The classification criteria were based on the features definition given by the International Hydrographic Organization [108].

4.2.3 Results

The general bathymetry of the study area appears from the bathymetric map (Fig. 10) and the bathymetry hill-shade view map (Fig. 11). It is characterized by the presence of the Norwegian Trench and the widespread flats to the south.

The Norwegian Trench is an elongated depression in the sea floor off the southern coast of Norway with a width between 50 and 95 kilometres and water depths up to 700 metres compared to average depth below 100m of the North Sea. Looking into the hill-shade view (Fig. 11) it is, however, possible to designate several elongated shallow bank-like structures in the north-eastern part of the North Sea.

When looking into the slope index map (Fig. 12) the highest slopes are obviously connected to the Norwegian Trench and incised valleys in the northern Kattegat. On the contrary very low slopes as expected are connected to the low-relief flats in the north-eastern part of the North Sea and in the Kattegat.

The bathymetry of the Kattegat part of the study area is more complex due to the presence of incised valleys and complex systems of anastomosing valley structures off the west coast of Sweden.

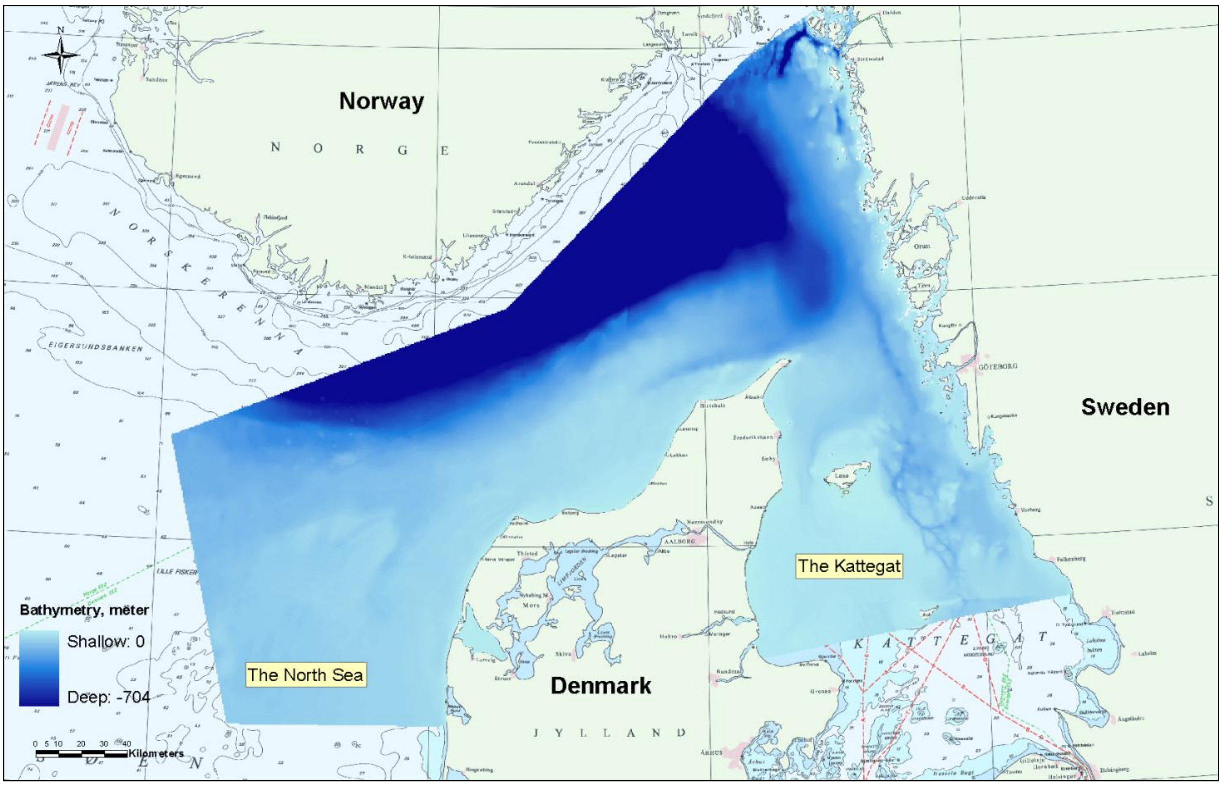


Figure 10. Bathymetry map of the study area.

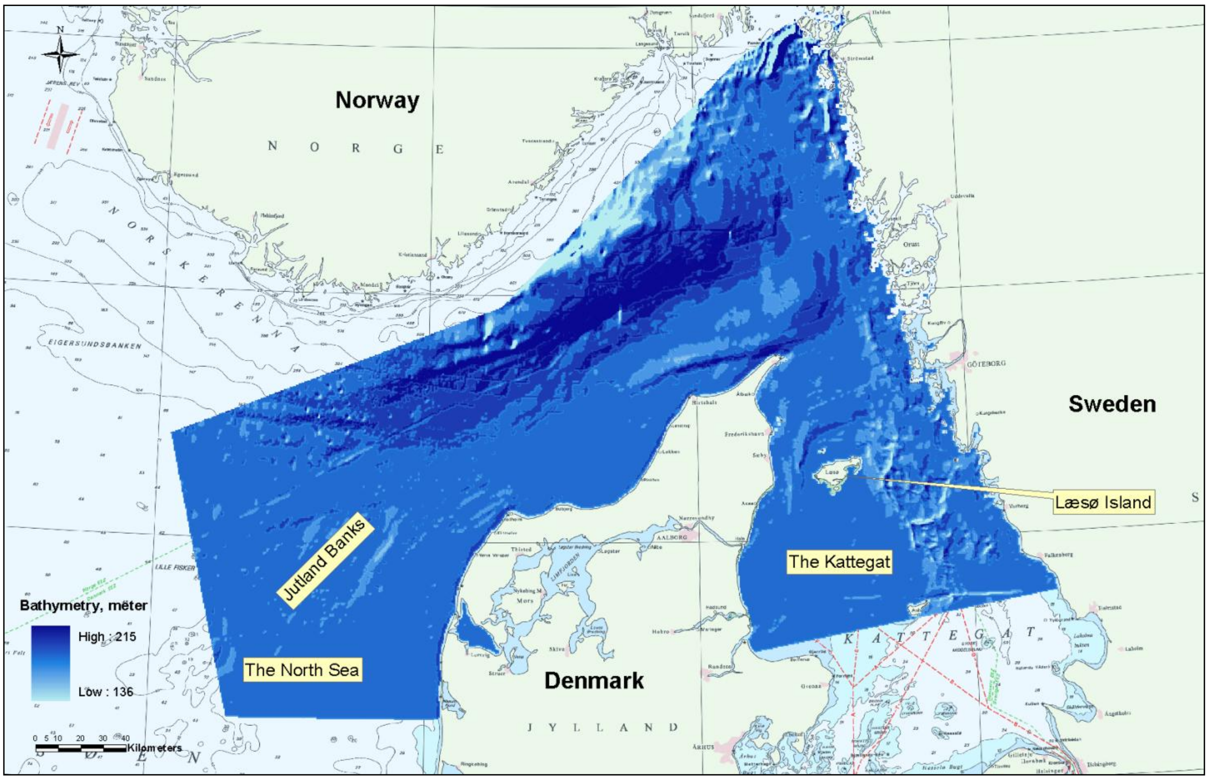


Figure 11. Bathymetry hill-shade view map of the study area.

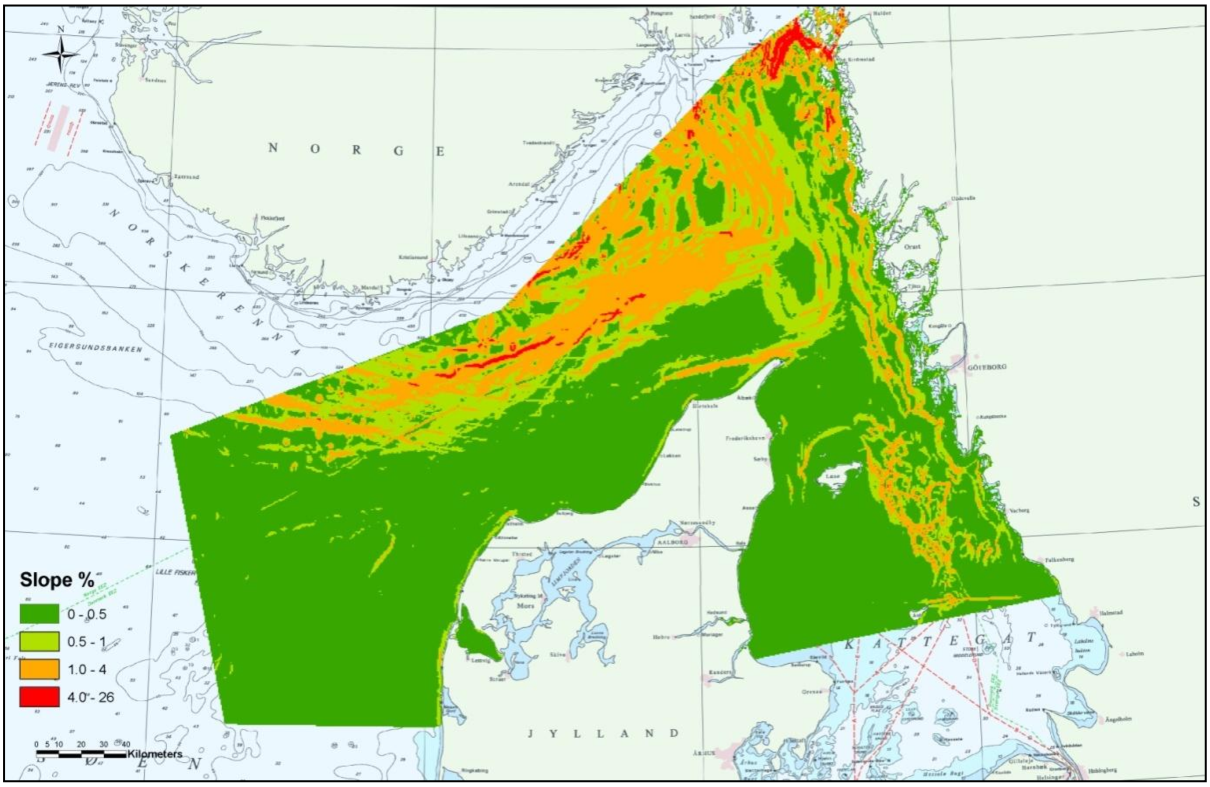


Figure 12. Slope index map produced by ArcGIS®.

