

EUSeaMap

Technical Report No. X

Bathymetry and thresholds

DRAFT

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1 Introduction

Bathymetry is one of the key deliverables for EUSeaMap from the EMODNET hydrography project. The DEM being developed by the EMODNET Hydrography consortium is of a minimum quarter minute resolution, with the latest half minute resolution GEBCO (General Bathymetric Chart of the Oceans) release incorporated for areas where sufficient data cannot be made available. The EMODNET Hydrography project covers the North and Celtic Seas and the Western Mediterranean. An initial draft of this dataset for the North and Celtic Seas was received in May 2010. The preparation of this North Sea and Celtic Seas DEM is described in more detail in the Hydrography project Interim Report¹. In the Western Mediterranean, EUSeaMap partners are also partners in the EMODNET Hydrography project. The projects have elaborated a Mediterranean global DEM with a resolution of 0.0027 decimal degrees.

2 Data layer preparation

2.1 Baltic Sea

The Baltic Sea bathymetry map was compiled from four regional bathymetry maps (Figure 1), these are:

- The Swedish 1:500,000 scale map
- The Swedish 1:50,000 scale map
- The Finnish 1:50,000 scale map
- The Danish 1:500,000 scale map

¹ <https://webgate.ec.europa.eu/fpfis/iwt/sites/default/files/Hydrography-1st-Interim-Report.pdf>

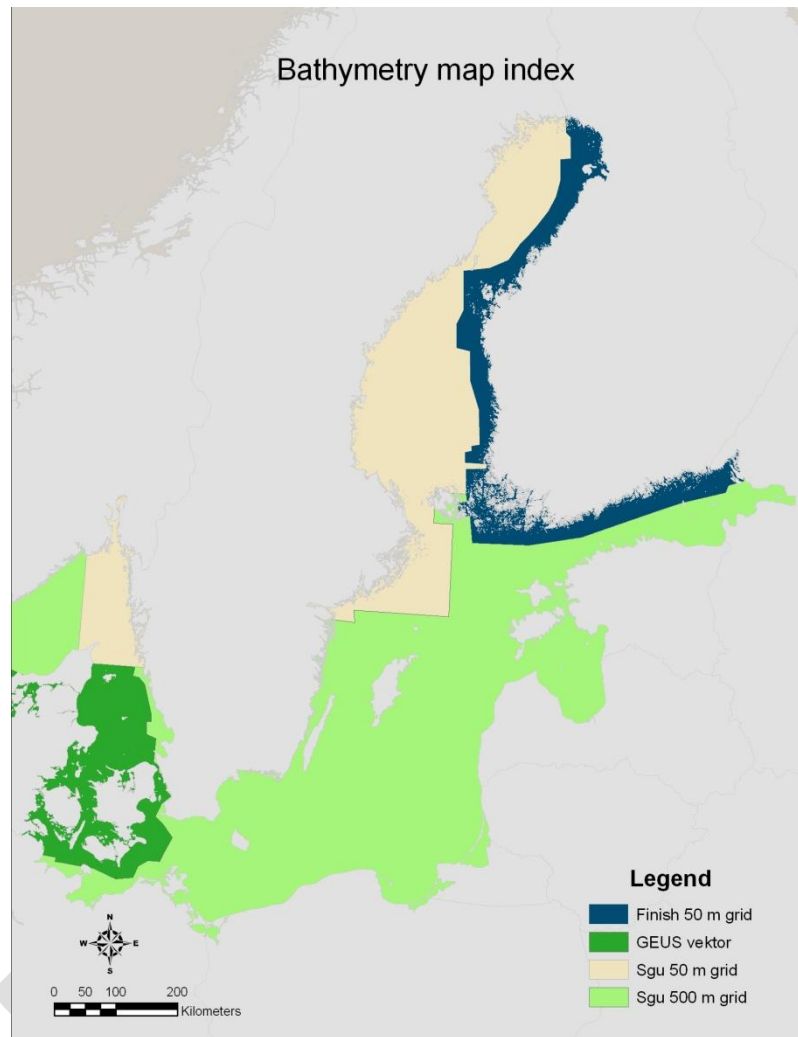


Figure 1 Baltic Sea bathymetry map index, showing coverage of four regional sources.

Joining bathymetry maps from different sources is not a straightforward task. Differences in bathymetry values at the boarder lines are readily shown in the merged map. It is also difficult to produce a reasonable and flawless slope values out of such maps. Therefore care was taken to inspect the boarder zone of each two different maps and try to merge them by finding the average value at the overlap if they do not match.

Another problem was to join maps of different resolution; this immediately appears at the joint boarder so at some area it was decided to under sample the high resolution map to match it with the neighbouring low resolution one. In other occasions the high resolution map was used as it is, and others it was replaced by a lower resolution map. The final Baltic bathymetry map used in EUSeaMap is shown in Figure 2.

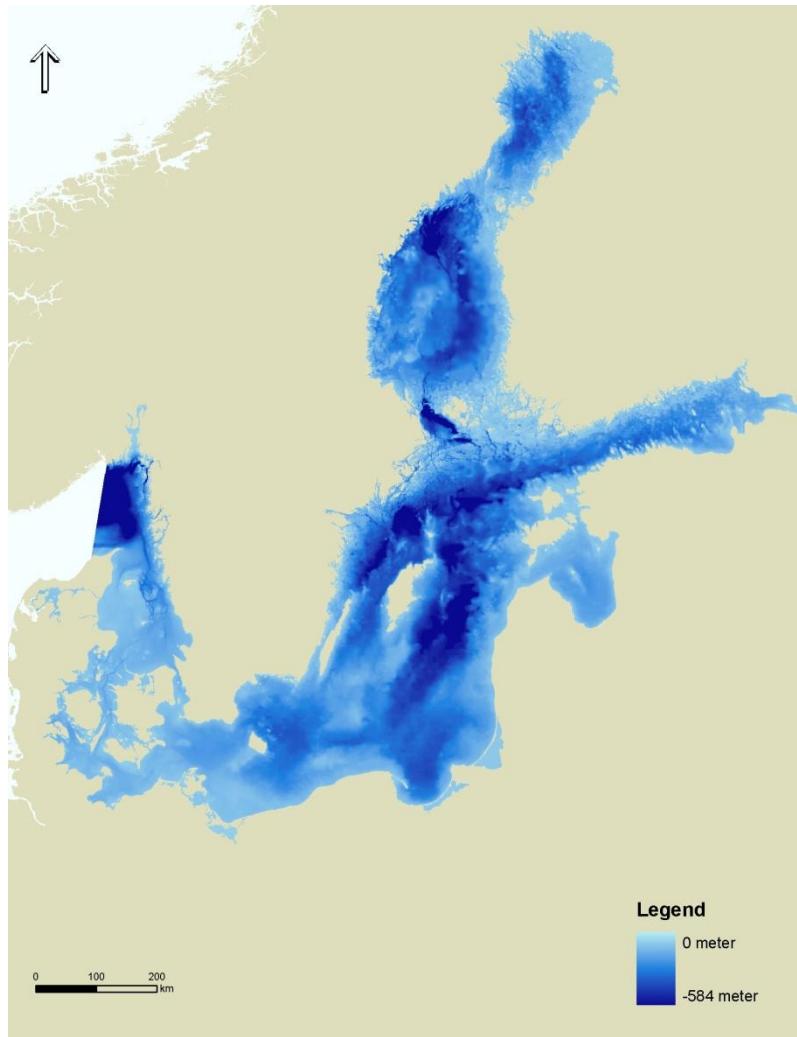


Figure 2 Baltic bathymetry map used in EUSeaMap, sourced from BALANCE project.

2.2 North and Celtic Seas

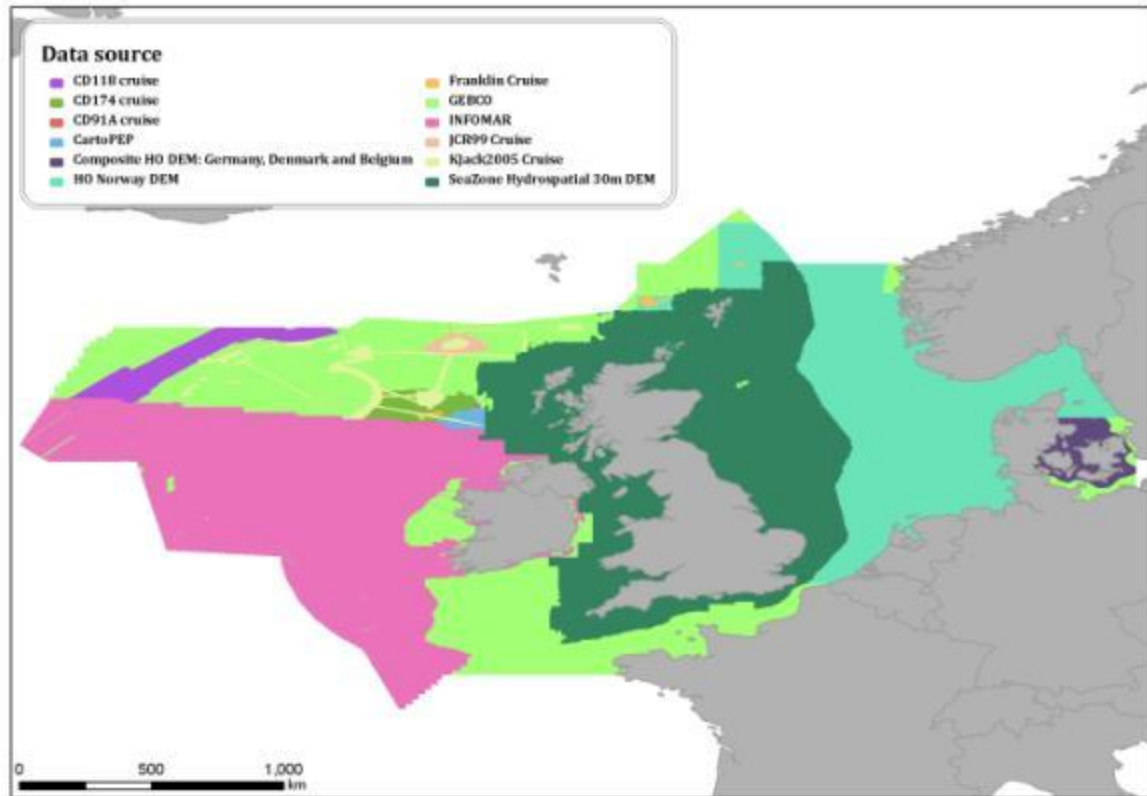


Figure 3 Data sources for the North and Celtic Seas. All data sources contributed to the EMODNET DEM except the SeaZone hydrospatial 30m DEM. This licenced product was included within this project to improve the modelled habitats for coastal and shelf regions of UK waters, and in lieu of access to UKHO data.

Due to difficulties encountered by EMODNET Hydrography group in obtaining data from the UK Hydrographic Office (UKHO), the EUSeaMap group used UKHO depth data obtained through a licensed SeaZone product (the 'SeaZone dataset' hereafter) for much of the UK shelf waters: these data cover a large part of the UK shelf area, but do not extend as far as the deep sea. EMODNET has since obtained data from the UKHO and is in the process for incorporating it into an update of the DEM, due in March 2011. There are some gaps in the SeaZone dataset, which were filled as follows:

- Use EXTRACT BY MASK to select GEBCO data for the area, in order to cover the 'large gaps'
- Convert extracted GEBCO data to points then apply Inverse Distance Weighting (IDW) function to interpolate to the resolution of EMODnet hydrography project (0.0020833333)
- Mosaic a 0.0025 'resample mosaic'* of SeaZone (all) and their Seazone IDW interpolation (the 'small gaps')
- Resample the above (c.) to 0.0020833333
- Mosaic (d.) and (b.), giving precedence to (d.)

**SeaZone data were provided as a set of raster tiles at 30m resolution. A script was written which converted all the tiles to points, interpolated them to 0.0025 (IDW) and then mosaiced them together.*

In order to join the EMODnet hydrography GRID and SeaZone dataset, the following steps were carried out:

- a. Multiply EMODNET bathymetry by (-1)
- b. Mosaic output (e.) above and the EMODnet bathymetry

The final North and Celtic Seas bathymetry map used in EUSeaMap is shown in **Figure 4**.

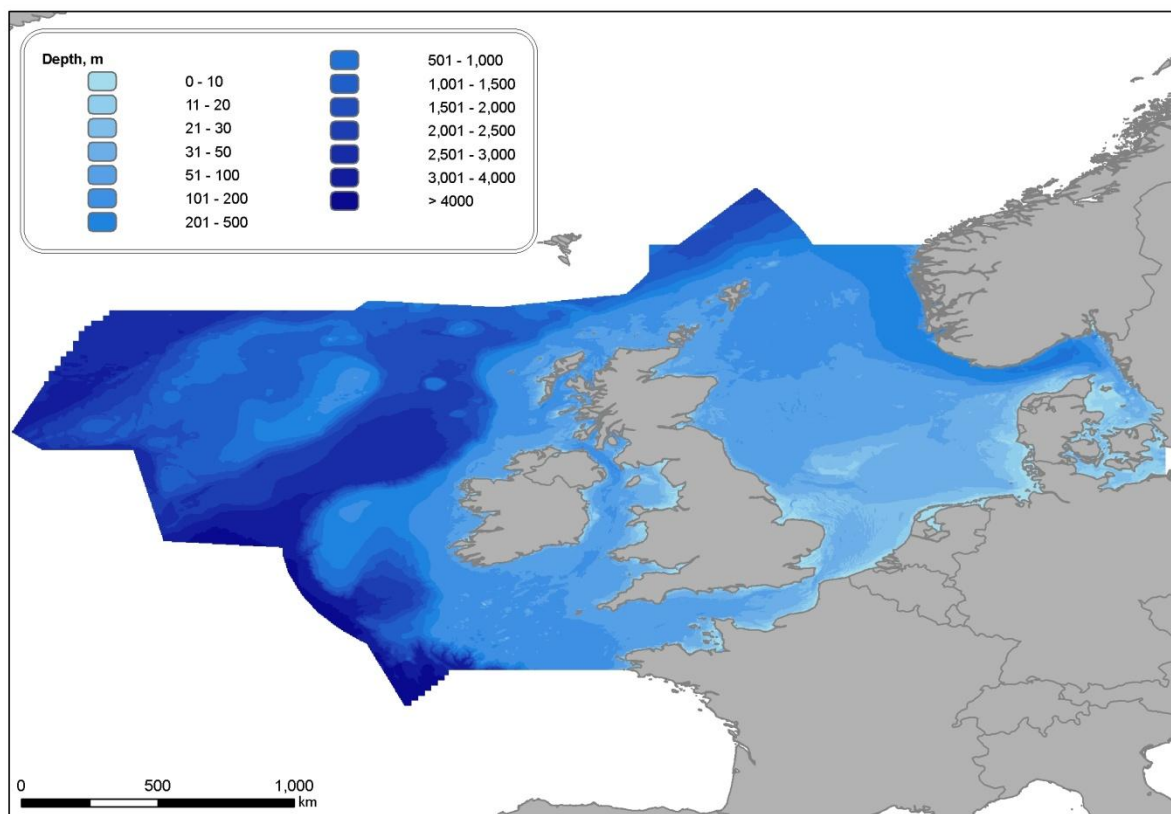


Figure 4 Bathymetry map for the North and Celtic Seas.

2.3 Western Mediterranean Sea

2.3.1 Introduction

A Digital Terrain Model (DTM) for the Western Mediterranean was produced with a resolution of 0.0027 decimal degrees. This DTM was made from DTMs covering different parts of the area (Figure 5).

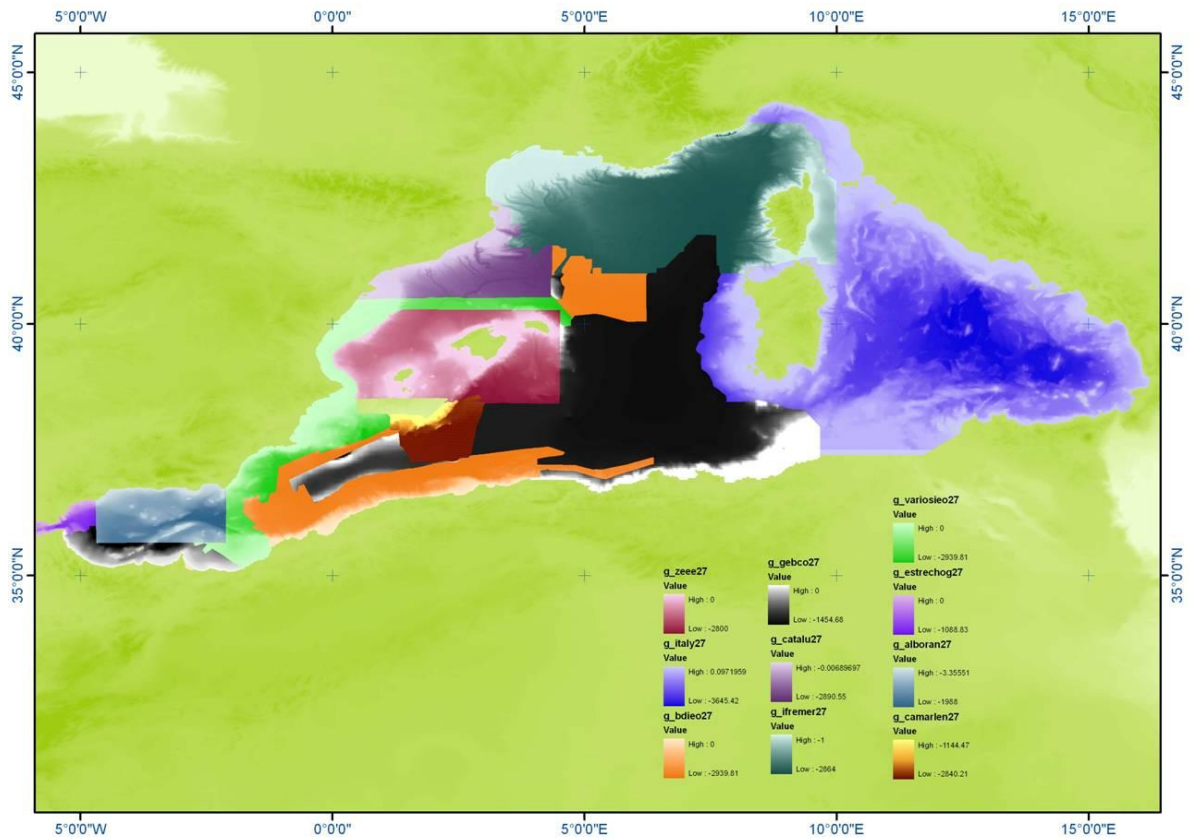


Figure 5 DTMs covering parts of the Western Mediterranean.