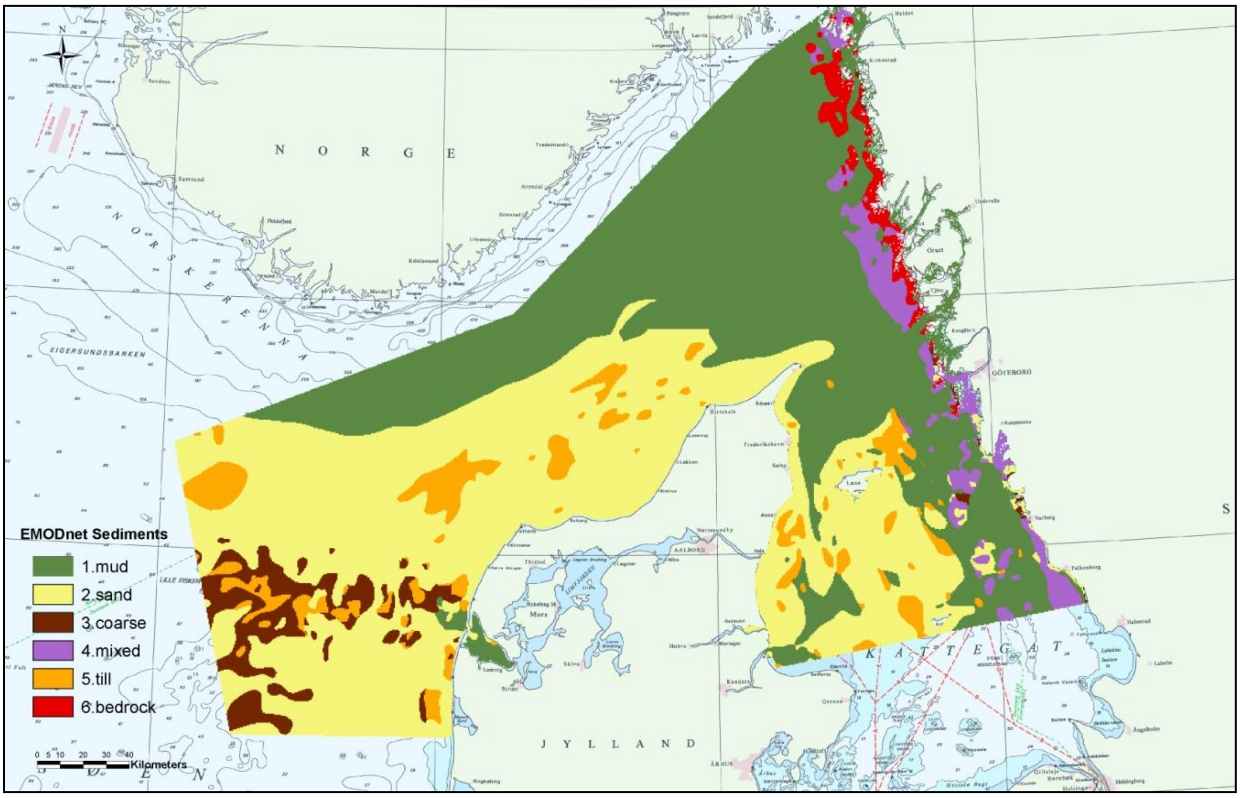


Figure 13. The harmonized seabed sediment map of the study area compiled within EMODNET Geology .

These benthic morphologic features were then combined with sediment datasets to produce the broad scale seafloor geomorphologic structures.

Table 6 shows the broad scale geomorphic features defined in this work following the criteria given by Kaskela et al. [109] for the Baltic Sea.

Table 6. The definition of broad scale geomorphic features used in the present study.

BPI class	Geomorph. Equivalent	Description	Substrate	Remarks
Crest	Mound (IHO Hill)	An elevation on the seafloor	Sand Hard substrate	Sand bank? Possible reef
Flat	Plateau or Plains	A flat or nearly flat area (< 1% slope)	Mud Sand & coarse sand Hard substrate	Mud flats, slope ≤ 1%
Basin	Basins	Depression in the seafloor variable in extent	Soft sediment Complex & hard sediment	Mud & sand basins
Narrow depression	Trough	Long depression with steep sides	Soft sediment Complex & hard sediments	Slope ≥ 4%
Narrow depression	Valleys	Relatively shallow depression with gentle, continuous gradient.	Soft sediment. Complex & hard sediment.	
Slopes	Slope	Sloping seafloor (>1%)	Varies	

This classification scheme results in 15 different seafloor geomorphological features which will be presented in the next paragraph.

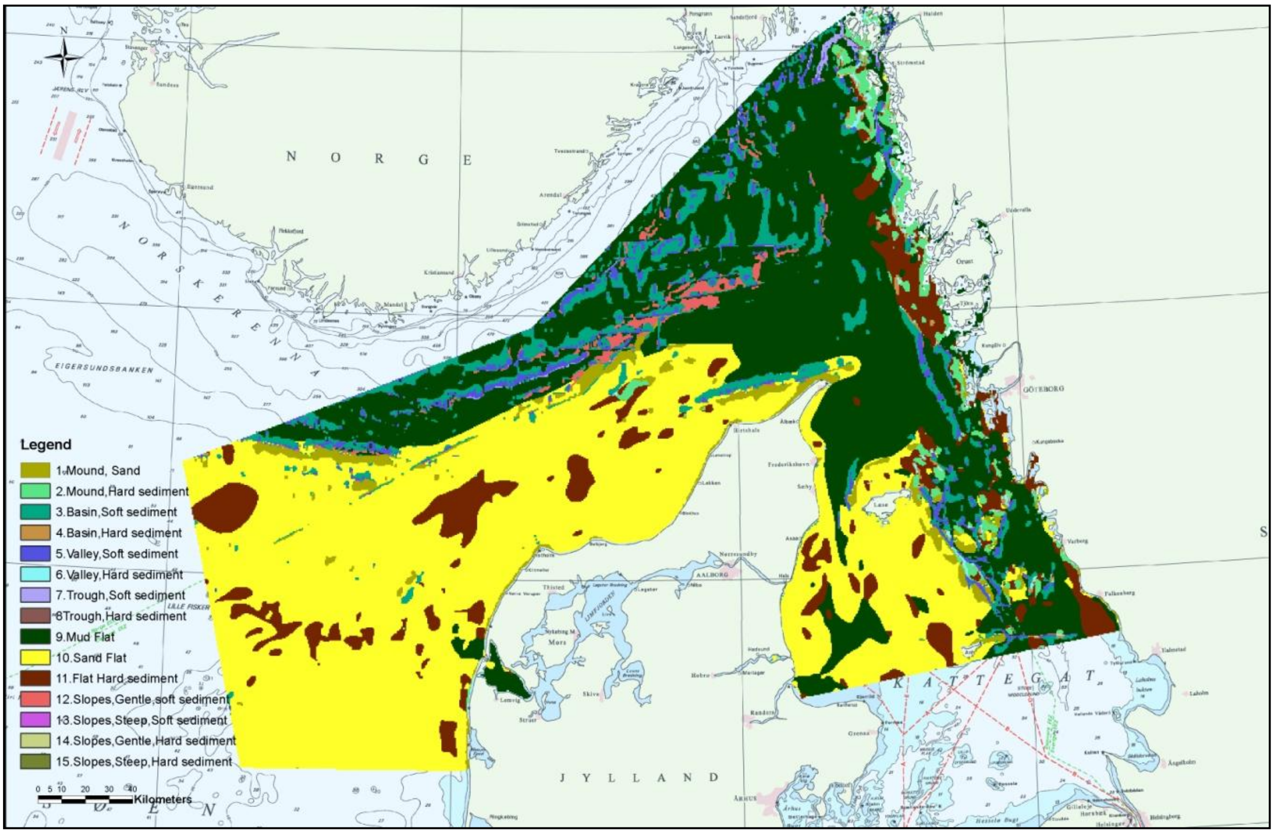


Figure 14. The combined bathymetry and seabed sediment map.

4.2.4 **Discussion and Conclusion**

A low resolution small scale bathymetry map was used to model seabed morphological features in the Kattegat and the north-eastern part of the North Sea. We have inspected the study area for morphological features visually and the general characteristics of these features were deduced and deployed at later stages in the modelling processes.

The general geological setting of the study area has been used as background information for defining the morphological features i.e. structures from the glacial advances such as troughs, mounds and valleys.

The confidence level of the sediment map used in this study varies from one region to another. That manifests itself in the output of the predicted morphological structures.

The BPI-values were calculated for different inner and outer circle radii and the optimal value was chosen to ensure maximum representation of the real morphological structures of the study area.

The model output contains a lot of outliers due to very nature of the raster routine in the GIS analysis. These outliers were filtered out using the ArcGIS® generalization tool to the extent where the real structures were preserved.

Comparing visual inspection and previous geological knowledge with the predicted geomorphological features of the study area reveals some non-matching features. E.g. the reefs in the northern Kattegat north of the island of Læsø (see Fig. 11) and the sandbanks in the north-eastern part of the North Sea (see Fig. 11, Jutland Bank). In both cases the model failed to predict the small-scale elevations which form these structures. These structures were recently mapped by Leth et al., [110] and shown to via ground truthing to be reefs and sandbank structures respectively.

4.3 **Case study from the Celtic Sea – using 50 metre resolution**

4.3.1 **Introduction**

This contribution describes a submarine canyon system on the Celtic margin, offshore Ireland using high resolution multibeam bathymetric data acquired during the Irish National Seabed Survey. The study area encompasses the outer continental shelf, shelf break and upper continental slope. In general two types of canyons occur along the Celtic margin, canyons with long, narrow upper reaches and V-shaped profiles that incise the shelf-break; and canyons with short, broad upper reaches, and U-shaped profiles. The canyons occur densely spaced along the margin extending from the continental shelf to the deep abyssal waters over a depth range 130m-3940 m. Here we present an overview of the canyons' main geomorphic features based on a 50 m grid cell size bathymetric dataset.

High-resolution multibeam echosounder bathymetric data acquired during the Irish National Seabed Survey 1999-2005 [111] has revealed the detailed geomorphology of the Celtic margin. The margin comprises a great number of submarine canyons and these prominent morphological features extend from the shelf break at ~150 mwd to the lower continental rise at approximately 2500 m. Whilst the margin exhibits mean gradients of 11° in parts, steep vertical gradients along canyon walls have been recorded locally by Cunningham et al., [112]) and the margin is heavily indented by a number of canyons which form the major morphological features along the margin. Bourillet and Lericolais [113] describe an incised paleovalley network occurring near the shelf break and suggest a connection between the incised valleys and the upper region of the canyons located on the Celtic Margin. Specifically the Whittard Canyon at the Celtic margin approximately 320 km south of Cork, Ireland is examined in this study. Canyon incision has occurred by head-ward erosion and retrogressive slope failure and canyon development has been largely influenced by the location of existing NNW-SSE trending fault systems, older buried canyons and natural depressions in the seafloor [112]. The canyon has been subject in recent years to intensive investigations primarily within the framework of the EU FP6 HERMES project [114] and the follow on EU FP7 HERMIONE [115] along with the MESH (Mapping European Seabed Habitats) programme[116].