Nine DTMs were available for the Spanish margin and deep zones:

1. 353_291001 (Alborán Sea)
2. 353_291002 (Catalan Continental Margin)
3. 353_291003 (South of the Ibiza Island – Balearic Islands)
4. 353_291004 (South of the Formentera Island – Balearic Islands)
5. 353_291005 (Strait of Gibraltar)
6. 353_291006 (East Mediterranean Margin)
7. 353_291007 (ZEEE: Spanish Exclusive Economic Zone – Balearic Islands)
8. 353_291008 (IBCM: South Alborán Sea)
9. 353_291009 (IBCM: Deep zone of Mediterranean Sea)

One DTM covered the French margin:

10. 353_291010 (IFREMER)

Two DTMs for the Italian margin:

11. 353_291011 (Shallow water Tyrrhenian Sea)
12. 353_291012 (Deep water Tyrrhenian Sea)

The data processing has been different for each DTM, with the type of processing required determined by the data source and format of the original data.

2.3.2 Processing for the Spanish margin data

Data have been collected from several sources to prepare these DTMs. The data owners have provided data in two formats.

In most the data source was a DTM in GRID format (raster format ArcGIS, structured in a regular matrix), with the depth value associated in the centre of the cell. These DTMs have different resolutions. The process executed in this case has been:

- a) From each GRID, and ESRI™ Shapefile of points has been exported, with each point corresponding to the centre of the cell on the original GRID and having the associated the depth value of each cell.
- b) With each point Shapefile the standard ArcGIS Inverse Distance Weighting (IDW) interpolation command was applied to interpolate between the points.
- c) Several tests were made, changing the search radius and the number of points used to interpolate the new value. The number of points that produced the least error in each case was used.

In other cases the data sources were ISOBATHS with variable equidistance, in which case the process was as follows:

- a) From the polyline Shapefiles, a GRID was interpolated with the algorithms used by ArcGIS Software in the TOPOGRID command.
- b) The results depend on the distance between the ISOBATHS.

A small overlap zone occurs where different datasets meet, to avoid areas of 'no data'. Further information is given below about the data source for each grid:

1. 353_291001 – Alborán Sea

This DTM was elaborated from two GRIDs, both interpolated with the IDW method:

- 1.1 A GRID of 25 x 25 metres resolution with information about the continental shelf and slope. The depths vary between 5 and 160 metres. This information has been obtained using multibeam echo-sounder: ESPACE Project; 2000-2005; Spanish Institute of Oceanography (IEO) and Spanish Sea Secretary General (SGM).
- 1.2 A GRID of 100 x 100 metres resolution with information for depths greater than 160 metres, for the whole Alborán sea. This information has been obtained using multibeam echo-sounder: CARPEMA Project; 2002-2007; IEO-SGM.

2. 353_291002 – Catalan Continental Margin

This DTM was elaborated from three GRIDs:

- 2.1 Two GRIDS of 25 x 25 metres resolution with information about the continental shelf and slope. The depths vary between 5 and 160 metres. This information has been obtained using multibeam echo-sounder: ESPACE project; 2000-2005; IEO-SGM.

- 2.2 A GRID of 250 x 250 metres resolution provided by the University of Barcelona (Spain), Dr Miquel Canals. The GRID was interpolated from information obtained using multibeam echo-sounder.
3. 353_291003 – South of the Ibiza Island – Balearic Islands
This DTM is formed only by a GRID, interpolated with the IDW method:
- 3.1 This 200 x 200 metre resolution GRID is derived from to the multibeam information obtained in the SBAL-DEEP Project: 2005; OGS (Italy).
4. 353_291004 - South of the Formentera Island – Balearic Islands
This DTM is composed of one GRID interpolated with the IDW method:
- 4.1 The grid corresponds to the information provided for the Secretary General of Sea (Ministry of Environment of Spain), with a resolution of 100 x 100 metres, obtained using multibeam echo-sounder: Balcom Project; 2002.
5. 353_291005- Strait of Gibraltar
This DTM was elaborated from three data sources:
- 5.1 Information obtained in the TARIK surveys using single-beam echo-sounder: 1980-1992; IEO. The data source has been ISOBATHS with an equidistance of 2 metres. The grid has been obtained by the TOPOGRID command of ArcGIS.
- 5.2 Information obtained in the HERCULES survey Single Beam (1983; IEO). The data source was ISOBATHS. The GRID has been obtained by the TOPOGRID command of ArcGIS.
- 5.3 Information collected with multibeam echo-sounder during several surveys (EZA survey; LE SUROIT – 91 survey; MARGUAL survey; MARSIBAL Project) was used to produce a grid for each survey. The composite grid was interpolated with the IDW method.
6. 353_291006 – East Mediterranean Margin
This DTM was elaborated from several data source:
- 6.1 Six grids corresponding to the information obtained from isobaths with variable equidistance depending on the zone of study. The data source of these isobaths is the MARINE GIS of Spanish Institute of Oceanography. These grids have been obtained by de TOPOGRID command of ArcGIS.
- 6.2 The rest of information has been obtained with echo-sounder multibeam in several surveys, obtained a grid for each survey. The final grid has been interpolated with the IDW method.
7. 353_291007 – ZEEE: Spain Exclusive Economic Zone – Balearic Islands
This DTM was elaborated from eight different types of data sources:

7.1 Information obtained with multibeam echo-sounder in several surveys for the IHM (Marine Hydrographical Institute) and the IEO, concerning the EEZ in the margin of the Balearic Islands. The information used has been a grid of 100 x 100 metres resolution. The composite grid has been interpolated with the IDW method.

7.2 The rest of the information has been obtained from isobaths (MARIEN GIS IEO) with variable equidistance of different zones. These grids have been obtained by the TOPOGRID command of ArcGIS.

8. 353_291008 – IBCM: South Alborán Sea

8.1 This DTM is composed by one grid. The origin of this information is the IBCM database.

9. 353_291008 – IBCM: Deep zone of Mediterranean Sea

9.1 This DTM is composed by one grid. The origin of this information is the IBCM database.

In all cases, multiple tests have been made in order to use the method which would introduce least error in the result.

2.3.3 Processing for the French margin data

10. 353_291010 – IFREMER

IFREMER provided a DTM in GRID format, referenced in Mercator projection, with a resolution of 250 metres. Therefore it was not necessary to run any process of interpolation; it only has been necessary change the projection.

To make this change the original GRID from IFREMER was transformed into a GRID format in geographic coordinates, with a resolution of 0.0027 decimal degrees, according to the technical specification of the project. Two different transformation processes were tested; the method selected was the one associated with least error produced:

Method 1

- Transform the GRID data in Mercator to GRID format in geographic coordinates with the PROJECT command (ArcGIS), using as a parameter the cell size of the new raster = 0.0027 decimal degrees. PROJECT command used the nearest method to interpolate the new GRID.

Method 2

- Convert the original GRID data to a point Shapefile, where each point corresponded to the centre of each cell of the GRID. This point has the depth as the associated value.
- Next, project the point Shapefile from Mercator projection to geographic coordinates with the PROJECT command (ArcGIS).

- Finally, from the point Shapefile in geographic coordinates, an interpolation was made of new GRID with the IDW method (ArcGIS command) to obtain a resolution 0.0027. Several tests were made, and a different number of points was used to interpolate each time, which varied between 4 and 12.

After using these two methods, error estimation was made and Method 1 was shown to produce less error.

2.3.4 Italian margin data

ISPRA provided a DTM in GRID format with a resolution of 0.0027 decimal degrees, therefore was not necessary to carry out any processing. This DTM was elaborated from two different data sources.

11. 353_291011 (Shallow water Tyrrhenian Sea)

12. 353_291012 (Deep water Tyrrhenian Sea)

An error was detected in the data in the deep zone; therefore these data were replaced with the data from the morpho-bathymetry of the Mediterranean Sea: CIEMS; Medimap group; 2005.

2.3.5 Process to elaborate the DTM for the Western Mediterranean

Finally the global DTM (Figure 6) was produced from a union of all partial DTMs, with the MOSAIC command (ArcGIS Software).

- When the DTM is made from several grids with MOSAIC command of ArcGIS, the grids are adjacent with a small zone of intersection to avoid the appearance of holes.

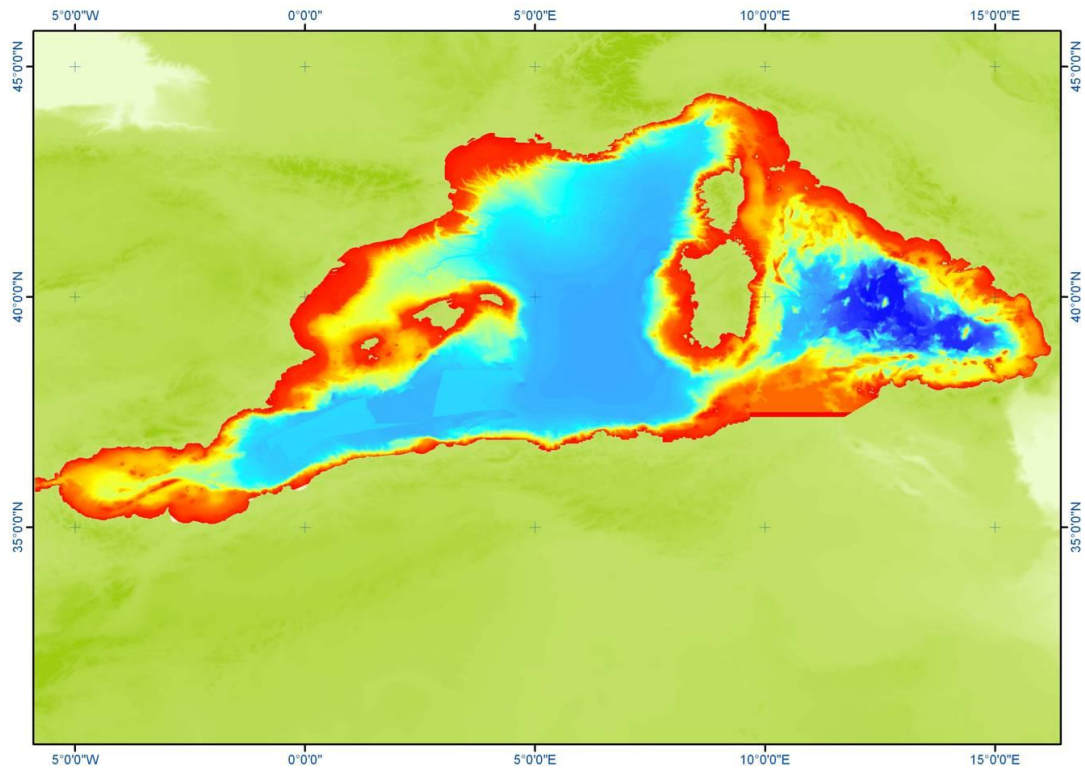


Figure 6 Final DTM for Western Mediterranean.

3 Development of thresholds

3.1 Definition of bathymetric threshold values in the North and Celtic Seas

In the current version of the EUNIS classification scheme (2007-11), the deep sea is a single biological zone, defined as areas deeper than 200m. Recent work has proposed division of the deep sea into five ecologically-relevant zones (Howell, 2010). These divisions have been applied here to increase the level of detail in the deep sea of the North and Celtic seas, towards a level of detail more comparable with that on the shelf. The zones proposed are: upper slope, upper bathyal, mid bathyal, lower bathyal, and abyssal. Howell (2010) used depth as a proxy for variation in the biological communities due to environmental conditions, such as temperature, pressure, oxygen minimum and food supply. Depth thresholds used are show in Table 1

Table 1 Depth bands applied to deep sea zones in the North and Celtic Seas.

Deep sea zones	Depth bands
Upper slope	200 – 750
Upper bathyal	750 – 1,100
Mid bathyal	1,100 – 1,800
Lower bathyal	1,800 – 2,700

3.2 Definition of bathymetric threshold values in the Western Mediterranean Sea

Bathymetry is the abiotic variable that was used to identify the threshold value to delimit the boundary between the lower circalittoral and the bathyal biological zone, and between the bathyal and the abyssal zone. In fact in both these biological zones it is the change in bottom slope angle, resulting from geological processes operating on the seafloor over time, that actually contributes to different environmental conditions influencing the formation of discreet biological communities of the bathyal and abyssal biological zones.

The deep circalittoral-bathyal boundary coincides with the margin of the continental shelf and can be identified on the basis of a change in slope angle followed by the higher slope values of the continental slope. Bibliographic information reports this break as occurring between 110-260m (Carpine, 1970) with a median value range occurring between 170-210m.

The bathyal-abyssal boundary instead coincides with a gradual change in slope angle occurring just after the base of the continental slope. Bibliographic information reports this as occurring in the depth range 2500-3000m. Given the reported heterogeneity in depth associated with both the continental shelf edge limit and the continental slope angle change, it was decided to identify these boundaries manually.

The manual identification of changes in slope angle at the seabed revealed more than one feature needing consideration for the definition of the deep circalittoral-bathyal and bathyal-abyssal boundaries. In particular, a first rupture of slope change (hereafter called 'shelf break') was observed at shallower depths than expected, and shallower than the continental shelf edge. The 'shelf edge' limit was identified for a good part of the basin but in some instances no shelf edge limit was identifiable due to the absence of a strong change in slope angle. An alternative bathyal-abyssal boundary ('bathyal basin limit') was identified in some areas, occurring at shallower depths than expected. The set of manually identified lines indicating slope angle changes and topographic features is displayed in Figure 7.

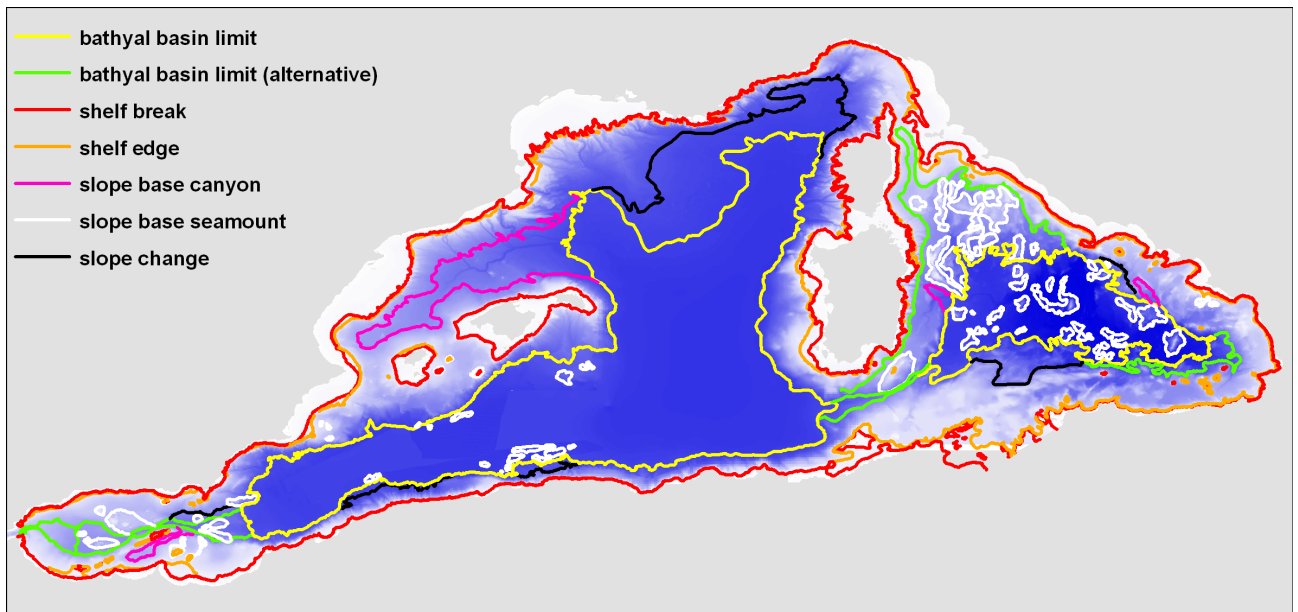


Figure 7 Seabed slope angle change observed in the western Mediterranean.

The definitions of the boundaries in Figure 7 are as follows:

Shelf break: Abrupt rupture of continental shelf.

Shelf edge: Lower limit of shelf break where the slope change is soft. Also, it can be the lower limit of a shelf with double slope rupture (this is frequent in the Tyrrhenian Sea). It usually appears around 140 to 200m.

Bathyal basin limit: Lower limit of continental margin. It is where the deepest and flat area of the basin begins. Habitually, in the sea Mediterranean Sea it is identified at 2500m (2400 to 2600m).

Bathyal basin limit (alternative): This is a limit that indicates areas where there is a strong slope change that could be the possible limit of the bathyal basin, although below this limit a part of the continental margin (very smoothed) still continues.

Slope base canyon: Lower limit of slopes of the most significant canyons or similar geomorphologic features (i.e.: Valencia Trough). It is at a shallow depth than bathyal basin limit, but it could define zones of interest for habitats.

Slope base seamount: In the Mediterranean there are a lot of seamounts and crests, especially in Tyrrhenian Sea and Alboran Sea. These features, usually, have a volcanogenic origin or they are associated with phenomena of this type. These structures appear above and below the bathyal limit. The line defines the base of geomorphologic features, which could be a single seamount or several associated seamounts.

The reason for drawing this limit is that seamounts can be areas of interest from a habitats point of view and their bathymetric ranges are not well matched to the zonation of biological zones.

Slope change: In several areas of the bathyal in the West Mediterranean basin, a change of slope has been identified that defines the border of a geomorphologic feature (scarps, accumulation of sediments, changes in lithology, slides, action of currents, etc.). This has been included as it might be of interest in the future.

The manually-drawn boundaries of the shelf break, shelf edge, and bathyal basin were analysed in order to identify the best depth values to be applied as hard thresholds for the circalittoral-bathyal and bathyal-abyssal delimitation. In order to compare the boundaries with the pixel values of the bathymetric grid it was necessary to associate an identification code to the different arcs and convert the vector feature to a raster grid having the same cell size and extension properties of the bathymetric layer. In this way a codified grid file was created. By converting this raster to points, a new shape file composed of a point for each grid cell was generated. Finally, using the spatial analyst tool “Extract Values to Points” the table associated to the point shape files was integrated with the bathymetric values. The obtained table contains both the identification code associated to the different boundaries and the relative depths.

The depth data of each limit defined by the boundaries were statistically processed in order to evaluate their distribution and to calculate the main statistical parameters which are summarised in Table 2. In a first instance, the statistical analysis was intended to compare the different depth values obtainable from each data set so as to determine a unique depth threshold value and respective fuzzy values that could be used for the creation of a biological zone confidence map. However, after various considerations and trials it was clear that the great heterogeneity observed in the depth values was indicative of the high heterogeneity of oceanographic-tectonic forces which over time have exerted their forces over the seabed morphology of the Mediterranean. It therefore became clear that the biological zone limitations should take into as much account as possible the seabed slope angle changes that were visually observable in the DTM model and that a statistical analysis of the depth range values and frequencies be used to confirm the suitability or integration of the identified boundaries. Hard limits for each of the biological zone limits were therefore sought and a decision was made to avoid using any fuzzy value for such limits.

Table 2 Main statistical parameters of the depth data.

	Count	Mean	Median	Min	Max	LQ	UQ	Pct10	Pct90	SD
Shelf edge	32960	220	212	798	0	246	187	285	154	71
Shelf break	35912	126	115	738	0	133	100	157	76	69
S. edge + S. break	46812	188	194	798	0	231	126	269	94	82
Bathyal basin	29257	2705	2675	3584	1359	2748	2544	3194	2423	285
Bathyal basin alternative	9123	1476	1260	3016	418	2080	869	2630	760	710
Bathyal + alternative	34316	2568	2638	3584	1061	2731	2450	3124	1950	440

3.2.1 Defining deep circalittoral-bathyal limit

Three different boundary datasets were analysed for the identification the deep circalittoral-bathyal boundary:

a) shelf edge

b) shelf break

c) shelf edge + shelf break (includes the shelf edge limit data integrated with the shelf break depth data for those areas where the shelf edge limit was missing)

Figure 8, Figure 9 and Figure 10 show the frequency histogram of the depth values of these respective data sets.

Figure 8 shows that the depth value distribution of the manually identified shelf edge appears relatively normal and very few occurrences can be observed for values < 100m. Even if the distribution is slightly skewed with a robust number of occurrences > 350m, the main parts of the data are included in the central part of the graph thereby indicating the suitability to use the median value in cases in which the shelf edge limit is not easily identifiable.

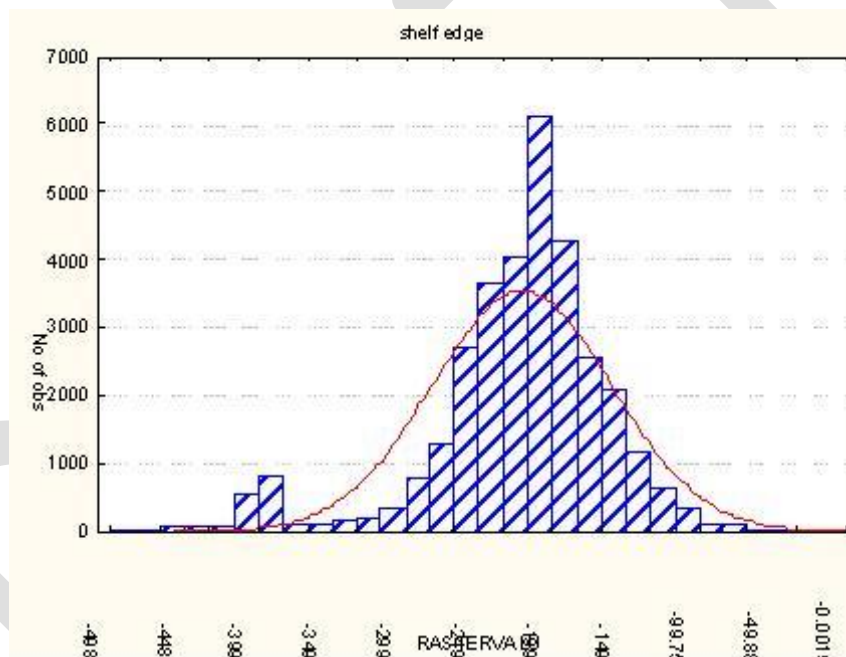


Figure 8 Frequency histogram of the shelf edge.

The frequency histogram estimated using only the depth extracted in correspondence of the shelf break limit (Figure 9) highlights the presence of a very high number of occurrences < -100 which are unusual for the definition of the deep circa /bathyal limit. A closer look at these shallow water data values indicated in fact that they are localised principally along the North African coasts and that this observed shelf break is mostly likely to be an artefact influenced by the poor bathymetric detail available for this geographic area. Nevertheless, the depth values of the principal part of the shelf break histogram (median = 115; mean =126) are also linked to areas where a sharp change in sea bottom slope creates a shelf break at shallower depths than those where a shelf edge is subsequently observed in the very same given area. These shelf break bathymetric values are in any case lower than the depth values of the circalittoral limit as defined in bibliography and as such the shelf break

dataset observed is to be considered with caution with respect to its suitability to indicate the lower limit of the circalittoral zone.

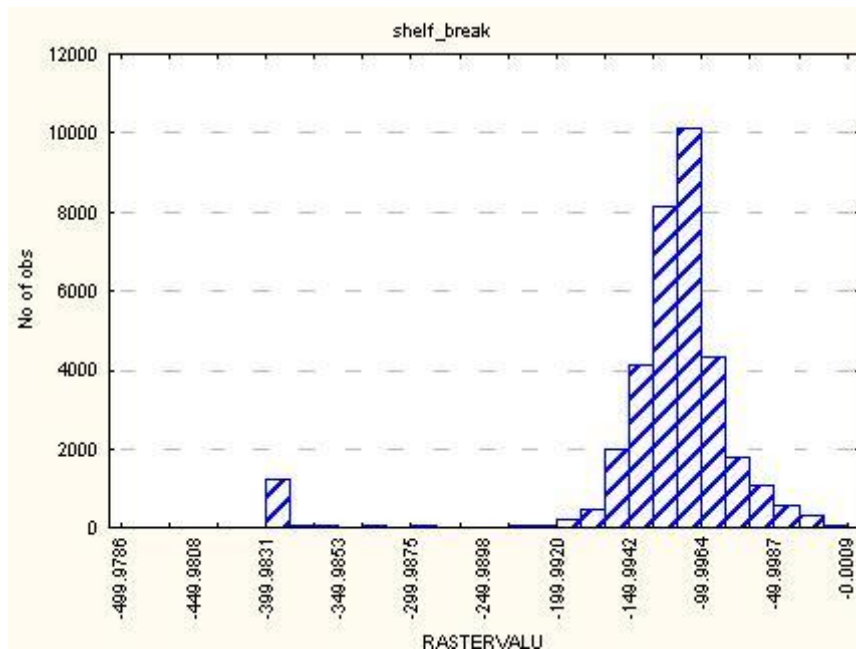


Figure 9 Frequency histogram of the shelf break.

The frequency histogram of the shelf edge + shelf break depth data (Figure 10) shows a more complex distribution in which two different frequency peaks are observed. A first peak consisting in a low depth value dataset is mainly due to the high number of pixels extracted in correspondence of the North Africans coasts where the shelf edge was not identified.

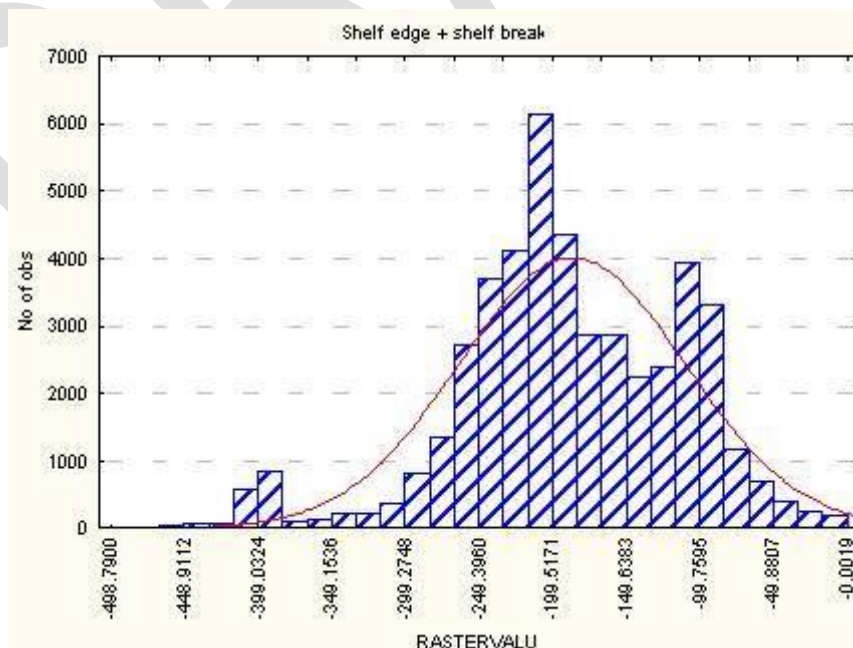


Figure 10 Frequency histogram of the shelf edge and the shelf break datasets combined.

The statistical parameters (Table 2) obtained for the shelf edge and shelf edge + shelf break depth data appear similar. In contrast, the statistical parameters of the shelf break are totally different showing values significantly lower than the other two datasets. A general comment is the unexpected maximum values observed in all three datasets as being 0. This suggests the presence of some likely artefact deriving from how the bathymetric layer was used to identify the first change in bottom slope angle (i.e. if the change in bottom slope angle is detected in cells having a bathymetric value of 0-100 this should not biologically-speaking be considered indicative of a circalittoral habitat). The error is therefore probably due to an artefact probably generated both by the interpolation and the cell size.

The depth frequency histograms and the statistical parameters suggest that the shelf break dataset could be affected by some data interpretation errors due maybe to the original quality of the bathymetry and it therefore seemed inappropriate to use the shelf break isoline or its statistical parameters as deep circa/bathyal thresholds. Moreover, when the shelf break data was integrated with the shelf edge dataset, though the statistical results of this dataset gave similar values to the statistical values of only the shelf edge dataset, the frequency histogram of both datasets combined revealed the presence of two peaks derived from a minor number of depth records indicating the presence of a shelf break at underestimated depths. In light of both the statistical parameters as well as what is known from bibliography about the depth range at which the circalittoral lower limit occurs (range 110m-260m with 170m-210m as optimum central values), the estimated statistical values derived from the analysis of the shelf edge dataset seemed to confirm the validity of the manually identified shelf edge line and its suitability to define the boundary between circalittoral and bathyal zone.

One problem needing resolution however was how to define the shelf edge limit for those areas for which the shelf edge limit was visibly not identifiable (either due to poor bathymetric data such as in the north African coasts or in cases where the shelf edge limit is marked by a slope angle change that is too soft to be picked up by manual inspection). Two possible solutions were hypothesized:

- a) usage of the visually observed shelf break line
- b) usage of the statistical median value (212m) obtained from the analysis of the shelf edge dataset where the shelf edge line was not visually identifiable

Both approaches were tested and the resulting circalittoral boundaries were compared to known circalittoral / bathyal habitat maps to verify which one best defined the circalittoral boundary.

The application of these two approaches produced a habitat map of the Western Mediterranean having 68776 pixels that were attributed to different biozones. The application of the approach using the shelf edge line integrated with shelf break line produced a modelled map output, for some areas, where the infralittoral merged directly into the bathyal zone in a manner that appeared too abrupt and unacceptable from a benthic zonation point of view. Moreover, if one compares sub areas modelled using the two different approaches, the passage from one biological zone to another occurs at resulting depth values that are not coherent with the depth values described in literature for the biological zones. Figure 5 clearly indicates this flaw. In particular Figure 11a shows how

the first approach yielded areas in which the modelled infralittoral zone merged directly into the bathyal zone at shallow depth values of 74-97 metres whereas in Figure 11b, the usage of the median shelf edge depth value (212m) allows to model a wider zone of deep circalittoral habitat and the resulting bathyal zone begins at depth ranges >200 metres.

The circalittoral boundaries obtained with the two approaches were also tested by comparing the modelled output map with known mapped biocenotic circalittoral habitats available for the Tuscan Archipelago in Italy where the shelf edge and shelf break approach yielded 1131 pixels attributed to habitats other than the circalittoral. When these pixels were compared with the available biocenotic maps it was found that all of them belonged to habitats proper to the circalittoral (1% coastal terrigenous muds, 66 % Muddy detritic / Shelf-edge detritic bottoms, 33% coastal detritic). In light of all of the above it was therefore decided that the circalittoral / bathyal boundary utilised in the modelled habitat map be the shelf edge line integrated with the 212m median value for those areas where the shelf edge limit had not been visually identified.

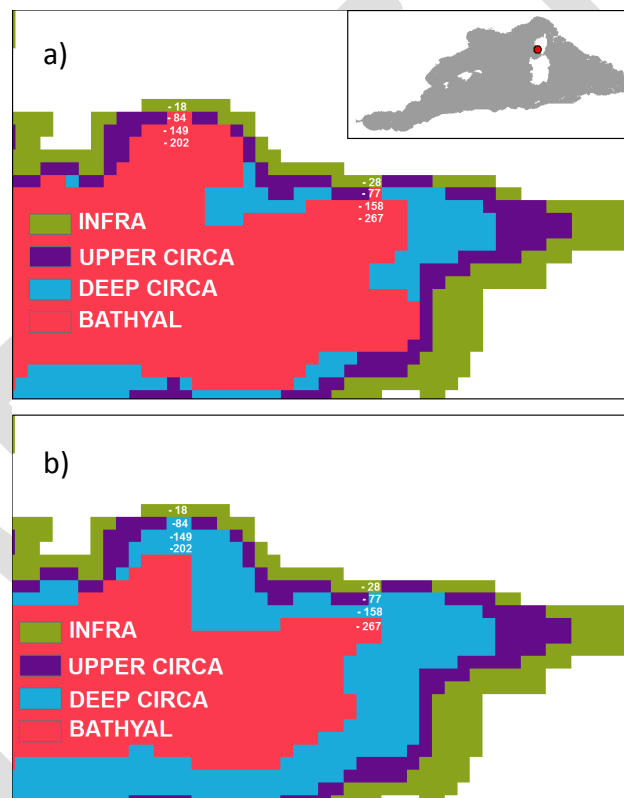


Figure 11 Comparison of the application using the shelf edge line integrated with the shelf break line(a) and the shelf edge line integrated with the median value of 212m (b) in an area of south-western Corsica.

Defining the limit between bathyal / abyssal zones

The second group of features (Bathyal basin, Bathyal basin alternative and the combined Bathyal + alternative) that define the bathyal basin were used to analyse the depth values observed in the changes in slope angle occurring at the base of the continental margin. The combined Bathyal + Bathyal alternative layer was created by adding some arcs of the original alternative bathyal to the bathyal basin for the area of the Alboran Sea and in the area lying between the southern part of Sardinia and northern Tunisia/Sicily (Figure 12).

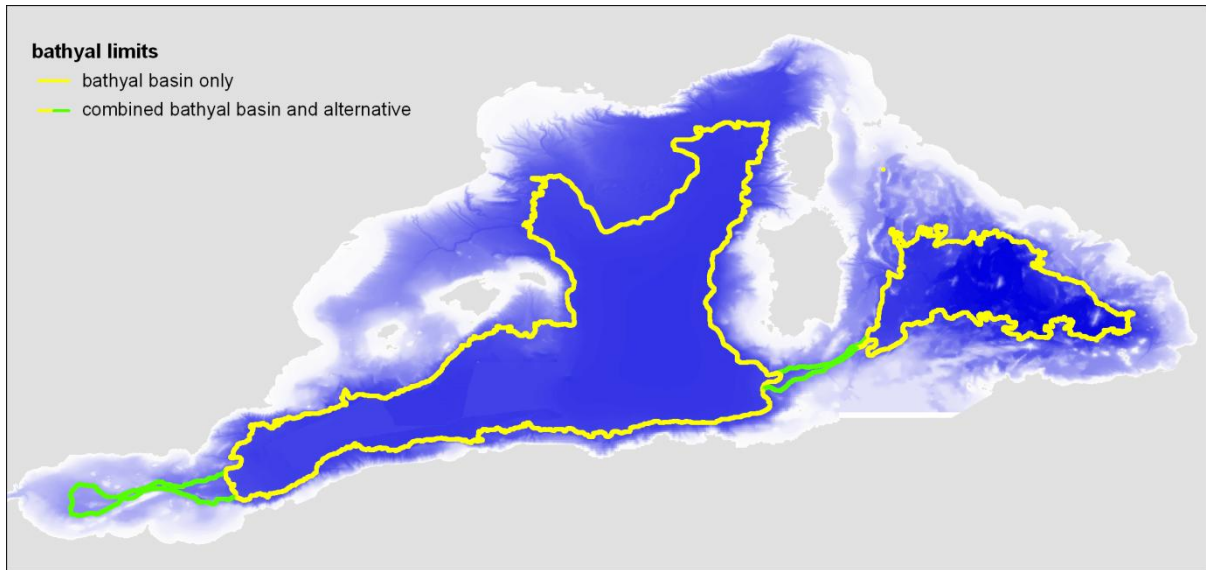


Figure 12 Identified bathyal basin limits and alternative basin limit occurring at shallower depths.