4.3.2 **Location, oceanography and data resolution**

The Celtic margin extends from the Goban Spur to the Berthois Spur with the continental shelf characterised by two large indentations: the Irish Sea and the English Channel. Sandbanks 40-180 km long, 5-10 km wide and 40 m high, occur on the south part of the Celtic outer shelf [117]. The morphology of the continental slope is characterised by spurs and canyons organised in submarine drainage basins. The southern Celtic margin includes two major drainage basins which link directly to the Celtic deep-sea system via the Whittard and Shamrock canyons: (1) the Grand Sole drainage basin located southwards of the Irish Sea; (2) the Little Sole drainage basin located seawards of the Western approaches. Two types of canyons occur along the margin, canyons with long narrow upper reaches and V-shaped profiles that incise at the shelf-break; and canyons with short, broad upper reaches, U-shaped profiles and heads occurring below the shelf break on the continental slope. In general, younger canyons are incised several hundred metres below the shelf break, whilst older canyons tend to be more deeply recessed into the slope, suggesting they have developed up-slope by head-ward erosion [118]. The Whittard Canyon system with a large, persistent, slightly sinuous channel, is linked to the southern end of the Irish Sea River system connecting the broad shelf at ca. 200 m with the Whittard Channel and Celtic Fan at 400 m [119].

High-energy hydrodynamics characterize the Celtic margin with spring tides and storm surges influencing sediment transport. The study area is influenced by two main water masses, the North Atlantic Central Water from the thermocline down to 800 m, and the Mediterranean Outflow Water (MOW) from 800 m to 1200 m. Below the MOW, the North

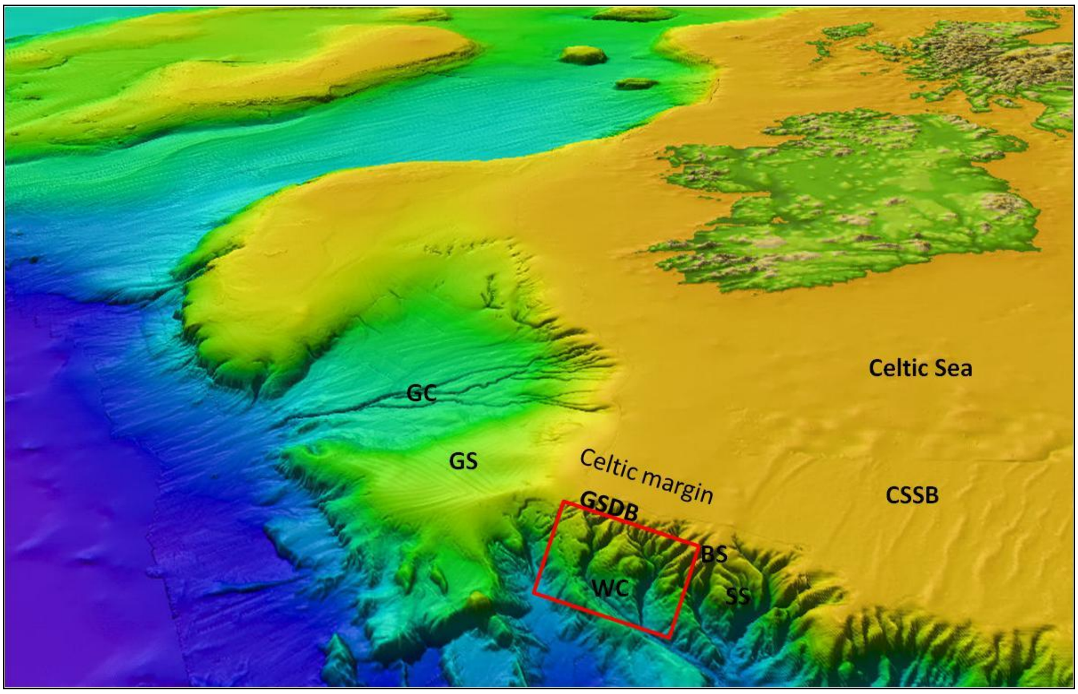
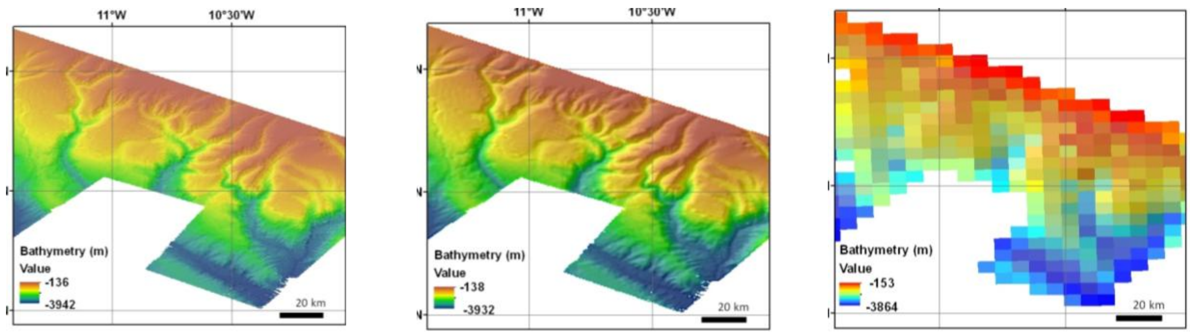


Figure 15. Overview shaded relief of the study area showing the geomorphology of the canyons at the Celtic margin. GC-Gollum Channel, GS-Goban Spur, GSDB-Grand Sole Drainage Basin, WC-Whittard Canyon, BS-Brenot Spur, SS-Shamrock System, CSSB-Celtic Sea Sand Banks. WC highlighted by red box area.

Atlantic Deep Water (NADW), which includes a component of Labrador Sea Water, extends from 1200 m down to 3000-3500 m depth. Below the NADW, the Antarctic Bottom Water or Lower Deep Water is found with a low temperature and salinity content [120]. Along-slope currents move in a northerly and north-westerly direction [121] and internal waves and tides are considered important to sediment transport. Whilst long- and short-term current measurements at the Celtic Shelf and shelf edge are available, measurements of near-bed (in lower 3 m of the water column) currents with direct relevance to sediment transport of resuspension are scarce. The interplay between tides and waves at the Celtic Sea shelf edge is described by Reynaud et al. [122] indicating that both generate mixing at the shelf with internal waves running parallel to the slope.



A B C

Figure 16. Multibeam echosounder bathymetry data gridded at three resolutions (A) 50 m, (B) 500 m and (C) 5 km

Seabed mapping data are typically collected for a specific purpose e.g. to ensure safe navigation, exploit a natural resource or to better model marine biodiversity. The spatial resolution at which data is acquired and presented will depend largely on the type of application. For the purpose of this report, we use a bathymetric dataset to demonstrate how different data resolutions have implications for interpretation of the geomorphology. In figures 16A and B the terrain features of the canyon are readily identified. The shaded relief bathymetry highlights the complexity and nature of the terrain however in 16C it is impossible to relate the features visible in 16A and B given the low resolution of the dataset. If we are to effectively manage the seabed terrain the requirement for high resolution data is critical.

4.3.3 **Methods – data sources and bathymetric digital terrain analysis**

The study area (Fig. 17) was mapped using an EM1002 multibeam echosounder during the INSS in 2000 by the R.V. *Siren.* The EM1002 has up to 111 receiver beam widths of 2° (across track) x 3.3° (along track). Bathymetric data were processed using industry-standard software according to the SP44 Order 3 accuracy requirements of the International Hydrographic Organisation. The bathymetric data were geo-referenced to the World Geodetic System 1984 ellipsoid, converted to coordinates (in metres) within Zone 28N of the Universal Transverse Mercator projection. Given the quality of backscatter data acquired from the study area, the data does not lend itself to backscatter analysis. Data sets were managed and integrated within a Geographic Information System (GIS).

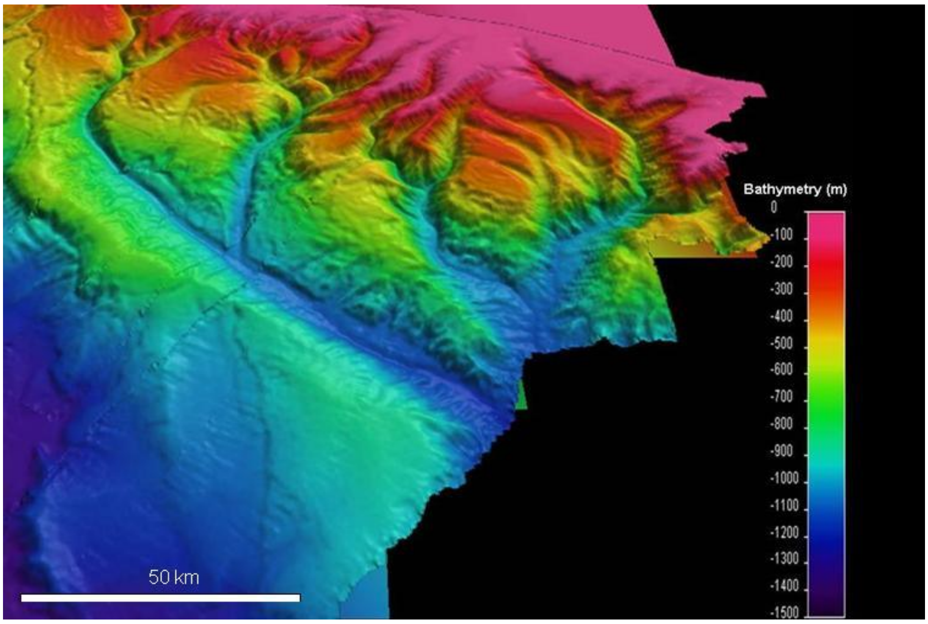


Figure 17. A 3-dimensional view of Whittard Canyon, Celtic margin. The 3-D bathymetric model highlights the complex terrain associated with the canyon system in the form of channels.

GIS based terrain analysis techniques are well established as a potential approach to marine geomorphological mapping in deep water [65]. Multibeam bathymetric data can be used to generate derived quantitative variables describing the seafloor terrain. Dorschel et al. [123] detected canyons in the Irish offshore by their increased slope inclination of canyon walls (steeper than 5°) compared to the surrounding seabed (rarely steeper than 2°). For the purpose of this study ArcGIS® tools were used to derive the terrain variables slope; terrain variability (rugosity) and relative position (Benthic Position Index (BPI)) from the bathymetric data. Slope calculations provide information on the characteristics of the seafloor and indicate regions of flat and undulating seabed. Slope can also be useful in identifying areas of rock outcrop and seafloor structures such as sandbanks and other bedforms. The rugosity analysis helps identify areas with potentially high biodiversity by describing a topographic roughness with a surface area to planar area ratio. Rugosity values near one indicate flat, smooth locations; higher values indicate areas of high-relief. Rugosity calculated using this technique is highly correlated with slope. In the resultant BPI dataset crests, ridges or elevated areas, such as rock outcrop are characterized by positive values. Areas of negative cell values generally characterize depressions and other associated features within a bathymetric data set. BPI values near zero are either flat areas (where the slope is near zero) or areas of constant slope (where the slope of the point is significantly greater than zero). It is important to note that the calculation of a BPI dataset is highly scale dependant [124]. This applies to the input bathymetric grid used, the scale factor applied and the chosen neighborhood of analysis. The BPI is usually calculated at fine and broad scales. Applying different scales to a BPI calculation will classify similar terrain into small scale and large scale structures see Figure 18C.