The frequency diagrams of these two datasets (Figure 13) shows a similar disperse distribution trend for the depth values between the two datasets though the bathyal basin + bathyal alternative dataset yields a more dispersed distribution in the shallower end of the bathymetric interval due to the fact that the bathyal alternative basin limit was observed in areas where the continental slope seabed angle starts changing at shallower depths than in the rest of the Mediterranean. Even though the peak depth range observed for the end of the bathyal zone lies mostly around the 2500-2600m range the histograms confirm a vast heterogeneity in depth values in which the seabed slope changes and which is a result of the different oceanographic-tectonic conditions that have operated through time on the evolution of the Mediterranean seabed. The bathyal basin alternative line identified in the Alboran sea was not considered to be effectively indicative of a real bathyal basin due to the oceanographic features of the Alboran sea. To this effect, the bathyal/abyssal limit that was used for the purpose of the modelling is that generated by the visual detection of the bathyal basin integrated with the bathyal basin alternative identified in the Sardinian – Sicilian – Tunisian area.

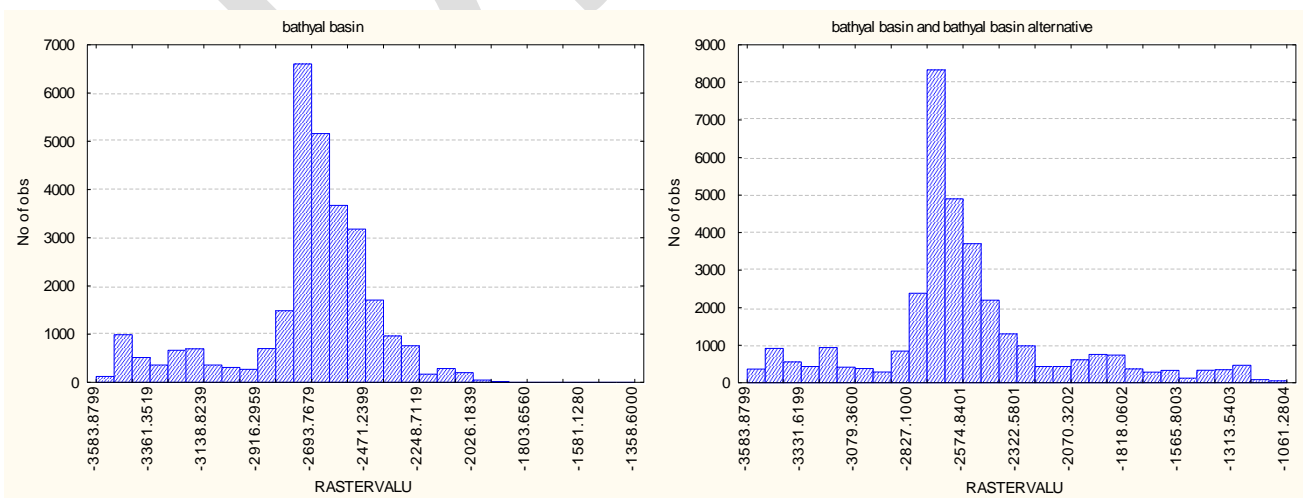


Figure 13 Frequency histogram of the bathyal basin and bathyal basin + bathyal basin alternative.

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EUSeaMap

Technical Report No. X

Confidence

DRAFT

Assessment of the EUSeaMap global modelled map

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Introduction

There are basically two ways of considering the assessment of the EUSeaMap modelled map. As the resultant map is no more than a combination of source layers, one straightforward way is to assess the confidence of the broad-scale physical data layers that form the basis of the Eunis model and compute a weighted sum of the scores. This “internal assessment” can go from local to regional depending on the method used. Methods that could provide an assessment on each pixel would likely be deemed the best ones but their output would be a map at the same resolution as the modelled map itself, hence potentially difficult for users to read if they varied too much locally. Other methods of assessing at regional level (per blocks of data, as e.g. is the case in nautical chart showing origins of soundings) would be of easier use albeit less precisely informative.

A second aspect of internal confidence is that associated with thresholds. Even in the case where we would have highly reliable layers, the relevance of a given threshold (an amount of light or energy at the seabed) is questionable as it is at best founded on approximate field data. Therefore it is advisable to associate a fuzzy area around a sharp limit between two categories.

The other possible way (or “external assessment”) is statistical. Based on local checks carried out against external data, it would yield what is referred to in land use mapping as a “contingency matrix”, simply a global score for the whole map. Depending of the amount of ground truth data available, it could also be regionalised, i.e. computed per basin (or even sub-basin). Along with the internal assessment it could then bring an additional insight into the quality of the modelled map.

1. Assessing base data layers

This kind of assessment is either local if each pixel of each layer is assessed for the modelled area or regional when assessing base layers per regional data blocks and intersecting them.

1.1 Pixel-based assessment of input layers

The former method is the most thorough and precise, yet complex method. It is described in detail in the ABPMer- coordinated study lead for UK Defra “Assessing the confidence of broad-scale classification maps”. The uncertainty of each data layer

(biological zone, substrate and energy) is assessed using a combination of three types of uncertainty: measurement error, processing error and natural variability. A probability of occurrence is computed for each parameter at each location. These probabilities are then multiplied and the result subtracted to one to yield a total probability.

The EuSeaMap could have decided to go for such an assessment, however two difficulties arose:

- the fact that data layers were generated by a number of different teams (actually at least the seven teams associated in the project, not to mention sub-contractors), hence a need for a comprehensive investigation on the methods employed and substantial uncertainty in obtaining reliable results,
- the associated costs were likely to be high, as it was necessary to hire experts of each data layer, preferably those who have computed them.

Yet the advantage of this method is its fully spatial aspect, which would lead to a reliability map at the same scale as the modelled map with assessment provided for each pixel, in line with EuSeaMap requirements. It would also enable the project to give feedback on physical layers to their providers, a condition of future improved deliveries.

However, given the above difficulties, this method was not deemed feasible within the EuSeamap frame but could be recommended for a later version.

1.2 Global assessment as a weighted sum of regional scores

1.2.1 Assessing the sediment layer

The global sediment layer is mostly historical, a result of the compilation of vintage maps made prior to the “acoustic era” with polygons drafted based on mere sample contents. Recent acoustic surveys have shown to which extent these maps gave a coarse view of the seabed reality, hence an urgent need to be quality assessed. In some cases, small size maps made from surveys are also incorporated to the final assemblage, hence The assessment of the vector substrate layer can inspire from the Mesh habitat map confidence assessment and be made per individual map. Basically the ways a substrate map and a habitat map are produced are quite similar and the method implemented in Mesh for habitat maps can easily be adapted to sediment maps.

Three types of parameters were considered (Annex 1):

- five parameters qualifying the remote sensing surveys
- six parameters qualifying the collection of field data
- another four parameters accounting for the quality of the map making process.

In Mesh these amounted to 15 individual scores which were then summarised into a final weighted sum. Most of these items hold true in the case of a sediment map except the one describing biological field data collection. A closer look could also be given to the interpretation section as to whether the four parameters are free of redundancy. The final score is a percentage. Typically low resolution vintage maps assessed with this method get scores in the range of 50 to 65%.

1.2.2 The Emodnet lots

It is noteworthy that the Emodnet project requires that each lot provides an accuracy assessment of its delivered layers. Two lots are of relevance to the EuSeaMap habitat map, namely bathymetry and geology (seabed substratum). However the geographic gaps between the lots are a drawback (e.g. there is no Emodnet substrate layer for the

Mediterranean as yet). Besides, the assessment of both the biological zones and the energy layers is not in their remits and thus rests fully with EuSeaMap. The geology lot is currently looking at a polygon-based assessment, whereby the map assessment methodology designed by Mesh is taken down to polygon level to express the confidence of the polygon content. This represents an intermediate way not as reliable as the full spatial pixel-based method but still yielding more detail than just using global scores as attempted here.

1.2.3 Assessing the depth zone layer

The depth zone layer is complex as each zone is made by intersecting different variables.

- a) Definitions of the the infralittoral and upper circalittoral zones (the latter for the Mediterranean only) are based on the interaction between depth and respectively 1% and 0.01% of incident light. The light parameter K_{par} is computed with an algorithm consistent over the whole of western Europe so no distinction can be made between locations. The accuracy with which this K_{par} value is determined is bound to be fairly constant except in shallow waters where it is biased because of bottom reflection, yet with no consequence since these shallow waters are by definition infralittoral. Therefore as a simplification we can consider that the depth value is the main factor affecting confidence - at least in relative terms - on the determination of these two zones.
- b) The Atlantic upper circalittoral is based on the wave base, itself the limit of wave-induced bottom disturbance computed using statistics from wave models. Similarly we have no way of simply assessing the accuracy of these statistics and are therefore reduced to consider them as consistent over the whole study area. The computation of the wave base was made using Gebco low resolution depth values, another data layer whose reliability is quite difficult to inform. Unless we use probabilities based on model computations we have no grip on the reliability of such individual layers.
- c) The Mediterranean lower limit of the lower circalittoral zone is defined as the “shelf break line”, a sharper slope value located in the 120-180m range. Likewise the lower bathyal limit is the depth break line at the foot of the continental slope. In the Atlantic the lower circalittoral is more simply limited by the 200m depth line. These boundaries are directly affected by the quality of the underlying bathymetry so as a first approximation we could use a depth quality index to summarize the confidence on depth zones.

To summarise points a) to c), it appears that bathymetry is the only variable common to depth zones that could bear a criterion of quality.

1.2.4 Assessing the energy layer

We have no knowledge on the reliability of energy computed from hydrodynamical models of waves and currents, let alone on their statistical combination at the seabed. One very global way of assessing the energy would be to rank the fineness of these models, in fist approximation their resolution. When looking at this on the French part of the Channel, we actually have three types of models for currents (Rivier, 2010) going from the more offshore model with 2km resolution to coastal models with either 200m resolution at best . However let's summarise the role of energy in our modelling. In the Atlantic wave data (wave length) are used for the low limit of the upper circalittoral zone (not the case in the Mediterranean). Currents and wave data ought to be used for rocky substrates in all basins but in the Mediterranean this had to be given up due to the coarseness of wave models close to the coast.

As a conclusion, given the relatively moderate role of energy data in the modelling, assessing the confidence in energy layers would remain marginal in an overall assessment. To lessen the contribution of this factor, we can also consider the quality of energy data as being reflected by that of the bathymetry.

1.2.5 Assessing the bathymetry

Resolution and data density

These are two different factors indeed and theoretically resolution should reflect data density. However it may happen that high resolution has been achieved even with low density data. The best way to account for this would be to have access to data density at each cell but this is beyond the scope of this assessment and left to deal with by the Emodnet hydrography lot.

To deal with quality assessment in more simple and feasible terms, we take it for granted DTM providers have appropriately adapted their cell size to the mean density of their cloud of points. Of course this assumption is likely to be false in places with lower density data but at our level we accept this fact and deem resolution does account for data density altogether. Therefore as a first approximation we are going to consider the resolution of individual DTMs as the leading factor.

We suggest to adopt:

- for hectometric resolution : score 1
- for 500m range resolution : score 2
- for kilometric resolution : score 3

Vintage

Usually individual DTMs are made using a variety of data sources and even though the adopted resolution is assumed to be representative of them all, it is important to take account of data vintage (as is shown for example in the cartouche of nautical charts). This criterion is most important for soft bottom that change over time and probably of less relevance on hard bottom. It is common to see historical soundings collected over a century ago be collated along with more recent data to produce a DTM. According to practise it seems reasonable to split data age in three categories.

We suggest to adopt:

- before 1945 : score 1
- 1945 to 1980 : score 2
- 1980 to present day : score 3

Origin of data

What is relevant here is not the primary origin of data but that of actual data used to build the DTMs.

The most common source of data is from individual soundings and many local DTM have used certified digital bathymetry fair sheets. These soundings were collected in the old days with a lead line until the advent of single beam sounder. It would be very difficult to assess the quality of such data in great detail, as even very old lead data at the coast can be quite accurate. It is sufficient to say these data have been used by hydrographic surveys to produce their nautical charts and as such are guaranteed. Swath systems (e.g. multibeam) used in modern hydrography are recognised of highest

quality. Associated with recent positioning techniques they provide highly relevant DTMs, even away from the coast.

In cases where the bathymetry fair sheets are not available an alternative solution is to pick out soundings from map values (points or isolines). In this case depth data are biased and of lesser quality.

To summarise we suggest to adopt:

- multibeam : score 3
- survey data (fair sheets) : score 2
- map data : score 1

The three factors above are reasonably decorrelated and even though they do not account for the full variety of depth data types and DTM processing modes, they can be taken as a first approach to measuring confidence.

Table 1: Example of scoring for French bathymetry maps

Depth data outline	Data set name	DTM resolution KM : 1 500m : 2 100m : 3	Vintage Y<1945: 1 1945<Y<1980 : 2 Y>1980 : 3	Data origin Chart values : 1 Fair sheets : 2 Multibeam : 3	Total depth score (DS)
Frame 1	1/10000 digital minute (Cap d'Agde)	3	2	2	7
Frame 2	Multibeam French EEZ	2	3	3	8
.....					
Frame n					

**Further
consi**

derations

A deeper insight into confidence would imply looking at how some of the DTMs were produced. Basically depth data come two from types of sounding tools. In the case of full coverage multibeam data, DTM reliability is very high at all locations and can be considered homogeneous. In the case of single beam sounders, as data density varies dramatically in the two directions within a single fair sheet, the quality of depth determination is commensurate to the interpolation quality (i.e. the interpolation error, easily obtainable for each pixel from advanced algorithms such as kriging). When such an error is available from the map producer, we can obtain a true spatial confidence assessment with a high spatial resolution.

1.3 Scoring maps in the Mediterranean basin

1.3.1 Sediment maps

Sediment maps come from many sources, as was illustrated by the report section on source data layers. For example on the French Mediterranean coasts four types of maps are concerned a) the Lima project sediment maps for Corsica at scale 1/100000, the “G series” maps from SHOM at scale 1/50000, the BRGM series for the PACA region at scale 1/50000 and the sediment map of the Golfe du Lion from the University of Perpignan (scale 1/250000). These maps originally all featured different classifications as adopted by their authors.

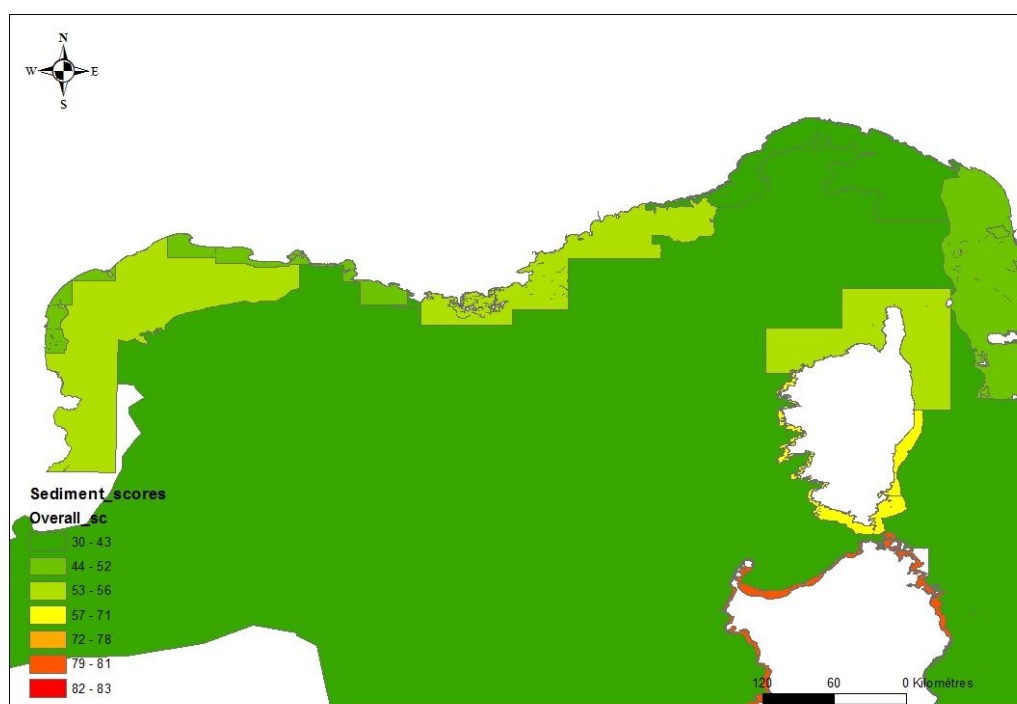


Figure 1: Scores of sediment maps for northern part of western Mediterranean.