4.3.4 **Results - geomorphic features and habitats**

The multibeam echosounder data reveals in exceptional detail the network of submarine features characterized by a combination of V- and U-shaped canyons incising the shelf break at between 100 m and 250 m. The Whittard Canyon is seen to consist of a dendritic array of main channels with numerous tributaries and is characterised by a number of deeply incised branches that extend from the shelf break south of the Goban Spur. The branching nature of the canyon extends towards the canyon fan at abyssal depths. Different geomorphologic features can be interpreted from the canyon such as ridges, terraces and isolated topographic highs (pinnacles) which are ideal terrain for biological habitats. Here we highlight the main geomorphic features.

The flat interfluve areas between the canyons occur at between 100 m and 200 m water depth. The upper channel thalwegs of the canyons occur in water depths of ~500 m extending to 2600 m water depth in parts at the lower channel thalwegs. Near-vertical walls characterize the upper parts of the canyon with gradient values of between 15° and 70° in parts. Depositional features are evident in the form of sediment waves whilst the highly dissected continental slope shows evidence of erosional processes. A number of amphitheatre indentations are incised at the upper canyon walls (Fig. 18A).

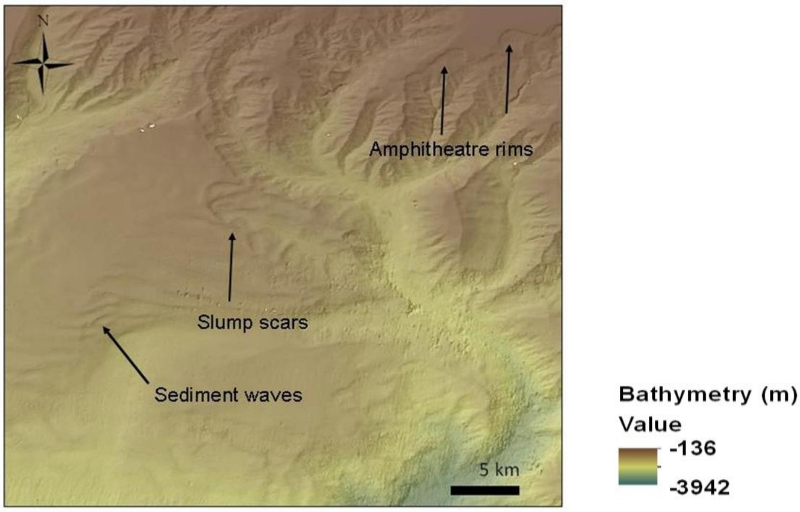


Figure 18A. Shaded relief bathymetry showing erosion and depositional features associated with the canyon system. Amphitheatre rims on the upper channels walls are highlighted. Retrogressive slumping in the form of slump scars is evident from the data along with depositional sediment waves.

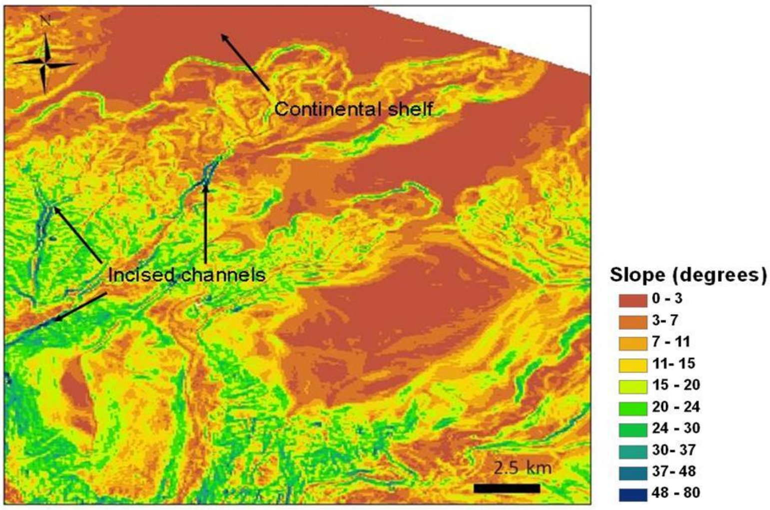


Figure 18B. Slope values (degrees) calculated in ArcGIS® using a 3x3 neighbourhood window and grid cell size 50m. The slope values highlight the range of seabed gradients in the study area from flat terrain to steeper areas e.g. canyon walls and terraces represented by higher slope values.

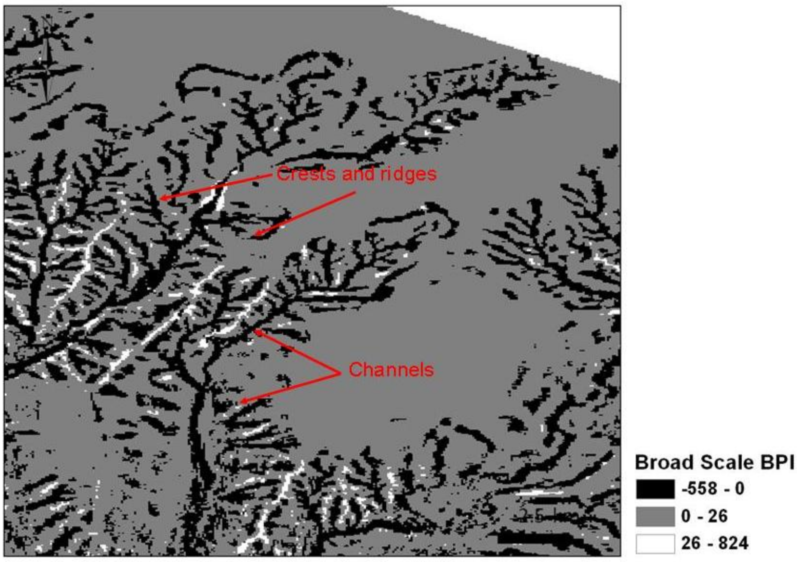


Figure 18C. Benthic Position Index calculated using a 3x3 neighbourhood window (Benthic Terrain Modeller (Wright et al., 2005)) and grid cell size 50m highlights the negative and positive features of the terrain. Depressions are characterised by negative values and the ridge, shelf and crest features are represented by positive BPI values. The BPI values show the dendritic patterns associated with the canyon system suggesting the terrain is highly variable.

Biological communities in submarine canyons tend to be poorly understood given the difficulty associated with access for sampling. Submarine canyons provide conduits for the transport of sediment and organic matter from the shelf to the abyssal plain and over-bank turbidity currents, which deposit on terraces and spurs. Organic matter in the form of macroalgae and/or particulate organic matter accumulate within canyons and in some cases macrophyte detritus will cover the canyon floor. Typical megabenthic filter feeders such as sea whips, holothurians, sponges, basket stars, anemones and corals have been observed in high densities in canyons [115,125-127]. In addition to providing favourable oceanographic conditions, the hard substrates characteristic of canyons provides substrates for habitats including living cold water corals to settle on. Cold-water corals dominated by the soft coral *Anthomastus* sp., the scleractinian coral *Lophelia pertusa* and several octocorals have been observed on the locally steeper slopes (e.g. cliffs, ledges or large boulders) in Whittard Canyon [115]. Similarly *Lophelia pertusa* has been reported in lower densities from the steep walls of other canyon environments [125,128].

4.3.5 **Assessment of mapping costs**

In general eestimates' on mapping costs will depend on water depths/area. Information provided is based on a recent cost benefit analysis study conducted as part of the INFOMAR Irish national seabed mapping programme (Table 7). Estimates of cost associated with multibeam echosounder data processing are also provided (Table 8).

Table 7 Seabed mapping costs based on utilisation of the Irish State research vessels R.V. Celtic Explorer and R.V. Celtic Voyager (PricewaterhouseCoopers, [129]).

Table 3		Table 4	State vessel effort									
Areas to be surveyed		Days to survey	R.V. Celtic Explorer			R.V. Celtic Voyager			Totals			
Water depth	Areas to be surveyed (sq km) updated Sept 2006	Number of days by areas /day coverage	day cost (€)	Survey days at 30 days per year for 7 years	Cost (€)	day cost (€)	Survey days at 30 days per year for 7 years	Cost (€)	Total cost (€)	Total area surveyed	Areas remaining sq km	Days effort remaining
100 to 200m	10,000	80		80	1,920,000		0	0	1,920,000	10,000	-	-
50 to 100m	10,000	111	24,000	60	1,440,000	15,400	51	785,400	2,225,400	9,990	10	0
10 to 50m	5,944	383		0	0		150	2,310,000	2,310,000	2,250	3,694	233
0 to 10m	1,160	72	n/a	0	0	n/a	0	0	-	-	1,160	72
Totals	27,104	646		140	3,360,000		201	3,095,400	6,455,400	22,240	4,864	305

Table 8 Estimate of costs associated with processing multibeam data acquired at different water depths. (INFOMAR team pers. comm. 2012).

Water depth	**Data Processing**
Shallow (0-50 m)	2 days per day of data acquisition
Intermediate (50-200 m)	1 day per day of data acquisition
Deep (200-4500 m)	1 day per day of data acquisition

Acknowledgements

The authors wish to acknowledge the INSS and successor INFOMAR Programme, funded by the Irish Government through the Department of Communications, Energy and Natural Resources as part of the National Development Plan, 2007 – 2013 and jointly managed by the Geological Survey of Ireland and Marine Institute.

4.4 Case study from the North Sea - using 5 m resolution

4.4.1 Introduction

The importance of fine-scale terrain characterization (< 5m) is demonstrated along the Belgian part of the North Sea, a sandy shelf environment with water depths of 0 to -55m. Morphological entities comprise mainly sandbanks, tidal channels and sand dunes of various dimensions. In combination with the available sediments, and underlying geology, interaction of this geomorphology with tidal currents gives rise also to hotspots of biodiversity. Very-high resolution acoustic imagery showed patches or small mound features in these areas. Their mapping is important within various European Directives, such as the Bird and Habitat Directive, as also the Marine Strategy Framework Directive. In this context, the fine-scale mapping approach assists in the delineation and quantification of soft substratum habitat types, but also in the assessment of the impact of human activities (e.g. fisheries impact; or scour by other activities). Also the distribution of some invasive species can be mapped, provided high densities of these species occur, altering the topography of the seafloor. Coarser terrain characterization (e.g. 50 m) cannot be used for these aims. The importance of increased system and process knowledge is highlighted; this can considerably reduce the time- and cost-efficiency of the fine-scale mapping approach over vast areas.