1.3.2 Bathymetry maps

The EuSeaMap depth data in the Mediterranean come basically from three sources.

a) Participating countries have their own bathymetric DTMs built from local data sets. These are usually limited to continental platforms and in the case of steep shelves have a limited extension seaward. The original resolution of these data was usually higher than EuSeaMap's current resolution of 250m and therefore several pixels or soundings may have been averaged in 250m cells.

b) Further offshore a compilation of Mediterranean depth data is available from CIESM, with a current resolution of 500m. All of these were obtained from recent multibeam surveys, so their quality is homogeneous throughout the map.

c) In the centre of the basin and Tyrrhenian Sea, the default bathymetry is from Gebco (1 km resolution).

The simplest way to go about confidence would be to consider resolution as the key quality flag for each block of data, however this could be over-simplistic.

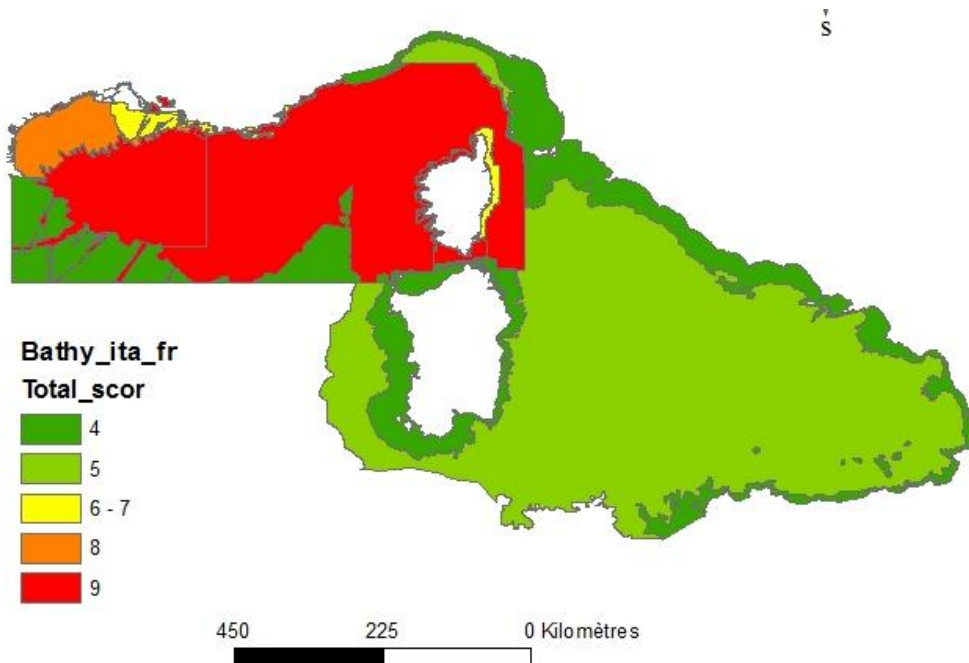


Figure 2: Scores of bathymetry maps for Italy and France.

1.3.3 Overall assessment: a weighted sum

Let DS and SS be respectively the bathymetry and substrate scores. The DS range is from 0 to 9 while the SS range is theoretically 0-100%. However even the highest quality substrate maps will never reach 100% (more currently 80%), so there may be a need to normalize these two values.

We suggest to apply the following formula to reach the final score:

$$FS (\%) = 0.5 [(8.3DS+5.1) + 100 SS] / 100$$

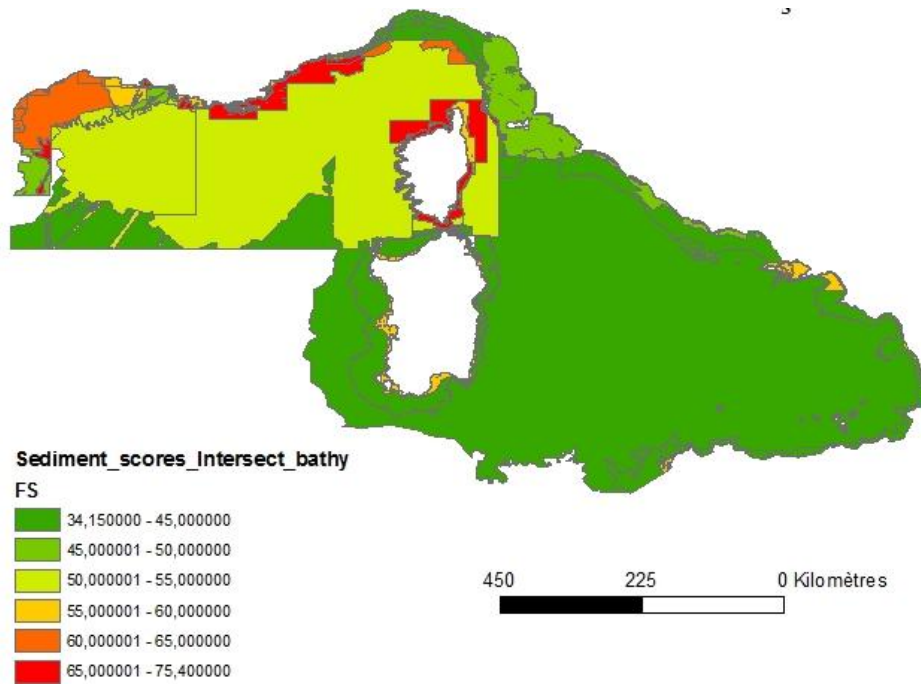


Figure 3: Global score for Italy and France.

2. Assessment of modelled maps versus recent habitat maps

2.1 The contingency matrix

The second way of assessing the EUSeaMap is referred to as an “external check” and is carried out by building a contingency matrix, i.e. a matrix with modelled data in one dimension and surveyed data from recent local habitat maps in the other.

Référence historique à la TD.

	Nephtys	Ophiura	Kelp	Faunal turf	Ophithrix
Nephtys	78	8	0	0	0
Ophiura	5	54	0	0	0
Kelp	0	0	8	0	0
Faunal turf	0	2	0	16	2
Ophithrix	0	0	0	1	18
% accuracy				90.6	
Kappa				0.89	

Figure 4: Example of contingency matrix (Mesh, 2008).

In our case, we have to make sure the assessment is significant, in other words that we are comparing comparable objects. In land use mapping polygons resulted from a classification of imagery, whereas here we are considering modelled polygons.

Despite being of somewhat different nature, ground truth points and modelled polygons are both classified according to Eunis, however they are a number of reasons why they are likely to depart which need to be detailed before proceeding to a comparison.

2.2 Main features of benthic ground truth data

Ground truth data is a description of the habitats expressed at the locations of the seabed samples or observations used to interpret the acoustic imagery of the seabed. These can be of several types, either observations (still camera, video) or samples (grab, trawl).

On rocky substrates, only the former can be used but this type of seabed is seldom investigated which results in little knowledge of them. When observations were indeed made and could provide a Eunis level 4 description (biological communities present on the substrate), it would be useless for us as what we need is level 3 with the description of energy at the seabed. In this case the comparison would not possibly go beyond level 2.

The latter type of ground truthing by sampling the sediment lends itself to the analysis of both the sediment grain size and the endofauna. From there authors describe the seabed in categories which at best are Eunis-labelled or otherwise remain in the author's classification. When translated these descriptions reach Eunis level 5 or possibly 6. However it may happen biologists do not describe the depth zone because they have no knowledge of it other than their measure of the depth and because the biology does not express it at all times, some sorts of endofauna being found irrespective of depth zones. This prevents the subsequent translation to Eunis and these types of sample data cannot be used.

2.3 Main features of the EUSeaMap modelled map

Likewise we need to summarise the main Eunis features of the EUSeaMap.

Substrate types come from historic sediment maps made by interpolating polygons from sample data. Therefore while being fully Eunis-compliant, these polygons have limited reliability away from the samples having defined them, leading to a potentially high discrepancy between the modelled map and the surveyed map.

Depth zones are defined from physical data layers (depth gradient, light, energy at the seabed) which do have a relation to the biology by virtue of proper thresholding but are not a direct expression of a biological content.

Energy at the seabed is a result of combining currents and waves statistical data which are also thresholded according to biological knowledge to ensure maximum relevance.

These three features when combined provide a Eunis level 3 map of the seabed. Note that in the relevance of seabed energy on hard substrate in the Mediterranean could not be established at the project's resolution.

2.4 Choice of ground truth samples

Ground truth samples are best chosen from recent surveys where their authors have translated them to a Eunis code. This is the most reliable case and the comparison will be as far as possible based on such points. In UK a large number of widespread Eunis benthic samples are available which makes the comparison fully relevant for the Celtic and North Seas. In the Mediterranean only a limited number of Italian points are currently available. The Baltic is more of a problem since benthos samples there are usually not Eunis-labelled.

Another way of running the comparison when actual survey samples are not available is to select polygons centroids from recent biocenosis maps. However this degrades the quality of the reference data and is likely to make the comparison more hazardous. For these points the Eunis class was summarised to level 2 for rocky substrate and level 3 for soft bottom using a point to polygon spatial link.

2.5 Results and discussion

The comparison has been run over each basin in a stepwise way. The first step was to select only survey points and check they were in sufficient numbers to allow reliable statistics. Otherwise polygons centroids were added to the point file to make it larger and hence significant.

The second step was to carry out comparisons separately for rocky and soft substrate points. As has been explained above, on the former the comparison can only be run to Eunis level 2, whereas on the latter it is possible to level 3. Again, the cardinal number of the comparison points should be checked to provide reliable statistics.

Two scores were therefore produced that were subsequently added together by a weighted sum.

MORE

3. Conclusion - Overall assessment

We do not provide here an off-the-shelf method to assess the confidence of our modelled map but rather a suite of tools to advise the user of the map of its potential limitations. Quite often users take the content of a map for granted. While it can be done with high reliability for surveyed maps, it is not the case here mainly owing to the fact we used available historic data sources whose quality is very hard to appraise. The so called “external validation” also has obvious limitations because of the largely different nature of the modelled map on one hand and the individual samples on the other.

As was explained above, further to an insight into the quality of the individual layers there is a need to consider all boundaries between categories with caution since sharp boundaries are quite rare in nature. This is the reason why a third method for quality assessment was developed by building fuzzy limits around sharp boundaries to qualifying the uncertainty of their positions.

These views are tricky to reconcile. Rather, we advise the users to consult each of these “confidence layers” for its own right in order to make up their minds as best they can. On

paper this would certainly be irksome, however today's webGIS capabilities offer this capability at no extra cost. It is planned in this contract to make available for each pixel of the modelled map the quality values found in the underlying layers.

4. References

ABP Mer report
Mesh confidence assessment
Emodnet geology document
Rivier, 2010

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EUSEaMap

Technical Report No. X

Energy data and thresholds

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1 Introduction

Energy exerted on the seabed can be characterised in a variety of ways that account for effects due to waves or tidal currents, or their combined effects. For example, waves can be characterised by their height, period, or orbital velocity of water particles that varies with depth. Currents can be characterised by measures such as tidal current magnitude or kinetic energy over a tidal cycle. One variable common in ocean modelling to capture the effects of both waves and tides and also their combined effect on the seabed is bed shear stress. Bed shear stress is a measure of the force exerted by waves and/or currents on sediments by the water movement over the seabed.

Comment [AC1]: Remove/reword since we don't use bed shear stress.

Energy regimes resulting from wave action and tidal currents have similar, but not always the same, effects on biological community character. Their relative importance varies significantly from one place to another, being quite different in a macrotidal¹ system such as the Channel compared to wind-dominated areas such as the Western Mediterranean. In coastal areas, the two variables typically work together; their separate effects are often difficult to distinguish and for simplicity they are combined for application in the EUNIS classification scheme.

Energy layers were calculated for the North and Celtic Seas, the western Mediterranean Sea and the Baltic Sea. For the North and Celtic Seas and the western Mediterranean Sea, kinetic energy models at the seabed were calculated for waves and currents. For the Mediterranean Sea bed shear stress was also calculated. For the Baltic Sea significant wave height and SWM (simplified wave model) layers were calculated and combined into a seamless layer in which significant wave height was recalculated to corresponding SWM values. This approach is necessary in the Baltic Sea since wave exposure can vary at a small spatial scale in coastal areas with a complex coastline, particularly archipelagos, in a way that is poorly described by large-scale oceanographic models.

Biologically relevant thresholds for energy were defined for the North and Celtic Seas and the Baltic Sea. Thresholds for energy regimes in the Mediterranean Sea were not defined since it was not possible to discriminate different energy levels associated to the habitat types. For the Baltic Sea two energy thresholds were defined; between high and moderate wave exposure and between moderate and low wave exposure. **Comment: Information about thresholds for the North and Celtic Seas to be added by JNCC.**

¹ In macrotidal areas the difference between mean high water springs and mean low water springs is between 4m and 6m.

2 Data layer preparation

2.1 North and Celtic Seas

Two layers were developed for the North and Celtic Seas, kinetic energy at the seabed due to waves and currents.

The EMODNET bathymetry data set was used as the primary bathymetry source; this data was merged with SeaZone data captured in the coastal wave models. The resolution of the EMODNET bathymetry is 0.0020833°. GEBCO data has also been used to cover those areas lying outside the extent of the SeaZone and EMODNET data coverage. Figure X shows the bathymetry coverage for the whole model area.

2.1.1 Kinetic energy model for waves – North and Celtic Seas

The primary source of wave data is from the 12km resolution ProWAM model, which covers the area 48°07'N to 62°53'N and 11°50'W to 12°50'E. Beyond the western limit of the ProWAM model, the water depths are greater than 150m and consequently, the seabed KE term due to waves will be comparatively small. In MB102 (ABPmer 2010), wave disturbance probability calculations were extended beyond the limit of ProWAM, as far as 24°W, by inferring comparable values of wave period from the NOAA product Wavewatch III. A similar approach has been applied to wave heights in areas beyond the limit of ProWAM, leading to an estimate of the seabed wave KE in those regions. In coastal areas along the European coastline and in particular the Kattegat Sea interpolated wave heights were adjusted to take account of breaking in shallow water. In all places where wave height is greater than $0.8 * \text{Water Depth}$, wave height was reduced to $0.8 * \text{Water Depth}$. This adjustment compensated for the lack of wave breaking which would have occurred if a local scale wave model had been used.

2.1.2 Kinetic energy model for currents – North and Celtic Seas

The National Oceanographic Centre (NOC) High Resolution Continental Shelf Model (CS20) has been used wherever possible, followed by the Continental Shelf Model (CS3/CS3X). For those parts of the project area not covered by either of these two models, information has been obtained from the North East Atlantic (NEA) model.

2.2 Western Mediterranean Sea

In the northern part of the western Mediterranean basin (roughly north of Balearic Islands) an energy model was built on PREVIMER² wave and current models (WAVEWATCH III at resolution of 10km and MENOR model at 1km respectively). The Mediterranean model was run at a time step of three hours for a period of three years (2001 and 2007-2009). Methods used to combine the effects of waves and currents for bed shear stress were based on Soulsby (1997). 90 percentile of the maximum bed shear stress is shown in figure 1. The energy layers developed for the Mediterranean

² PREVIMER Coastal observations and forecasts www.previmer.org

were eventually not used in the seabed habitat model after threshold analysis showed that the models were too coarse and there were insufficient field biological data available to be able to classify energy regimes in the Mediterranean (section 3.2).

The interactions between waves and current are non-linear. Soulsby, 1997:

$$\tau_m = \tau_c \left[1 + 1.2 \left(\frac{\tau_w}{\tau_w + \tau_c} \right)^{3.2} \right]$$

$$\tau_{cw} = \sqrt{[(\tau_m + \tau_w |\cos \varphi|)^2 + (\tau_w |\sin \varphi|)^2]}$$

where

τ_m represents the average shear stress in the current direction
 τ_{cw} is the maximum shear stress generating during a wave period
 φ is the angle between the current and wave directions

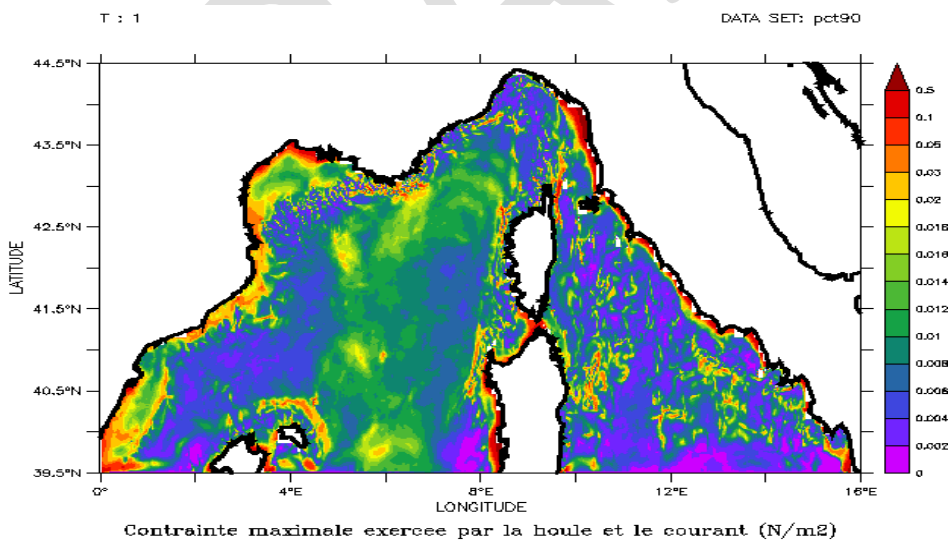


Figure 1. 90 percentile of the maximum bed shear stress due to the combined effects of waves and currents generated during a wave period.

Comment [AC3]: Check this, how tallies with next statement "computations concern..."

2.3 Baltic Sea

Two wave models have been developed for the Baltic: a coastal wave exposure model; and a model to be applied away from the coast. This dual approach is necessary because in coastal areas with a complex coastline, particularly archipelagos, the wave exposure can vary at a small spatial scale in a way that is poorly described by large-scale oceanographic models. In order to better describe energy in such areas of the Baltic Sea, the oceanographic wave model is complemented with a simpler fetch based model, SWM (Simplified Wave Model, Isaeus 2004). The energy layers were finally merged by recalculating mean significant wave height from the oceanographic model to corresponding SWM values. The final energy layer for the Baltic Sea was created from SWM-layers of very high spatial resolution for the coastal areas and mean significant wave height of lower spatial resolution for the open sea. [The oceanographic model](#) ~~Significant wave height~~ is described in section 2.3.1 below. SWM is described in section 2.3.2 and [the](#) recalculation and merging of the layers is described in section 2.3.3. Kinetic energy at the seabed was also calculated but not used [in the final model](#) since significant wave height corresponds best to SWM. Kinetic energy at the seabed is described in section 2.3.4.

2.3.1 Wave model – Baltic Sea

The applied wave model is based on the MIKE 21 SW modelling system. MIKE 21 SW is a state-of-the-art third generation spectral wind-wave model developed by DHI. The model simulates growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas. In this version of the model, the fully spectral formulation is used. This formulation is based on the wave action conservation equation. The basic conservation equations are formulated in polar spherical coordinates for large-scale applications.

The fully spectral model includes the following physical phenomena:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation due to white-capping
- Dissipation due to bottom friction
- Dissipation due to depth-induced wave breaking
- Refraction and shoaling due to depth variations
- Wave-current interaction (not included since this is mainly important in local coastal areas)
- Effect of time-varying water depth

The discretization of the governing equation in geographical and spectral space is performed using cell-centered finite volume method. In the geographical domain, an unstructured mesh technique is used. The time integration is performed using a fractional step approach where a multi-sequence explicit method is applied for the propagation of wave action.

For the present purpose, DHI's operational Northern Europe wave model, which forms part of DHI's water forecast service www.waterforecast.com, has been used. This model is based on MIKE 21 SW as described above and covers UK waters and part of the North Atlantic, the North Sea, the Belt Sea and the entire Baltic Sea. A section of the model area is shown in figure 2. The model mesh has a resolution of approximately 4 km to 20 km in the area of interest (finest in the Danish waters and coarsest in the Bothnian Bay).

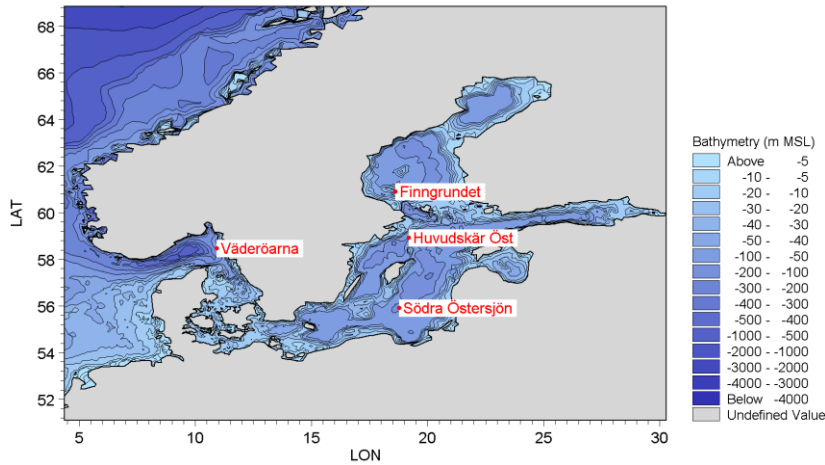


Figure 2. Section of applied MIKE 21 SW wave model showing model domain and location of measurement stations.

The model has been run in hindcast mode for a 3-year period from 1 January 2007 to 31 December 2009. The model is driven by wind fields from a meteorological model (Vejr2 and StormGeo's meteorological models), and also by open boundary conditions from a larger scale wave model. During the 3-year simulation period, wave parameters in terms of significant wave height and peak wave period were saved for every hour in every mesh element. For the present purpose only results from eastern Skagerrak/Kattegat to the Baltic Sea were used.

The wave model has been validated mainly on a case by case basis in connection with specific projects. In the present context the performance of the model has been checked by comparing model results to wave observations from SMHI in the stations Finngrundet, Huvudskär Öst, Södra Östersjön and Väderöarna. The comparisons are made for a 1-2 month period in autumn 2009, where events with high waves may be expected. In figure 3 and 4 the comparisons are shown. It is observed in the two figures that the model results compare well with the observations.

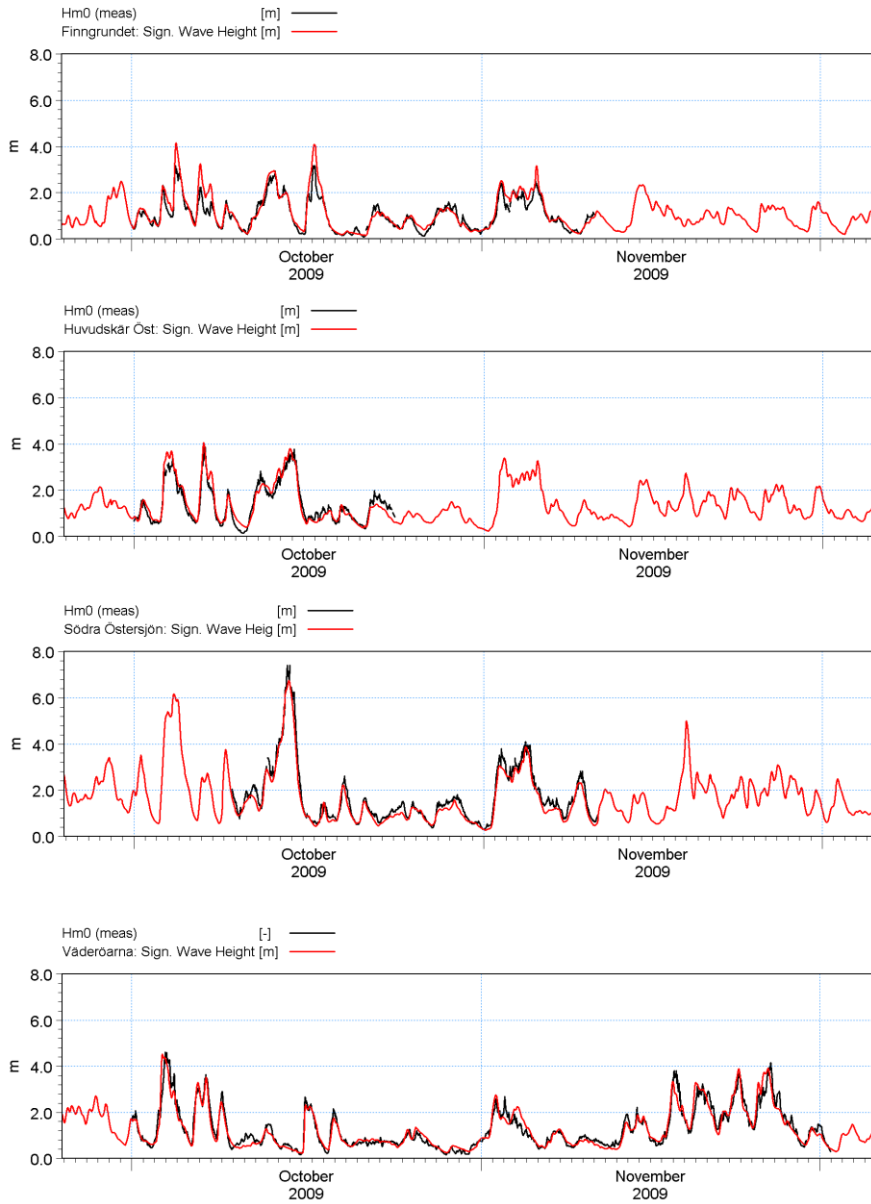


Figure 3. Comparison of observed (black line) and modelled (red line) significant wave height

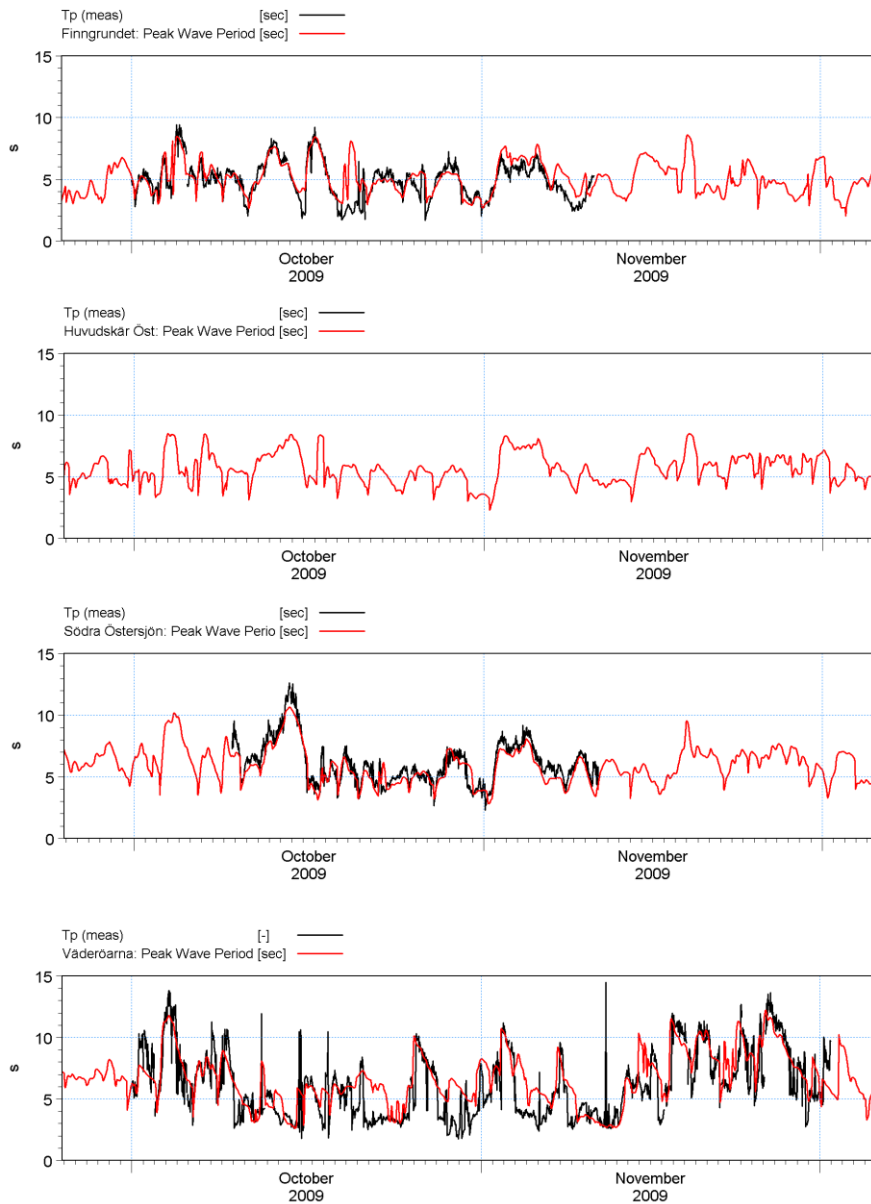


Figure 4. Comparison of observed (black line) and modeled (red line) peak wave period

The SWM layers (described in section 2.3.2) only cover coastal areas. For this purpose mean significant wave height was selected, since this layer corresponds best to SWM and was therefore selected for open sea areas in the merged energy layer for the entire Baltic Sea. The mean value of mean significant wave height for the years 2007, 2008 and 2009 was calculated and a GIS layer was created.

2.3.2 Simplified Wave Model – Baltic Sea

SWM was calculated with the software WaveImpact 1.0, which is fully described by Isæus (2004). The method is termed simplified since it uses the shoreline and not the bathymetry as input for describing the coastal shape. This is an adoption to the fact that bathymetry data of sufficient spatial resolution is often unavailable or confidential and therefore of restricted use. The method has been proved useful in several papers (Bekkby et al., 2009; Bekkby et al., 2008, a-c; Bekkby and Isæus 2008; Eriksson et al., 2004; Florin et al., 2009; Sandman et al., 2008; Sandström et al., 2005; Snickars et al., 2010; Soldal et al., 2009; Sundblad et al., 2009).

To ensure long distance effects on the local wave exposure regime, a nested-grids technique was used. In this case a coarse grid (500 m cell size) covering the major part of the Baltic Sea was used to support finer grids (100 m cell size) with input fetch values. These 100 m grids further provided input fetch values for the final 25 m grids (used in the SWM calculations). The extents of the 25 m grids were set to include coastline features that affect fetch locally, to overlap between each grid pair and to be of manageable size.

The fetch is calculated for every sea grid cell of the map. An advantage of using such a grid solution is that the values of adjacent cells can be used as input data, which facilitates the simulation of the patterns of refraction and diffraction. The wave exposure was calculated for mean wind conditions represented by hourly wind data for the five-year period between September 1, 2002 and August 31, 2007. Wind data were retrieved from the British Metoffice Unified Model, by the Interdisciplinary Centre for Mathematical and Computational Modelling, University of Warsaw. A total of 26 locations were used. For some grids there were several wind stations available. For those grids, the most representative wind station was selected. For the calculations, the wind data were divided in sixteen compass directions, each representing an angular sector of 22.5°.

The SWM was calculated by multiplying the value of each cell in the corresponding fetch grid by the mean wind speed for each wind direction separately, resulting in sixteen new grids. Finally the mean value of all grids was calculated in an overlay analysis. The separate SWM grids (25 m cell size) were integrated into three seamless descriptions of wave exposure along the coasts of Russia, Latvia, Lithuania, Germany and Denmark. In turn, these grids were integrated with earlier calculated grids for Sweden, Finland, Estonia and Poland into a seamless SWM-coverage for the Baltic coasts.

Calculation of SWM for the Baltic Sea is described in more detail in Isæus and Wijkmark, Wave Exposure Calculations for the Baltic Sea, Aquabiota report 2010:02.

2.3.3 Conversion of mean significant wave height to SWM and merging with SWM

In order to recalculate mean significant wave height layer to SWM a regression was performed using data points in overlapping areas. Data points with SWM values under 100,000 were not included since SWM and mean significant wave height differ drastically in areas with such low values due to the difference in spatial resolution between the models. In total 22639 overlapping points were included in the regression, equation below.

$$Y = 826787 X^{1.2017}$$
$$R^2 = 0.5593$$

where

$Y = SWM$

$X = \text{mean significant wave height}$

The mean significant wave height layer was transformed to SWM using the equation above.

The SWM and wave height layers were merged in GIS (ESRI ArcMap). It can be assumed that SWM is more accurate than wave height in coastal areas and archipelagos and that wave height is the most accurate layer in the open sea. The use of fetch based wave exposure models in coastal environments is supported a study by Hill et al. 2010 pointing out fetch based indices as the best predictors for occurrence and cover of algal genera and community-level patterns. Since the SWM layer also has a much higher spatial resolution it is more suitable for use in areas with complex coastlines and islands. In areas with SWM values over 500,000, the transformed wave height layer determines the value of the merged layer and in areas with lower values the SWM layer determines the value of the merged layer. The layer is shown in figure 5 below.

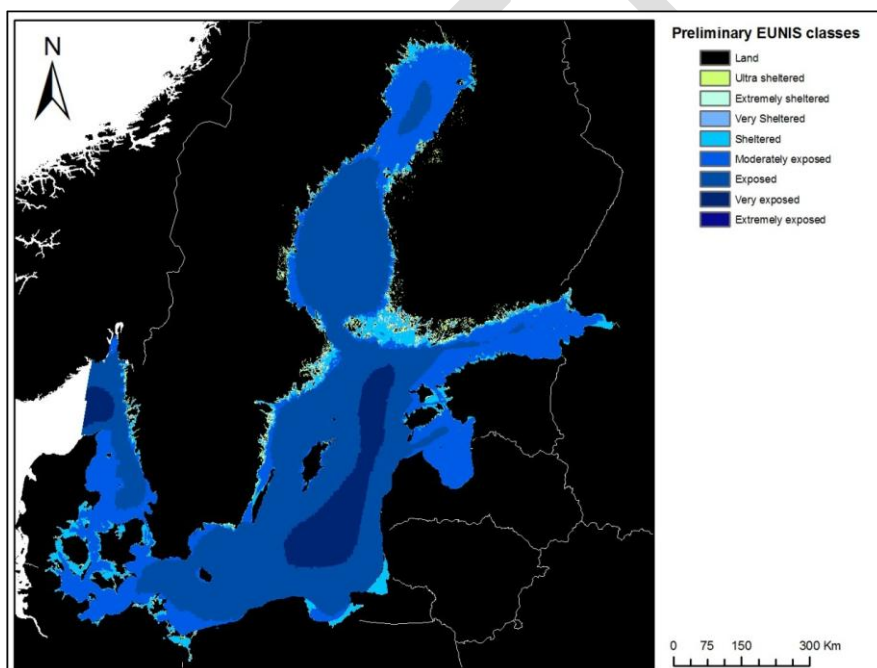


Figure 5. SWM layer for the Baltic Sea. SWM values for open sea areas are derived from recalculated significant wave height.

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2.3.4 Kinetic energy at the seabed

For the Baltic Sea kinetic energy at the seabed was calculated as both the wave induced kinetic energy and the current induced kinetic energy. However kinetic energy at the seabed was not used in

the final merged energy layer for the Baltic Sea since significant wave height corresponds better to SWM.

The kinetic energy at the seabed is calculated as both the wave induced kinetic energy and the current induced kinetic energy. In the former case the kinetic energy is based on the wave orbital velocity at the bottom and in the latter case the kinetic energy is based on the current speed at the bottom.

The calculation of the kinetic energy induced by waves is based on the modelled wave parameters, i.e. significant wave height and peak wave period, as well as on the local water depth.