The Belgian part of the North Sea (BPNS) (3600 km²) is a siliciclastic macro-tidal environment (tidal range of 4.5m) comprising several groups of sandbanks (Fig. 19). The sandbanks represent a thin and fragmented Quaternary cover, due to constant reworking of in-situ available sediments. In the troughs, Tertiary clayey sediments outcrop locally. Sediment transport is mainly driven by tidal currents (max. 1.2 m/s), though wind-induced currents may have a direct effect on sediment resuspension and bedform morphology. Human activities are widespread and relate mainly to harbour infrastructure works, dredging and disposal of dredged material, marine aggregate extraction and windmill farm implantation.

For fine-scale terrain mapping both side-scan sonar and multibeam technology can be used. For this case study, focussing on the terrain, only examples are shown derived from multibeam imagery.

4.4.2 Data sets and methods

For the multibeam data acquisition, results are presented that were obtained with a Kongsberg EM1002 multibeam echosounder (95 kHz) (*RV Belgica*), and more recently with a Kongsberg-Simrad EM3002 (300 kHz). Data were motion corrected and calibrated. Shallower than 30m, depth accuracy is around 0.2% of the depth. Neptune (Kongsberg-Simrad) or SonarScope (IFREMER) were used for post-processing and resulted in digital terrain models (DTM) with a 1 to 2-m grid resolution. From the DTM’s, slope calculations were performed, as also rugosity (Benthic Terrain Modeller, ArcGIS® tool; Wright et al., 2005). Rugosity, calculated as the ratio of surface area to planar area, is a measure of terrain complexity or 'bumpiness' of the terrain (Oregon State University and NOAA Coastal Services Center). It assists in the identification of seabed habitats with higher biodiversity. This will be demonstrated along the delta front of the ebb tidal delta of the Westerschelde estuary (Vlakte van de Raan; Fig. 20 and 21) where species density is high due to the existence of bed load convergence zones (where sand is transport to), in combination with enrichment of fines, both naturally- and anthropogenically-induced [130].

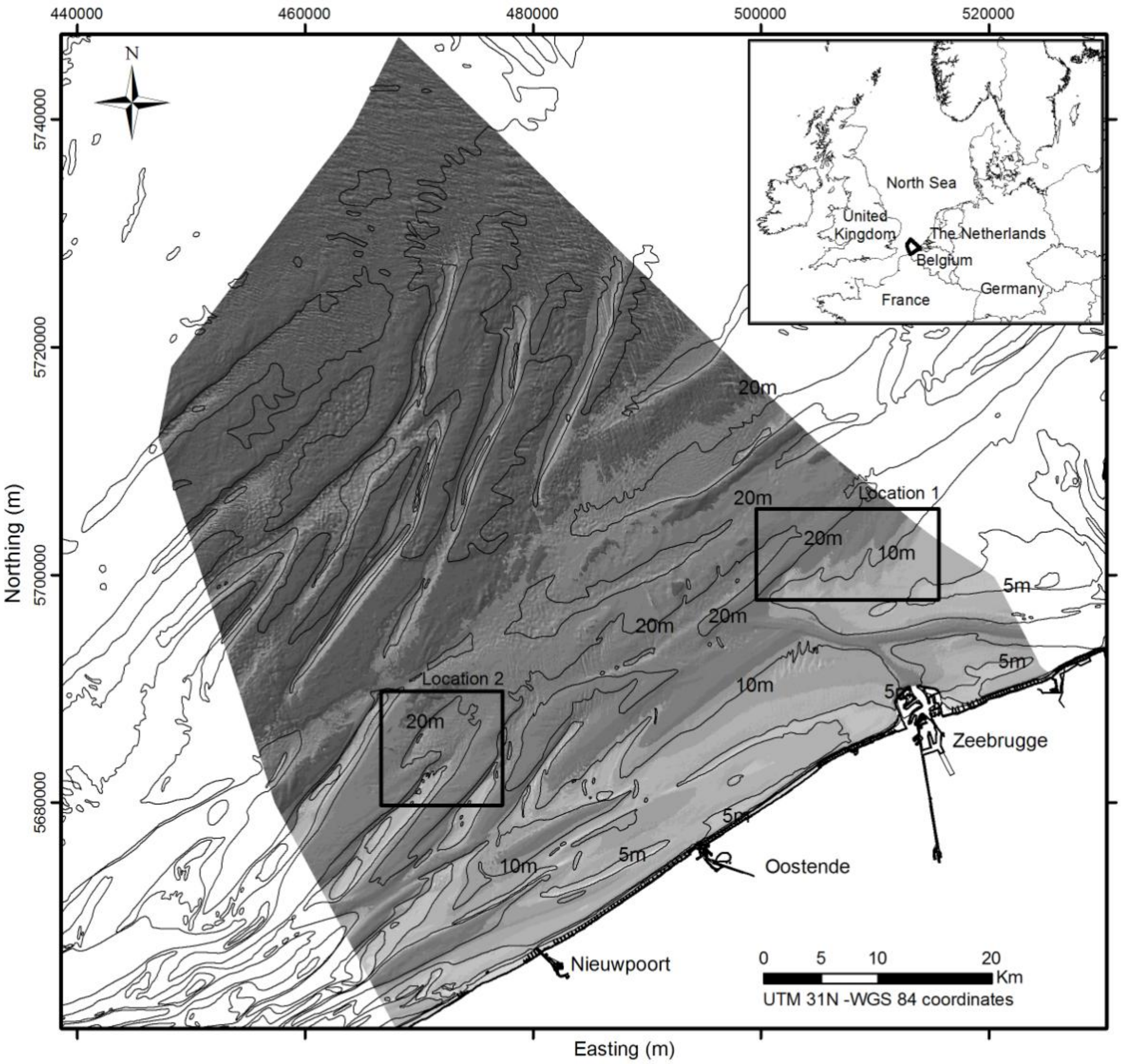


Figure 19. Sandbanks along the Belgian part of the North Sea. Water depths vary from 0-55m MLLWS. Locations of detailed seabed mapping are indicated. Location 1 is the study area of the Figures 20 to 22 and 24 to26. Location 2 refers to Figure 23.

4.4.3 **Geomorphic features - recommendations for their delineation**

In Van Lancker et al. [131] geomorphic features, comprising of sandbank troughs, sandbank slopes and sandbank topzones were described and linked to the occurrences of macrobenthic communities (benthic animals > 1 mm). This was done through fine-scale terrain classification, in combination with an interpretation in terms of sediment characteristics. Here recommendations are provided regarded the terrain classification, only.

A tiered approach in the terrain classification is recommended:

- Large-scale classification in terms of sandbanks and tidal channels,
- Within each of these morphological entities, discrimination of sub-entities: e.g. slopes; topzones of sandbanks; thalwegs and terraces within tidal channels;
- Within each of these sub-entities, identification of crest lines and troughs of dune features; from this bed load convergence and divergence zones can be identified (Fig. 21) (e.g. indicative of sediment transport, important for larvae distribution within a sedimentary system or to localize most depositional areas for aggregate extraction)

(Fig. 23). The ecological importance will depend on the large-scale hydrodynamic setting, as well as on the typical current-topography interaction within the small-scale zones. Especially, when this forcing induces small-scale variation in sediment type, a response of fauna is likely.

- Finally, quantification of small-scale relief differences, rough terrain, small mound features (dimensions larger than 10cm in height) or scour areas. Biologically-induced acoustic facies are typically mound shaped and are circular to elongate (Fig. 22). Visibility will depend on the density and aggregation of the species.

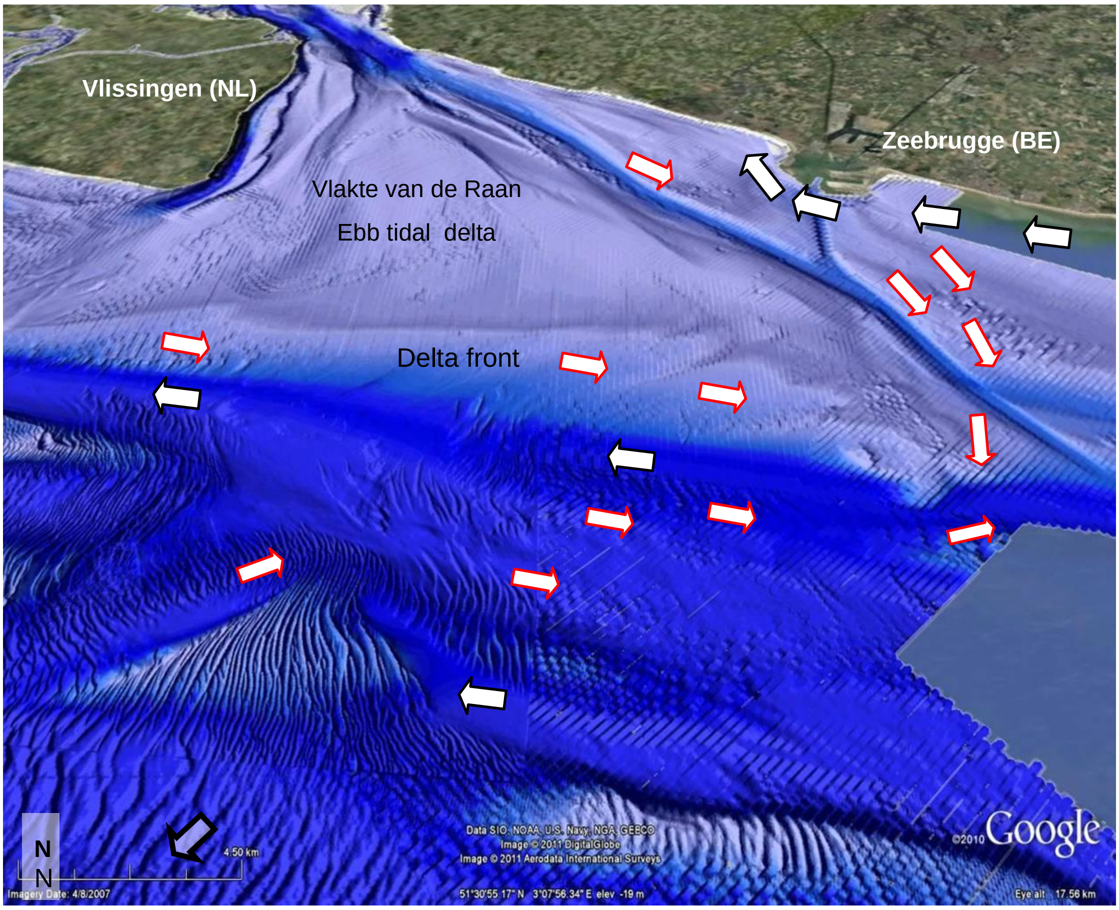


Figure 20. Morphology of the ebb tidal delta of the Vlakte van de Raan, derived from single-beam measurements. Note the navigation channels towards the harbour of Zeebrugge and Antwerp. Arrows provide a synthesis of modelled residual currents [132]. These are important to understand the complex of flood- and ebb dominated channels of sediment transport with relevancy towards the occurrence of seabed habitats with higher species densities. Bathymetric data from Deltares 2011 (Nederlandse Hydrografische Dienst & Rijkswaterstaat Dienst Noordzee). Data resolution 50x50m.