The calculation of the kinetic energy induced by current is based on modelled current velocities. The applied current model, or hydrodynamic model, is based on the MIKE 3 modelling system developed by DHI. The MIKE 3 model is a dynamic time-dependent 3-D baroclinic model for free surface flows. The mathematical foundation of the model are the Reynolds-averaged Navier-Stokes equations in three dimensions, including the effects of turbulence and variable density, together with conservation equations for mass, heat and salt, an equation of state for the density, a turbulence module and a heat exchange module. The equations are solved on a Cartesian grid by means of the finite difference techniques. The hydrodynamic model provides a full 3-D model representation of the water levels, flows, salinity, temperature and density within the modelling domain.

3 Development of Thresholds

3.1 North and Celtic Seas thresholds

The effect of energy at the seabed – **to be completed by JNCC**.

3.2 Western Mediterranean Sea thresholds

The effect of energy is a pivotal factor in determining the development of specific habitats such as rhodolith beds (Maerl) in the circalittoral as the intensity of the currents will enhance the rolling motion of specific red algae over sediments thereby stimulating the production of the algal concretion over the sediment granule resulting in the rhodolith (Bressan & Babbini, 2003). At the same time the effect of bottom currents together with other factors such as river inputs and other oceanographic factors will also contribute over very long terms to the deposition of specific sediment types and granulometries resulting in different habitat types (Tunesi & Peirano, 1985; Morri et al. 1986). Bibliographic data indicates that the coastal detritic and muddy detritic assemblages of the upper circalittoral are strongly influenced by the intensity of the bottom current typologies. In the first case medium constant currents contribute to the deposition of gravelly and sandy substrata originating from the nearby coast and infralittoral features (i.e. predominant local rocks, debris from mollusc shells, or dead bryozoan or Melobesiae) while in the second case currents of lower intensity contribute to the deposition of mud formed by terrigenous deposits over a detritic bottom (Pérès & Picard, 1959)".

To this effect, an attempt was made to use the modelled energy layers to:

a) define energy threshold values for rhodolith beds versus coastal detritic bottoms, because both habitats occur on the same type of substrate category and may be defined on the basis of differing energy levels. The resulting energy thresholds can therefore be used to model these two habitats in the final model.

b) define the energy range values for two soft bottom habitats (coastal detritic and muddy detritic) occurring in the upper circalittoral and occurring on two different substrate types. The threshold values obtained by comparing the energy layer against known distributions of these habitats could therefore be used as a second “proxy” variable to model these habitats in case substratum data entering into the model should not be exhaustive enough to do so in the first instance (each habitat-assembly would first be modelled based on the respective substrate category and its location in the upper circalittoral [as defined by the 0.01% light layer], and subsequently the modelled habitat distribution would be checked against the defined energy threshold values).

Information regarding all types of rhodolith associations was considered for the purpose of the validation procedure and all available rhodolith association types were grouped under one category. The validation was carried out taking into account the distribution of Maerl, Facies of free Peyssonneliaceae and non-specified rhodolith associations for four location in France (Antibes-Cape d’Ail, Cannes, Ciotat and Marseilles); rhodolith, coastal detritic and muddy detritic assemblages in Italy (Tuscan archipelago and Ligurian sea) and coastal detritic, coastal detritic rhodolith and Maerl in Spain (Baleari Archipelago). All rhodolith associations were grouped together

The validation was carried out by considering only the habitat polygons characterized by a size ≥ 20 pixels so as to enhance the possibility that only the polygons with a high spatial significance be used with respect to the scale of elaboration. The resulting collected number or records for the various habitat types amounts to 137 but only 28 polygons of size ≥ 20 pixels were considered in the analysis process (Table 1).

Table 1. Habitat polygons falling within energy layers.

Habitat	N° of polygons falling in the energy layer (Avg and Pct90)	N° of polygons with ≥ 20 pixels (Avg and Pct90)
Muddy Detritic	26	4
Coastal Detritic	56	12
Rhodolith associations	55	14
Total	137	28

Results of the zonal statistics of the above polygons with respect to all the modelled bottom current energy layers (minimum, maximum, average and 90th percentile), constructed on 1 Km resolution, were plotted in scatter plots. The mean values of the average and of the 90th percentile energy layers were further analysed and an attempt was made to identify cut off points for high, medium and low energy for the three habitat types (all rodolith associations, coastal detritic, muddy detritic). The scatter plot of the entire habitat datasets against the average modelled energy layer, as illustrated in figure 6 below, indicates that it is not possible to discriminate different energy levels associated to the three different assemblage types. The polygons of the muddy detritic (cod 2) and rhodolith associations (cod 5) are characterised by similar minimum energy values and the rodolith associations are also characterised by similar average to medium-high energy values as those of the coastal detritic (cod 1) polygons. A similar trend is also observed when plotting the polygons against the 90th percentile modelled energy layer.

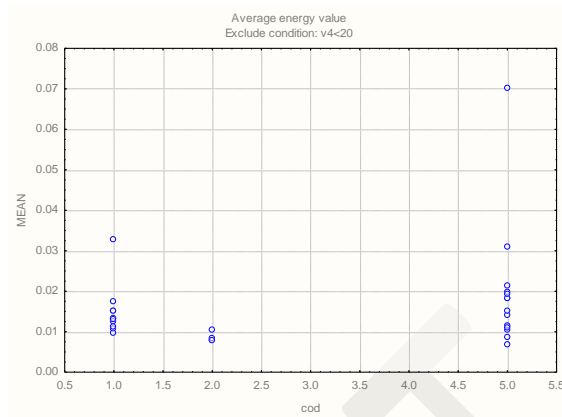


Figure 6. Scatter plot of the energy values for coastal detritic (cod 1), muddy detritic (cod 2) and rhodolith associations (cod 5) in Italian, French and Spanish waters using the model for average (bottom current) energy values.

A further attempt was also made to analyse the distribution of these polygons against the modelled energy layer involving both bottom currents and wave energy, but no significant energy differences were found capable of differentiating any of the three habitat types. It is likely that the coarse resolution of the modelled energy layer as well as the consistent data gap of the model for the inshore coastal areas hinders the application of this approach.

The results of the modelled energy output against the distribution of known habitats that are influenced by currents carried out in this specific exercise do not allow concluding on any specific energy threshold value with which to attempt modelling the three habitat categories. As a result, the initial attempt to consider mapping rhodolith beds in the Western Mediterranean based on modelled energy values was abandoned. Similarly no energy threshold value was identified to differentiate coastal detritic from muddy detritic habitats, though these two habitat types can be modelled based on the substrate typology and their distribution in the circalittoral and upper circalittoral zone.

3.3 Baltic Sea thresholds

In the present analysis, the threshold between high and moderate energy was defined by the occurrence of *Fucus*-dominated communities at < 3 m depth. High energy shores typically lack dense communities of the large perennial *Fucus* species, at least in the uppermost meters. Instead, these shores are typically dominated by communities of more disturbance-tolerant filamentous algae. *Fucus* may occur deeper; hence we only looked at the presence of *Fucus* in the uppermost meters.

The threshold between moderate and low energy was defined by the occurrence of species-rich charophyte- and phanerogam communities typical for low-energy shores. The definition was set to presence of at least 5 species from these groups occurring together, which excluded low-diverse communities of more hardy species such as *Zostera marina*, *Ruppia* sp., *Potamogeton pectinatus*, *Potamogeton perfoliatus* and *Chara aspera* that occur also in higher energy.

The field data set used to set the threshold values came from a total of 902 diving transects from the Swedish and Finnish coasts, 70 from the oligo- and 832 from the mesohaline salinity zones. The data

was compiled from a number of different studies, using a standard method for monitoring of phytobenthic communities in the Baltic Sea (Kautsky 1992; HELCOM 1999). In short, diving transects were placed perpendicular to the shoreline, from the shore to the deepest occurrence of macroalgae or plants and the substratum type and surface cover of all algae, plants and sessile animals were noted within depth sections in a 6-10 m wide corridor along the transect line.

For the threshold analyses, each transect section from the diving transects was classified into preliminary EUNIS classes using the BalMar tool (Backer et. al 2004, Alleco 2005). Exposure values for each transect was extracted from SWM grids with 25 m cell size, in order to get as correct value as possible for the threshold analysis.

The maximum SWM value recorded for a transect including a community type (shallow *Fucus* or species rich charophyte/phanerogam communities) was used as the upper limit of the fuzzy threshold, after removing a few extreme outliers that where apparently the result of errors in SWM layer. The 90 percentile of transects including the type was used as the lower limit of the fuzzy threshold. For both the thresholds, the 90 percentile represented an energy level below which the community type was occurring commonly, so this percentile level was regarded to be relevant.

The result from the threshold analyses is shown in Table 2. The max and 90 percentile values were generalized to the nearest 10 000 since this was regarded to be the relevant degree of precision in the dataset.

Thresholds for the Baltic Sea were defined using SWM (Simplified Wave Model) ranges in two coastal areas for selected species of macro algae and vascular plants.

A dataset of 19059 data points in total was used. The data were collected during scuba diving surveys and contains both transect and point data. Transects contain several data points.

The data were collected in two areas along the Swedish Baltic coast; the counties of Östergötland (approximately 58° N) and Västernorrland (approximately 63° N). Of the 19059 points in total, 16263 were collected in Östergötland and 2795 were collected in Västernorrland. Exposure values were extracted from SWM grids with 25 m cell size.

Fifteen species of vascular plants and algae from the genera *Callitriche*, *Ceratophyllum*, *Chara*, *Zostera*, *Ranunculus* and *Potamogeton* were investigated. Outliers were removed manually for some of the species. The threshold between sheltered and moderately exposed was defined as the interval between the maximum wave exposure values for the species *Ceratophyllum demersum*, *Chara aspera*, *Potamogeton perfoliatus* and *P. filiformis*. To establish the threshold between moderately exposed and exposed the maximum exposure values for the species *Zostera marina* and *Potamogeton pectinatus* were used.

Sheltered/moderately exposed threshold

The threshold between sheltered and moderately exposed was set to the SWM interval 40 000 to 80 000 based on maximum exposure values for the species used (table 3.3).

Moderately exposed/exposed threshold

The threshold between moderately exposed and exposed was set to the SWM interval 160 000 to 240 000 based on maximum exposure values for the species used (Table 2).

Table 2 The defined thresholds for energy levels in the Baltic Sea. The values are fetch values from the SWM model. The last column shows the threshold values used in the model. Maximum SWM values for each species used for the thresholds.

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Comment [AC4]: The SWM merged w DHI model version of the layer used? (see section 2.3)

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Species	Threshold	Maximum-SWM	n
<i>Ceratophyllum demersum</i>	Sheltered/Moderately exposed	40002	853
<i>Chara aspera</i>	Sheltered/Moderately exposed	60212	158
<i>Potamogeton perfoliatus</i>	Sheltered/Moderately exposed	64030	991
<i>Potamogeton filiformis</i>	Sheltered/Moderately exposed	81904	77
<i>Zostera marina</i>	Moderately exposed/exposed	174506	526
<i>Potamogeton pectinatus</i>	Moderately exposed/exposed	208279	519
>25% cover			
<i>Potamogeton pectinatus</i>	Moderately exposed/exposed	238594	1913

	Definition	Statistica	SWM value	Threshold value
High/moderate	Occurrence of <i>Fucus</i>	Max	673 000	680 000
	communities at < 3 m depth	90 percentile	522 000	520 000
Moderate/low	Occurrence of species-rich	Max	79 000	80 000
	(>4 species) of charophytes/ phanerogams	90 percentile	44 000	40 000

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EUSeaMap

Technical Report No. X

Light data and thresholds

DRAFT

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1 Introduction

Light availability in the water column and at the seabed varies considerably, affecting in particular the depth to which macrophytes (kelp, seaweeds, seagrass, e.g. *Posidonia spp.*) can grow. Light intensity decreases with depth due to the attenuating effects of scattering and absorption in the water column by water molecules, suspended particulate matter, phytoplankton and coloured dissolved organic matter. This attenuation tends to be higher in coastal waters, due to suspended and dissolved matter being washed down rivers, higher phytoplankton concentrations and suspension of sediment caused by wave action in shallow waters.

Light attenuation is the variable used to define the infralittoral zone, where irradiance from the sun is still sufficient to allow significant photosynthetic activity of vegetation such as kelp and seagrass. It can also be used to define the upper circalittoral zone where the light reaching the bottom is estimated to range between 1% - 0.01% of the surface light thereby allowing the photosynthesis of sciaphilic algae such as the Fucales (deep water *Cystoseira* and *Sargassum spp.*), Laminariales, Desmarestiales and Sporochnales as well as red algal (Rhodophycean) species. In the Mediterranean some characteristic communities such as coralligenous assemblages consisting of more or less massive bioconstructions formed by coralline algae, as well as Rhodolith (Maerl beds) thrive in this zone.

In the Baltic polyhaline and fully marine zones, the lower threshold of the infralittoral was mapped using the threshold developed for the North and Celtic Seas, i.e. corresponding to the depth limit of kelp (*Saccharina latissima*, *Laminaria digitata* and *L. hyperborea*). Further North the oligohaline and mesohaline zones lack kelp communities, which are used to define the lower threshold of the infralittoral in the Atlantic EUNIS. Instead, the threshold was defined by the deepest occurrence of algal-dominated biotopes.

2 Data layer preparation

2.1 Computing light in the water column

In the project two methods of accessing light levels in the water column were used. Ocean colour satellite imagery is quite effective to provide large extent maps of light attenuation at high spatial and temporal resolution. Several models are commonly used to derive K_{dPAR} (down-welling photosynthetically available radiation) maps from satellite imagery. For EUSeaMap, an improved K_{dPAR} layer has been estimated from radiance measured by MERIS (Saulquin *et al.*, in prep.), the Medium Resolution Imaging Spectrometer Instrument aboard the European Envisat satellite.

Depth zones can be determined by intersecting the depth data layer with these light attenuation values and using a pre-defined threshold. The fraction of surface light which reaches a given depth is computed using the formula:

$$Fr = e^{-h/D_m} \quad (1)$$

Where h is the depth and $D_m = Kd_{PAR}^{-1}$ is sometimes referred to as mean penetration depth.

High resolution MERIS imagery (HR with 250 m pixel size) was processed from 2003 to 2008 for the area shown in figure XXXX (limited by 13W, 18E, 36N, 60N. These 250m products are particularly relevant for the steeper shores found in the Mediterranean as well as for complex rocky shores like those found in some Atlantic shores. Within the work for EUSeaMap, the algorithm to predict Kd_{PAR} from the MERIS satellite data has been improved for coastal waters by statistical analysis against *in situ* data collected across the regions as described below on the various basins.

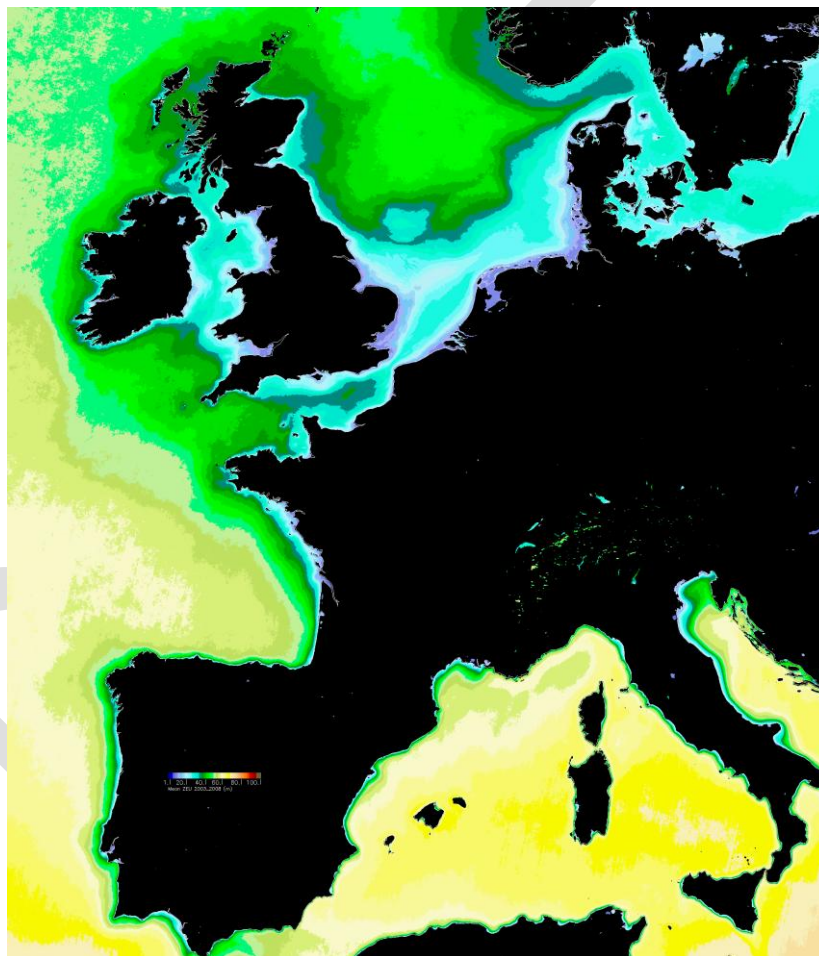


Figure 1: Overview Zeu (photic depth) as computed from MERIS imagery.

2.1.1 Kinetic energy model for waves – North and Celtic Seas

2.2 Validating light thresholds

In order to check the validity of the 1% and 0.01% light thresholds retrieved from satellite imagery, comparisons were carried out with ground-truth data for each basin. In the Atlantic, acoustic measurements of kelp forests from 2006 and 2007 surveys in Brittany at a number of sites were plotted against the photic zone as derived from the K_{PAR} . In the Mediterranean since *in situ* light values were not available, a more comprehensive validation was achieved (see Appendix XXXX). The modelled 1% light layer was tested against the known distribution of *Posidonia oceanica* meadows with a good health status and whose lower limit is known to be limited by decreasing light. The approach was carried out on 40 selected meadows sites in Spain, France and Italy by identifying the largest homogenous polygons and ensuring that fragmented areas were excluded in the process. The bathymetry used to intersect with the K_{PAR} file to yield the photic zone was from the best available DTMs (resolution of approximately 100m). The lowest percentage of light value from the 250m MERIS data was selected in each of the 40 polygons and the statistics were computed. In view of the log-normal distribution the median value of 0.82 % was therefore considered a valid threshold value for the hard limit of the infralittoral / circalittoral boundary and the lower quartile (0.34%) and upper quartile (1.6%) were considered as fuzzy values to be used in the creation of a confidence map for this limit.