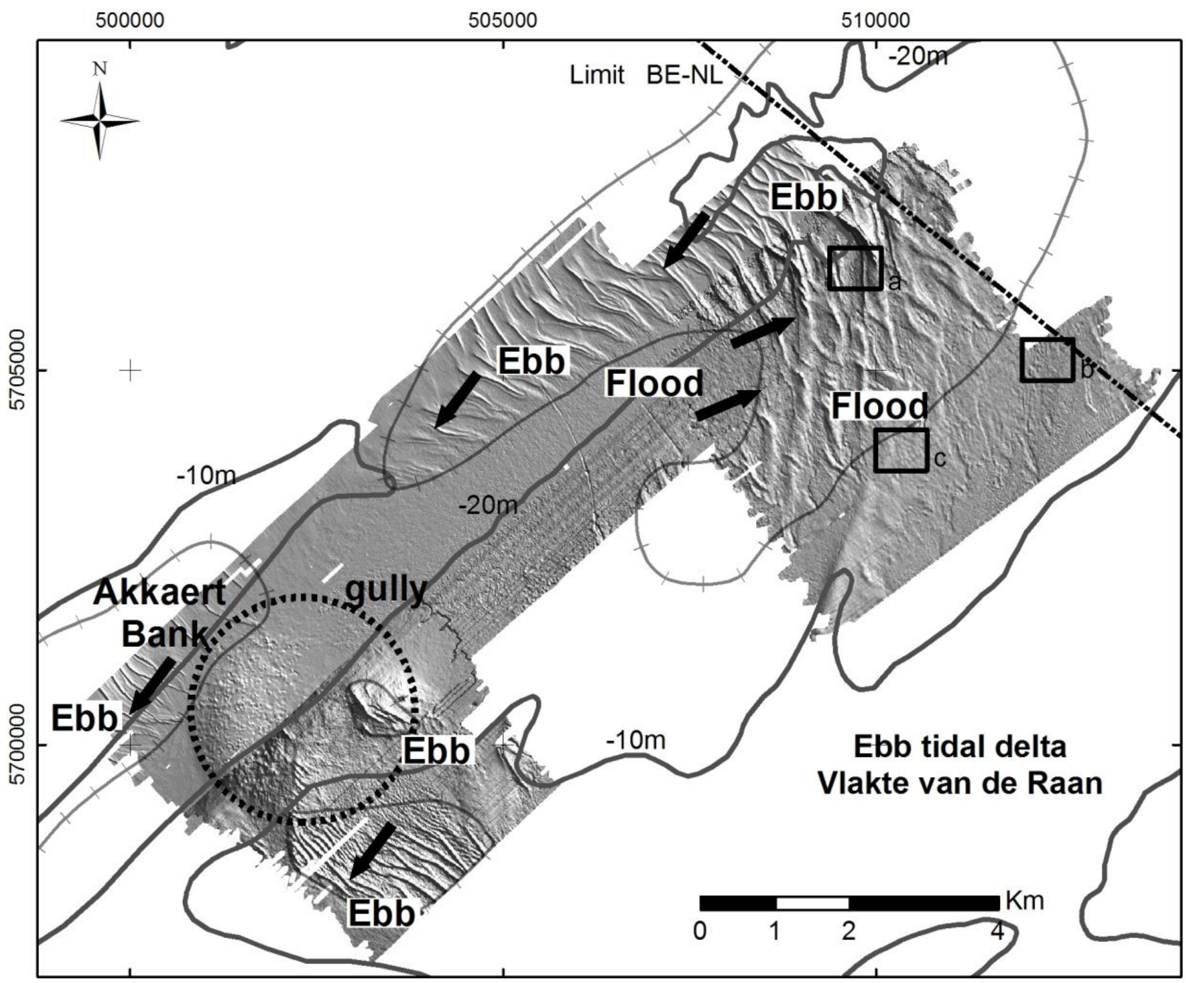
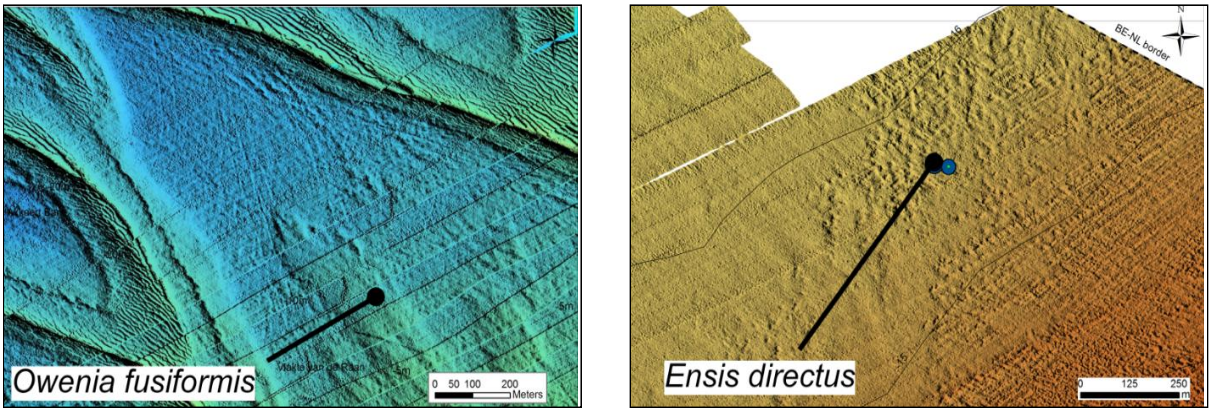


Figure 21. Fine-scale seabed morphology as derived from multibeam. To the west, a disposal ground of dredged material occurs (dashed circle), as also sand dune fields (2-4m in height). In the gully (west), small mound features are indicative of the disposal of dredged material (e.g. smothering). To the east of the gully, a complex of flood- and ebb dominated sand dunes occurs, indicative of a bedload convergence zone. Outside of this zone, along the upper slope of the Vlakte van de Raan, high species densities occur. Data resolution: 5x5m. Locations a, b and c refer respectively to Figure 22a, 22b and 26.

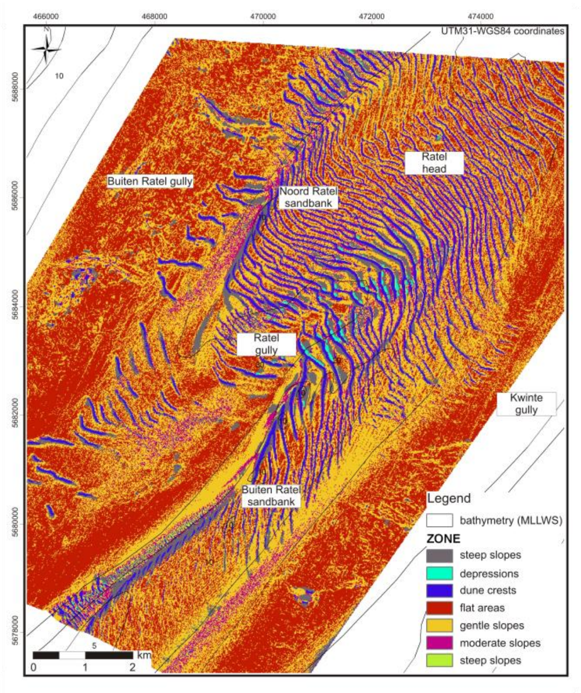


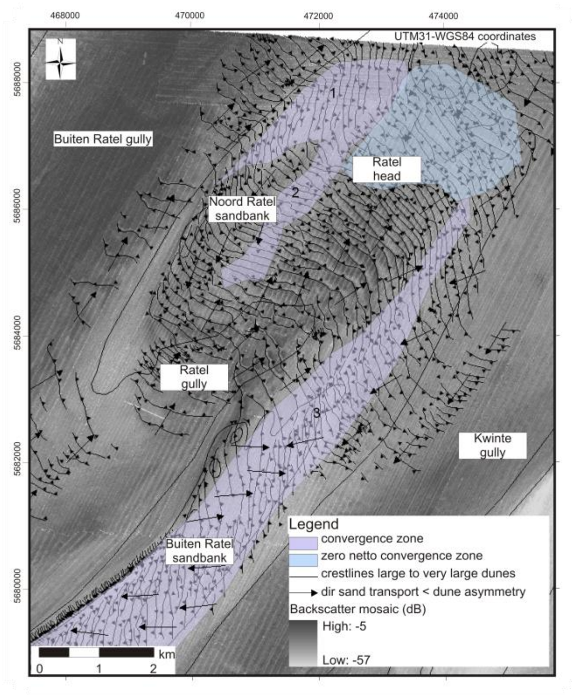
A **B**

Figure 22. A. Dense aggregations of O. fusiformis in the troughs of large dunes in a bedload convergence zone. Their occurrence is likely related to the transient fluxes of fine-grained material, both along-gully and cross-gully. B. Part of the elongated band (location Fig. 21) in which high densities of both O. fusiformis (~11.000 ind m^{-2}) E. directus (blue circles) and E. directus (>500 ind m^{-2}) were found along the upper slope. Here, the dimensions of the patterns are around 20m in diameter, with a height of around 20-40cm. Location, see Fig. 21. Data resolution 1x1m.

Terrain classification can be done automatically, using available terrain modules (e.g. Benthic Terrain Modeler [76]). These are able to distinguish between depressions, slopes and crests (Fig. 23, for an example). However, a multi-scale approach is needed to resolve the hierarchy of morphological features in the terrain. Analyses results can be combined afterwards. In many cases, a manual delineation is often more time-efficient and needed for verification of the significance of the results.

For the delineation of the smallest scale features (e.g. mound features or more generally biologically-induced positive relief), fine-scale slope or roughness maps can be used (e.g. Fig. 24). Along the Belgian part of the North Sea, biologically-induced acoustic facies could be more easily delineated evaluating slopes of more than 2° within homogeneous areas (Fig. 24B). Same areas were depicted based on roughness calculations (Fig. 24A). However, in both cases, no distinction can be made between slopes or roughness as a consequence of a pure current-topography interaction (e.g. ripples), or in combination with species and their interactions with current-topography, or as due to abrasion of the seafloor from trawling (Fig. 26). Terrain validation remains vital, necessitating thorough ground-truthing, by sampling and visual observations (e.g. video; photography).

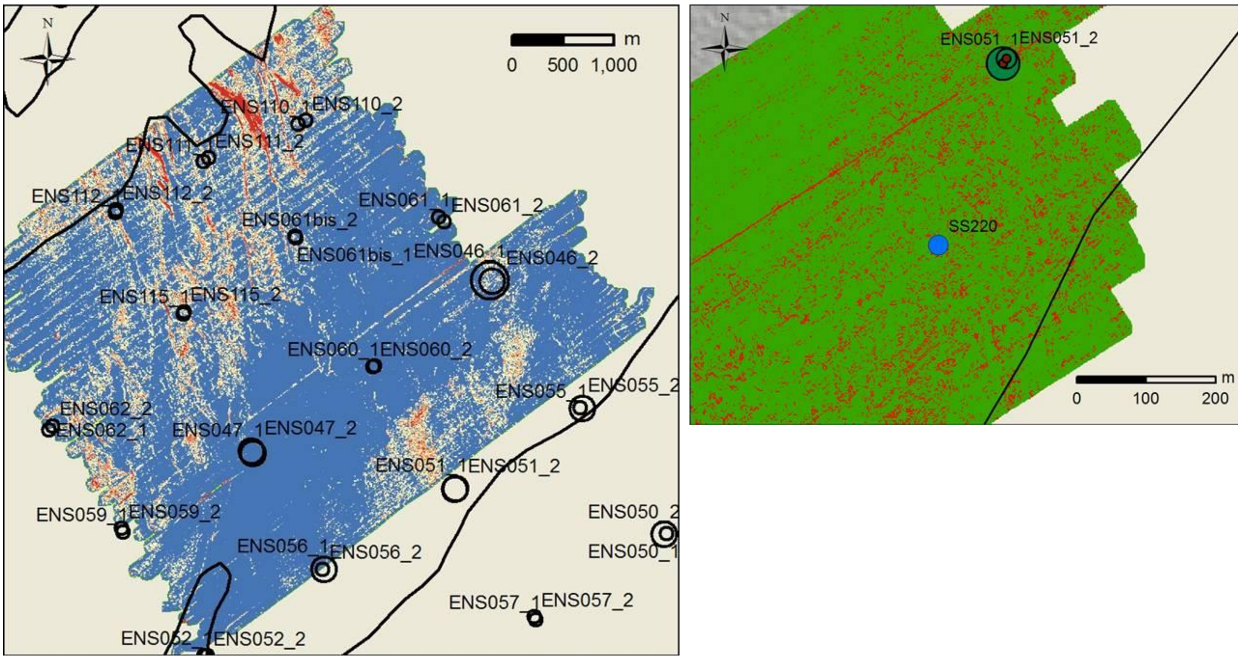




A B

Figure 23. A. Results from fine-scale benthic terrain modelling: automatic depiction of slopes, depressions, as also crestlines of sand dunes on a sandbank. B. Together with aspect information (orientation of slope) sand transport directions can be derived. The cyan area is where sand transport converges naturally (bedload convergence zone) and was proposed as best location to extract sand. It was hypothesized that seabed recovery would be rapid, causing minimal impact [133]. Location, see Fig.19.

Along slopes, small mound features were mostly observed in bands (200-400m wide), parallel to the slope (Fig. 21). Biologically-induced features have been identified from 7.5 to 11.5cm in height with patch sizes of 0.8-11.6m² (tubeworm and ecosystem engineer *Lanice conchilega*; [134]). Sometimes, the mounds are more circular to elongate; in the troughs of sand dunes mound features were observed of 15-40cm in height, with patch sizes of 0.6-12m² [130,131]. The topographic zonation that is often seen in the distribution of small-scale mound features indicates a certain forcing. As a consequence, it may prove more efficient to invest first in process studies to understand the forcing, before the fine-scale mapping approach is continued over vast areas. Suggestions include current and backscatter profiling (e.g. through the use of Acoustic Doppler Current profilers), albeit in combination with optical measurements of turbidity).



A B

Figure 24. A: Relative rugosity map (blue to red corresponds to low to high rugosities) along the northern slope of the Vlakte van de Raan (Benthic terrain modeller) (Location Fig. 21). Higher rugosity values to the north are related to bedforms (see previous figure). It is hypothesized that the higher rugosity to the south (upper slope) is related to higher densities of both E. directus and O. fusiformis. Note the relatively higher rugosity near sampling location 51 (2010), where up to 341 ind/m² of E. directus were counted. B: Detail of the slope map around sample location 51 (2010) (RV Belgica ST1029). Data resolution 1x1m.

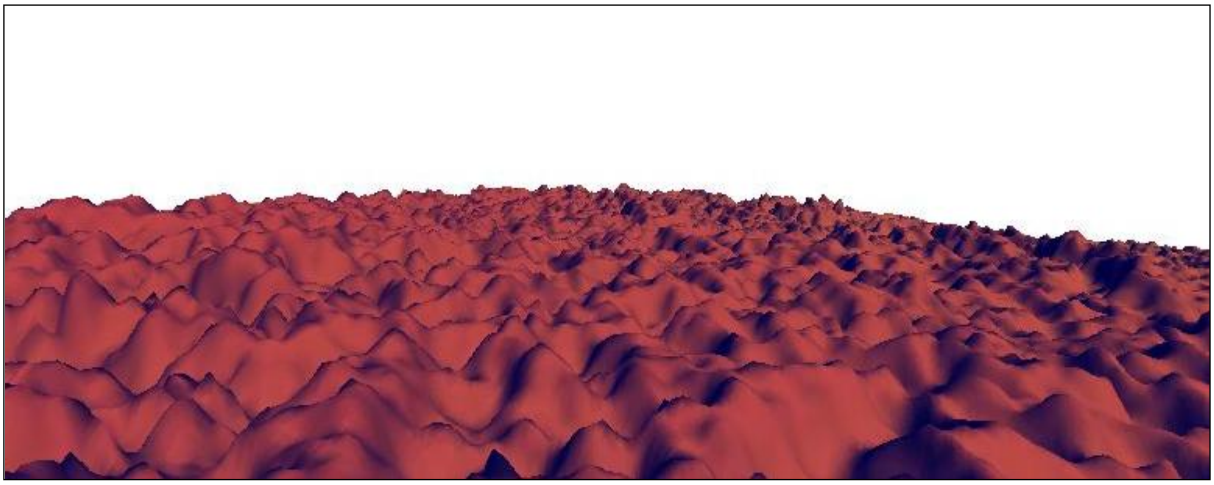


Figure 25. 3D acoustic seabed image (1x1m resolution) of where the invasive species E. directus thrives. Note the rough or bumpy character of the seafloor. Height differences are in the order of 20-40cm. Slope of the Vlakte van de Raan area (RV Belgica ST1029). Location corresponds to Figure 22B.

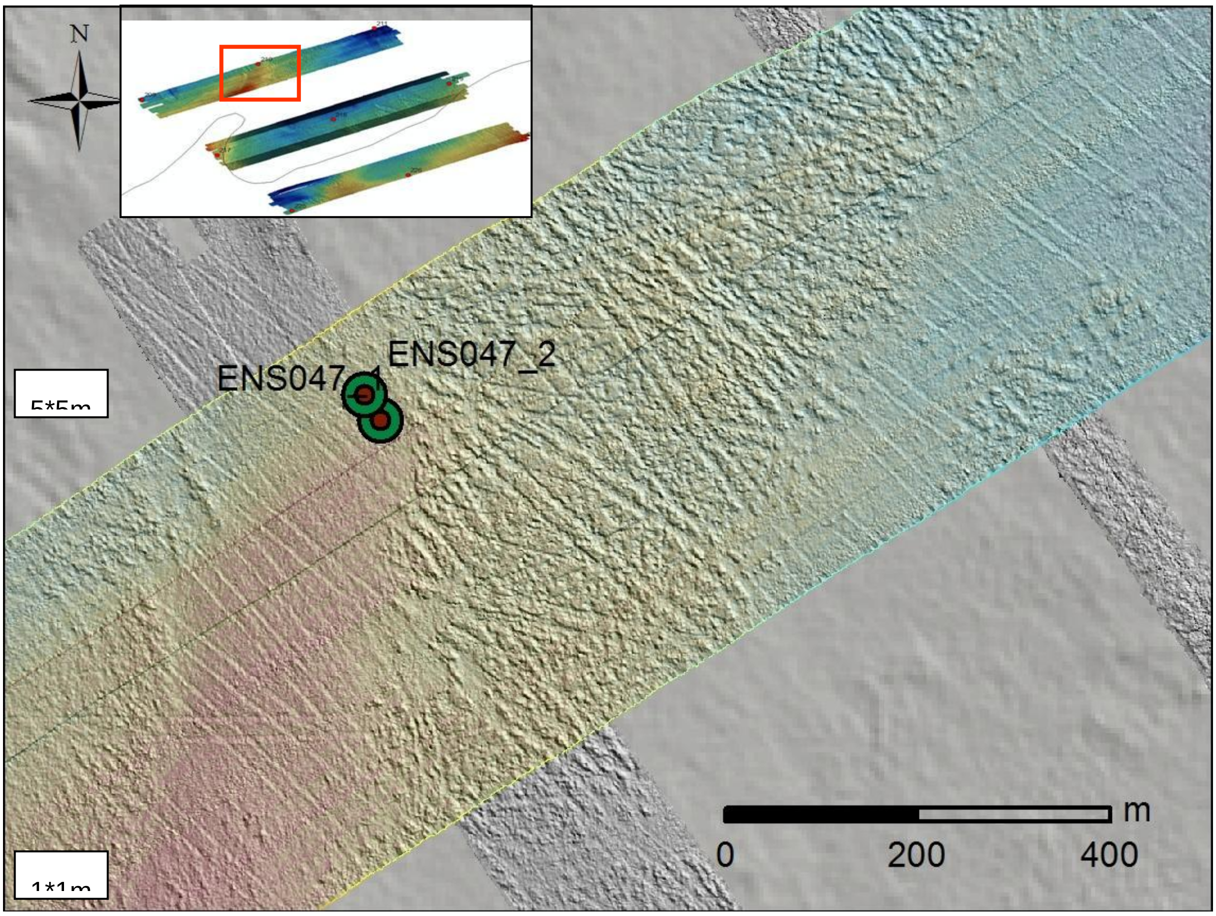


*Figure 26. High species densities where the seabed is fully scraped by beam trawling. Here roughness and slope calculations do not allow discriminating biologically- from anthropogenically-induced patchiness. Manual verification remains vital. Note the difference in the detection of small seabed features from the 1*1m against the 5*5m background digital terrain model. Location: Vlakte van de Raan, Figure 21.*

Methodological constraints are important to bear in mind when doing this kind of work. The value of fine-scale mapping products is determined by the quality of the underlying data. Quality assurance is primordial. In case of multibeam data, ideally IHO standards (MB Special or MB-1) are followed. This has implications on survey design (e.g. spacing of the tracklines ensuring sufficient overlap) and calibration of the echosounder (minimum roll and outer beam calibration; time delay). Fair weather conditions are a *conditio sine qua non*.

4.4.4 **Conclusions**

Very-high resolution acoustic systems (e.g. 300 kHz) allow depicting small-scale (< 5m) terrain variation of relevance for seabed management, science and industry. Sometimes a typical terrain morphology can be indicative of the occurrence of a sediment type (e.g. gravel lag), but in some cases there is even a direct link to the occurrence of high densities of species. Also seabed imagery can allow quantifying the impact of human activities on the seabed (e.g. abrasion; extraction within MSFD context). Data is processed ideally to data grids of 1x1m to reveal small-scale patchiness. Multibeam technology is preferred since the digital terrain models can be further analyzed in terms of slope or rugosity, 2 parameters that assist also in the delineation of biogenic reefs. Data interpretation remains hampered by the not always easy differentiation between physically- and biologically-induced structures (MESH Habitat Signature Catalogue [135]). More research is needed to distinguish between the acoustic signature of different species. In any case, adequate ground-truthing (incl. optical imagery) is needed of the acoustic signature. It needs emphasis that the appearance of patterns can vary also according to the ensonification angle, as well as to different survey conditions. Variations in substrate, sediment availability and energy regime may further alter the way small-scale terrain features are acoustically imaged.

In any case, detailed seabed imagery, in combination with other measurements and observations, is key to increase system and process knowledge (incl. morphological setting, substrate characteristics, sediment processes, habitats) being vital for seabed management, and particularly for assessing good environmental status within the context of Europe's Marine Strategy Framework Directive. To conclude a table provides an overview of relevant seabed terrain features following a fine-scale mapping approach.

Table 9: Seabed terrain features to observe through a fine-scale mapping approach (< 5 m) with relevance to EU Directives (MPA: Marine Protected Area; MSFD: Marine Strategy Framework Directive).

Terrain Feature	Identification	Relevance
Seabed lineations	Small- to medium dunes Wave ripples	Industry (e.g. resource evaluations)
Small-scale relief differences	Sediment gradients Smothering due to enhanced sedimentation of fines	Seabed management – MFSD
Rough terrain	Gravel lags (hummocky morphology) Shell debris accumulations	Seabed management – Delineation MPA's; MFSD
Small mound features (min. 10 cm in height)	Biogenic reefs Dense aggregations of some species* Cold water seeps	Seabed management – Delineation MPA's; MFSD
Scour/Abrasion	Trawl marks Scour around windmills	Seabed management – Quantification impact area human activities Industry (stability)

*Examples include some tube building polychaetes, shell fish (e.g. the invasive species Ensis directus). The visibility of the seabed feature is dependent on the density and aggregation of the species.

Acknowledgements

Unless stated, data were acquired in the framework of the Belgian Science Policy projects QUEST4D (QUantification of Erosion and Sedimentation patterns to Trace naturally- versus anthropogenically-induced sediment dynamics; BelSPO SD/NS/06B) and EnSIS (Ecosystem Sensitivity to Invasive Species; BelSPO SD/NS/09A). Ghent University, Renard Centre of Marine Geology is acknowledged for the use of the multibeam processing software Sonarscope (IFREMER).

5 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Ecosystem-based management of the European waters as outlined in the Marine Strategy Framework Directive (MFSD), the EU Water Framework Directive and the EU Habitats Directive require a sound knowledge of benthic habitats. Nearly half of the habitats listed in the Habitats Directive are either geomorphic features or features that can be identified through geomorphic analysis. Marine habitats listed in the directive that are directly identifiable by geomorphology (with appropriate supporting information) include sandbanks, seagrass (*Posidonia*) beds, estuaries, large shallow inlets and bays, reefs, submarine structures made by leaking gases, mudflats/sandflats, and coastal lagoons. The OSPAR list of threatened and/or declining species includes habitats with a geomorphic signature – carbonate mounds, seamounts and *Lophelia pertusa* reefs.

This study has reviewed the marine habitat classification systems used globally, including EUNIS. Many of the habitats listed in the EU Habitats Directive can be identified on the basis of bathymetry, but the EUNIS system does not include terrain information or geomorphology as an input. Recent work has shown that terrain characterisation may be used in an indirect manner. It should be considered in the future development of EUNIS to include bathymetry and terrain in a more structured and formal way. In particular it may be worth looking closer at the recently developed US Coastal and Marine Ecological Classification Standard (CMECS).

Identification of ecologically relevant geomorphic structures relies heavily on automated or semi-automated classification which can be taken further by experts to a true geomorphic classification. The results depend on the scale of bathymetry used, and the programs/algorithms used. There is a need for a harmonisation of the resolution of the data sets used, and the tools used for the analysis. Standardised scales like 500 m – 50 m – 5 m and corresponding map scales of 1:1.000.000 – 1:100.000 – 1:10.000 can be one option. The important thing is to develop a harmonised approach to terrain characterisation in European waters, in order to achieve a classification of ecologically relevant geomorphic structures that can be valid across basins and national boundaries.

The case studies show that classification of ecologically relevant geomorphic structures in the future will also be based on multi-scale bathymetry data sets. Broad-scale features can be defined using coarse data sets, such as the 500 metre grid supplied by the EMODNET hydrography portal. On the other hand, it is critical to have very high resolution data sets from multibeam echo sounders in areas with complex geomorphic structures and habitats, particularly close to the coast. Data sets with 5 metre resolution and better will be crucial in order to map important structures in areas of high complexity.

The case study from Danish waters in the North Sea used bathymetric data from the EMODNET Hydrography portal. It showed that the 500 m grid data is very useful to define submarine structures like e.g. troughs, valleys and slopes, adapting the classification scheme developed in the EU supported Balance project (for details, see http://balance-eu.org/). However, some small features like reefs and small banks were not possible to be identified.

The case study from the Celtic margin in the Celtic Sea demonstrated how a 50 m grid is suitable for defining canyons, with a wide range of topographic/geologic features such as ridges, terraces, pinnacles, sediment waves, slump scars and channels. These features provide the physical environment for different habitats, including hard substrate suitable for cold water coral reefs. The Irish study also provides an overview of the costs associated with seabed mapping using multibeam echo sounder. An important conclusion is that the cost of multibeam mapping is considerably higher in shallow waters.

The case study from the Belgian shelf used a 5 metre grid dataset, and demonstrates how topographic features like sandbank troughs, slopes and top zones can be linked to the occurrence of macrobenthic communities. It also showed that biologically-induced acoustic facies can be identified, and in some cases linked to the occurrence of biological communities or to dense aggregations of some seafloor structuring species..

The resolution of the bathymetric data to be used for ecologically relevant terrain modelling must be directly linked to the scope of the analysis. The resolution currently provided by the EMODnet Hydrography portal (c. 500 metre) is suitable for broad classifications at a basin-wide scale. A 50 metre resolution is necessary to define medium-scale features like canyons and associated possible habitats. When fine-scale classification is the scope, bathymetric data from multibeam echo sounders with a resolution of 5 metre or better is required. Bathymetric data needs to comply with commonly used formats. ESRI's ArcGIS® software is extensively used among the scientific community, and the ESRI ASCII grid format is directly useable in many other GIS software. For an easy exchange of data within the scientific community it is recommended that ESRI ASCII grid format should be available from data servers such as EMODNET Hydrography portal, in addition to standard ASCII xyz.

In conclusion - geomorphic structures readily identified from bathymetry contribute significantly to the knowledge base needed for implementation of the Marine Strategy Framework Directive. Future development of the EUNIS system should consider integrating geomorphology, perhaps using the US CMECS system for inspiration. There is a need to develop a harmonised approach for classification of ecologically relevant geomorphological structures in European waters.

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Annex B. Figures and Tables

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Figure 15: Overview shaded relief of the study area showing the geomorphology of the canyons at the Celtic margin. GC-Gollum Channel, GS-Goban Spur, GSDB-Grand Sole Drainage Basin, WC-Whittard Canyon, BS-Brenot Spur, SS-Shamrock System, CSSB-Celtic Sea Sand Banks. WC highlighted by red box area.

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Figure 18: A. Shaded relief bathymetry showing erosion and depositional features associated with the canyon system. Amphitheatre rims on the upper channels walls are highlighted. Retrogressive slumping in the form of slump scars is evident from the data along with depositional sediment waves. B. Slope values (degrees) calculated in ArcGIS® using a 3x3 neighbourhood window and grid cell size 50m. The slope values highlight the range of seabed gradients in the study area from flat terrain to steeper areas e.g. canyon walls and terraces represented by higher slope values. C. Benthic Position Index calculated using a 3x3 neighbourhood window and grid cell size 50m highlights the negative and positive features of the terrain. Depressions are characterised by negative values and the ridge, shelf and crest features are represented by positive BPI values. The BPI values show the dendritic patterns associated with the canyon system suggesting the terrain is highly variable.

Figure 19: Sandbanks along the Belgian part of the North Sea. Water depths vary from 0-55m MLLWS. Locations of detailed seabed mapping are indicated. Location 1 is the study area of the Figures 20 to 22 and 24 to26. Location 2 refers to Figure 23.

Figure 20: Morphology of the ebb tidal delta of the Vlakte van de Raan, derived from single-beam measurements. Note the navigation channels towards the harbour of Zeebrugge and Antwerp. Arrows provide a synthesis of modelled residual currents. These are important to understand the complex of flood- and ebb dominated channels of sediment transport with relevancy towards the occurrence of seabed habitats with higher species densities. Bathymetric data from Deltares 2011 (Nederlandse Hydrografische Dienst & Rijkswaterstaat Dienst Noordzee). Data resolution 50x50m.

Figure 21: Fine-scale seabed morphology as derived from multibeam. To the west, a disposal ground of dredged material occurs (dashed circle), as also sand dune fields (2-4m in height). In the gully

B.2. List of Tables

Annex C. Terminology

Term	Description
Abiotic	Non-living chemical and physical factors in the environment, which affect ecosystems.
ArcGIS	An industry standard Geographic Information System.
Bathymetry	Study and mapping of seafloor elevations and the variations in water depth; the topography of the seafloor.
Benthic	Associated with the seafloor
CMECS	The United States Coastal and Marine Ecological Classification Standard that provides a comprehensive national framework for organizing information about coasts and oceans and their living systems.
Demersal	The **demersal** zone is the part of the sea or ocean (or deep lake) comprising the water column that is near to (and is significantly affected by) the seabed.
EMODnet	European Marine Observation and Data Network.
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.
GeoHab	Marine **Geo**logical and Biological **Hab**itat Mapping – an international scientific forum which meets annually.
LIDAR	Optical remote sensing technology for measuring height and range, sometimes used for shallow water bathymetric mapping
MESH	An EU-funded project for the development of a framework for **M**apping **E**uropean **S**eabed **H**abitats.
Multibeam	Multibeam echosounder – an acoustic technique for mapping the bathymetry and acoustic response (backscatter) of the seabed, which has become widely used in marine habitat mapping.
Pockmarks	Pockmarks are believed to be produced by the escape of fluids (gas or water) from the seafloor and are found in areas where the seabed sediments are soft, silty clays.
Rugosity	A measure of small-scale variations or amplitude in the height of a surface.
Rurrogate	Biophysical variables that can be mapped to the occurrence of benthic species.
Terrain curvature	The curvature of a line formed by intersecting a plane with the terrain surface.
Thalweg	The line defining the lowest points along the length of a river bed or sub-marine canyon.
Thermocline	The transition layer between the mixed layer at the surface and the deep water layer.

WISE-MARINE	A comprehensive and shared European data and information management system for the marine environment which supports implementation of the Marine Strategy Framework Directive. This will also include the use of the EMODnet and INSPIRE processes to establish the required infrastructure and data access.