The lower limit of the upper Circalittoral zone, reported to occur at 0.01% residual light, is defined by the limit of the deepest extension of sciaphilic algal. However, the distribution of these algae is not only poorly known and mapped but also limited in spatial extension and is far too fine scale with respect to the broad scale 250 pixel resolution of the model. The assessment was therefore not possible for lack of knowledge of these communities and the 0.01% value was taken for granted. In an attempt to express its uncertainty and give proper warning to users, it was decided to derive fuzzy limits of 0.005% and 0.015%] for this boundary.

In the Baltic Sea the above method was used for the polyhaline and fully marine parts of the Baltic Sea area (Kattegat and Skagerrak) and the 1% threshold was confirmed by checking against 198 diving transects.

In the oligo- and mesohaline parts of the Baltic Sea proper (inside Öresund and the Danish Belts), the ratio between Secchi depth and depth was instead used to map the thresholds. The maximum depth/Secchi depth ratio recorded (1.2 and 1.8 for respectively oligo- and mesohaline areas) was used as the lower limit of the fuzzy threshold. The 75 percentile (2 and 3.2 for respectively oligo- and mesohaline areas) was used as the upper limit of the fuzzy threshold for the transect data. The percentile levels were chosen as the expected fraction of the data that is likely to show the deepest occurrence of macroalgae and the resulting threshold values were examined and judged to give a reasonable result.

2.3 Rationale

Light availability in the water column and at the seabed varies considerably, affecting in particular the depth to which macrophytes (kelp, seaweeds, seagrass, e.g. *Posidonia spp.*) can grow. Light intensity decreases with depth due to the attenuating effects of scattering and absorption (by water molecules, suspended particulate matter, phytoplankton and coloured dissolved organic matter) in the water column (turbidity). This attenuation tends to be higher in coastal waters, due to suspended and dissolved matter being washed down rivers, higher phytoplankton concentrations and suspension of sediment caused by wave action in shallow waters.

Light attenuation is the variable used to define the infralittoral zone, where irradiance from the sun is still sufficient to allow significant photosynthetic activity. On Atlantic coasts the decrease in light levels with depth is typically reflected in four zones (Hiscock 1996):

- Infralittoral - dense kelp (*Laminaria*)
- Upper circalittoral - sparse seaweeds and sciaphilic algae
- Lower circalittoral - encrusting algae only

In the Mediterranean, the differences in light levels reaching the bottom delimit four basic zones:

- Infralittoral - seagrass and photophilic¹³ algae
- Upper circalittoral - sciaphilic¹⁴ brown and red algal species
- Lower circalittoral - survival of sparse sciaphilic algae originating from the upper circalittoral
- Abyssal - no light and no plant life

Biological zoning in the Mediterranean is affected by variables which are different from, but in some cases overlapping, those in the North and Celtic seas. In the Mediterranean, the infralittoral zone starts at low tide level and extends down to the deepest limit of *Posidonia oceanica* growth. The lower limit of the infralittoral is therefore defined as the area up to which the light intensity is such that seagrasses (i.e. *Posidonia oceanica*) and photophilic algae can survive. This threshold value is estimated to be equivalent to 1% of the light irradiance reaching the bottom of the seafloor.

The circalittoral zone starts from the lower limit of the infralittoral and extends to the maximum depth where multicellular photosynthetic forms can exist. The assemblages found in this zone are therefore characterised by the predominant presence of sciaphilic algal communities. The circalittoral can also be divided into upper circalittoral and lower circalittoral zones on the basis of the amount of light reaching the seabed. In the upper circalittoral, the light reaching the bottom is estimated to range between 1% - 0.01% of the surface light thereby allowing the photosynthesis of multicellular algae. The light reaching the bottom in the upper circalittoral is sufficient to allow the photosynthesis of different brown algae communities such as the Fucales (deep water *Cystoseira* and *Sargassum spp.*), Laminariales, Desmarestiales and Sporochnales as well as red algal (Rhodophycean) species. Characteristic communities present in this zone are the coralligenous assemblages consisting of more or less massive bioconstructions formed by coralline algae, as well as Rhodolith (*Maerl beds*)

consisting of loose lying, living or dead, coralline red algae, usually aggregated into masses on shell gravel mixed with coarse sand. On the contrary, the lower circalittoral is characterised by having less than 0.01% of the surface light reaching the seabed and multicellular algae are therefore generally not present in great quantities, as light becomes an increasingly limiting factor.

Computing light levels in the water column

There are two ways of accessing light levels in the water column. The first is by using the very simple “Secchi disk” method which is still the standard method used in oceanography cruises. While somewhat over-simplistic, this method enables comparisons between basins and also makes it possible to benefit from historic data sets. In the Baltic Sea where high concentrations of detritic matter in the ocean are a drawback to using satellite imagery, it can be a valuable alternative, as explained in the section on the Baltic below.

The second method uses satellite observations of the diffuse attenuation coefficient of the down-welling spectral irradiance at wavelength 490 nm (K_{d490}) or the diffuse attenuation coefficient for the down-welling photosynthetically available radiation (K_{dPAR}), which is an effective method to provide large extent maps of light attenuation at high spatial and temporal resolution. Several models are commonly used to derive the K_{d490} and K_{dPAR} maps from ocean colour satellite sensors, such as the Medium Resolution Imaging Spectrometer Instrument (MERIS) aboard the European Envisat satellite, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), and the Moderate Resolution Imaging Spectroradiometer (MODIS). Most of these existing models have been calibrated on open ocean waters and provide good results in these areas, but tend to underestimate the attenuation of light in turbid coastal waters.

The infralittoral zone can be determined by intersecting the depth data layer with these light attenuation values and using a pre-defined threshold. The 1% threshold is still the subject of discussion in the scientific community and it is within the remit of this project to attempt to validate it with suitable ground-truth data for both the Atlantic and the Mediterranean. This fraction (F_r) of surface light which reaches a given depth is computed using the formula:

$$F_r = e^{-h/D_m} \quad (1)$$

Where h is the depth and $D_m = K_{dPAR}^{-1}$ is sometimes referred to as mean penetration depth.

For EUSeaMap, an improved K_{dPAR} layer has been estimated from radiance measured by the MERIS sensor (Saulquin *et al.*, in prep.).



Figure 1: Overview of the MERIS swath zone.

Two types of products were processed. Level 2 Reduced Resolution (RR at 1 km) products were first processed from 2003 to 2008, including all four basins (limited by 13W, 18E, 36N, 60N). In the second phase, the same area was subsequently processed using high resolution Meris images for the same period (HR at 250 m), which made it possible to be fully in line with the resolution specifications of the project. Unfortunately, the latter products were not available for this study and will be delivered in October 2010 for use in a later update. These 250m products are particularly relevant for the steeper shores found in the Mediterranean as well as for complex rocky shores like those found in Brittany. These light layers represent a further significant improvement beyond the resolution of the data. Within the work for EUSeaMap, the algorithm to predict Kd_{PAR} from the MERIS satellite data has been improved for coastal waters by statistical analysis against *in situ* data collected across the regions as described below on the various basins.

Computing the photic zone boundary is simply a matter of intersecting the 1% light layer with the depth layer. If the actual depth at any location is shallower or deeper than the photic depth, the pixel is respectively flagged as infralittoral or upper circalittoral. It should be emphasised here that the quality of the bathymetry has a strong bearing on the quality of this result. This should be borne in mind in the comparison with ground truth data.

2.4 Light thresholds in the North and Celtic Seas

In order to check the validity of the 1% light threshold as retrieved from satellite imagery, a comparison was carried out with ground-truth data. In the Atlantic, acoustic measurements of kelp

forests from 2006 and 2007 surveys in Brittany at a number of sites (Abers, Héaux de Bréhat, Triagoz, Méloine, Molène and Ile de Groix, see Méléder *et al.* 2010) were plotted against the photic zone as derived from the 1km resolution K_{PAR} (Figure 1).

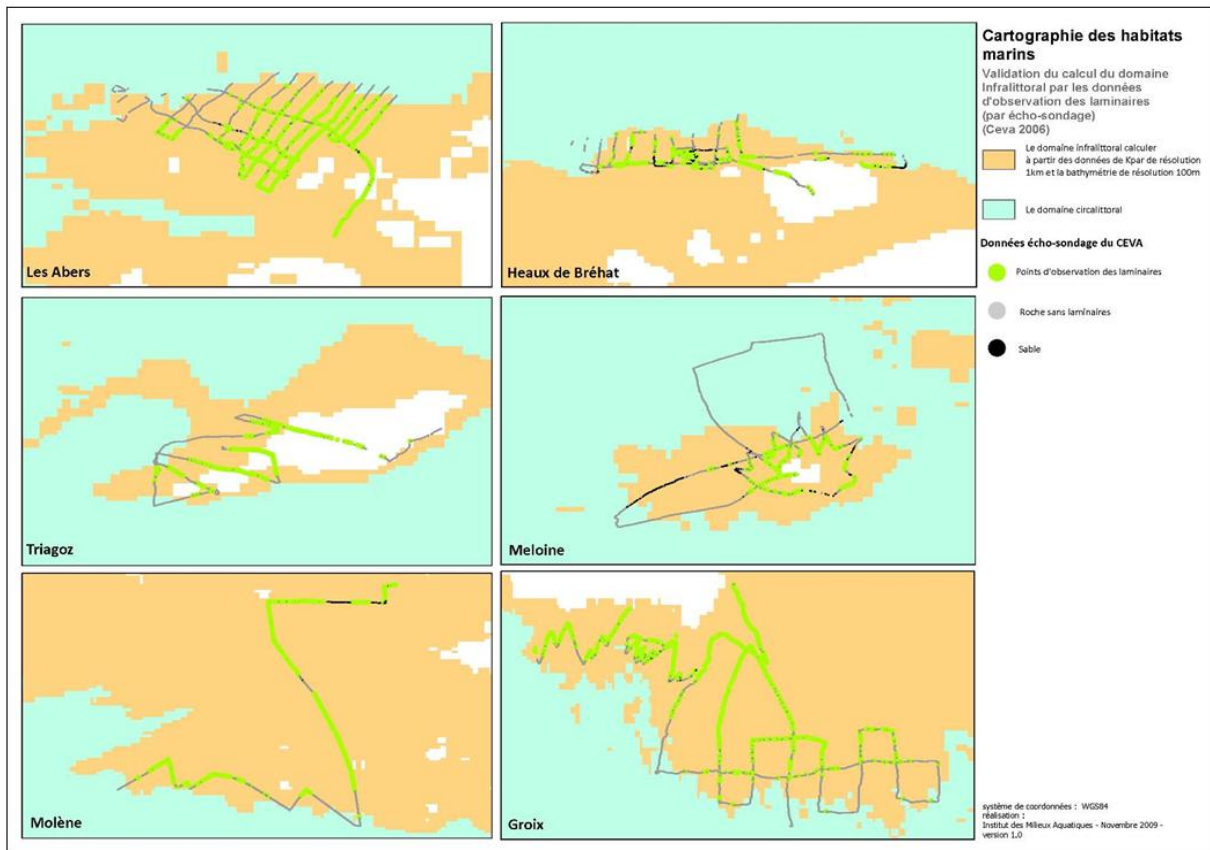


Figure 1 Echo-integration of single beam sounder data showing the presence of kelp forest (green dots, as opposed to bare rock shown as grey dots) overlaid on infralittoral zone (orange) from 1 km resolution Meris imager.

What can be seen from these maps is that kelp are very seldom present in the aphotic zone (in blue) and also that in quite a number of cases, kelp presence actually stops when the transects cross the photic zone boundary. However, limited value should be given to such comparisons, because the retrieval of the photic zone is based on best depth available data. In this case in Brittany, the depth file is a 100 m resolution DTM (Digital terrain model) derived from SHOM soundings. For an initial assessment of the quality of the comparison, the interpolation error map delivered with the DTM should be consulted to check whether the depth value at each location is reliable. Following that step, the 1% light value was propagated throughout the whole Atlantic area of the project to delineate the photic (or infralittoral) zone.

Some research questions still remain with regard to the use of such imagery. So far, mean annual values over a multiple year period have been used. It would be interesting to look at monthly or seasonal values as well. Discussions in meetings revolved around the seasonality for threshold testing, e.g. March – end of June to cover the recruitment and growth period, but there are many conflicting opinions in the literature. For example, the winter period might be important with respect to the length of time needed for species to store light energy, or perhaps it is best to examine a ratio

of the summer to winter means. Differences between regions for species (*Posidonia*, *Fucus* and *Laminaria*) must also be considered. It was also suggested that means corrected for seasonal variability be sought.

2.5 Light thresholds in the Mediterranean

2.5.1 Definition and validation of the infralittoral / circalittoral boundary

The passage from the infralittoral to the circalittoral zone is marked by the degree of light reaching the sea bottom, whereby past a certain threshold of light photosynthesis of seagrasses and photophilic algae cannot occur. According to bibliographical data, it is hypothesised that this limit is set at 1% of surface light reaching the sea bottom. However, since the hypothesised values may not necessarily coincide with those generated by the modelled light layer, it is important that the modelled light layer be validated. Since *in situ* light values were not available for the Mediterranean, the modelled 1% light layer (Buia et al., 2003) was tested against the known distribution of *Posidonia oceanica* meadows with a good health status and whose lower limit is known to be limited by decreasing light rather than to other anthropogenic causes (i.e. anchoring, pollution, water quality alteration or trawling).

Statistical analysis of the light values of the evaluated meadows was subsequently used to further define the final threshold value to be used in the model, as well as the values to be used as fuzzy values of this limit. The approach was carried out on selected meadows in Spain, France and Italy using the average daily light data obtained from MERIS images on a 1 km resolution averaged over the period 2003-2008. The bathymetry used to intersect with the K_d PAR file to yield the photic zone was from the best available DTMs in Italy and France (resolution of approximately 100m).

Two approaches were used to test the estimated 1% light value and define the value for the hard limit to be used in the definition of the infralittoral / circalittoral boundary which are described below.

2.5.2 Choice of good condition *Posidonia* meadows

In France, the meadows known to have the best conservation status based on scientific bibliography and expert knowledge, along with meadows located in noteworthy marine protected areas, were considered. Polygons were chosen within these meadows where the lower limit of the meadow was known to be in good health and where it is expected that its extension is limited only by decreasing light levels. Four sites were chosen on the French mainland located from Hyeres eastward and five sites were chosen around Corsica. The location names in which the polygons fall are given in Table 1.

In Italy, *Posidonia oceanica* meadows which were the object of validation procedures in Italy belong to three categories: a) meadows for which ISPRA-owned specific cartographic and bathymetric information on the good conservation status of the meadow lower limit (Elba island) exists, b) meadows hypothesised as having good conservation status on the basis of information derived from the *Posidonia* national monitoring scheme carried out since 2003 by the Italian Ministry of the Environment (*Programma di monitoraggio Legge 979*). In this case, the meadows considered in the validation process were chosen if the lower limit was identified as being progressive (which implies that the meadow lower limit distribution is influenced only by decreasing light levels). Meadows with

other types of lower limit (sharp, erosive, progressive) were considered for the validation process only if they had a conservation index (% live Posidonia: dead matte; from Moreno et al., 2001) range of 1.0-0.9, and their conservation status (defined on the basis of leaf density with respect to depth, from Buia et al., 2003) was classified as being excellent or in normal equilibrium, and c) an additional set of polygons identified in the Ligurian coastal area by selecting the meadows with the most intact lower limit on the basis of best expert judgement.

The Posidonia meadow polygons related to point b) above were selected by identifying the largest homogenous appearing polygon within which each station/point data was located and ensuring that fragmented sparse peripheral areas were excluded in the process. The names of the locations proximate to which each of the polygons holding Posidonia meadows is listed below and amounts to 20 locations (Table 2).

In Spain, the Posidonia meadows used in the validation process were those which were known to have good conservation status in terms of their lower limit and not exposed to the effects of fish trawling and anchoring, based on expert opinion. Only those meadows which had recently been mapped and which had high resolution cartographies were considered. A further refinement of the Spanish dataset was carried out in order to eliminate some polygons in which the bathymetric values were not coherent with the presence of Posidonia meadows. This process was performed manually by checking each polygon with the final bathymetric layer and/or (where available) with high resolution isobaths (i.e. Balearic Islands). The names of the 11 locations near which each of the polygons holds Posidonia meadows is listed in Table 1.

2.5.3 Light fraction estimated from pixels on lower limit of Posidonia meadows

This first approach looked at the light fraction value of all pixels intercepting the lower limit of 29 Posidonia meadows located in France and Italy and considered to have good conservation status. The lower limit was selected manually as being the boundary “furthest offshore”. This approach was tested mainly on the argumentation that it should provide a more robust statistical evaluation since it would entail evaluating a higher number of data records for all available Posidonia meadows. It only concerned selected French and Italian meadows.

Table 1 Posidonia sites selected for validation in the three Mediterranean countries.

Meadow location	Area
Port-Cros	SE France
Cannes	SE France
Iles de Lérins	SE France
Porquerolles	SE France
Southern Bastia	Corsica
Aléria	Corsica
Archipelago of Lavezzi	Corsica
Scandola	Corsica
Calvi	Corsica

Meadow location	Region
Punta Licosa	Campania
Camerota	Campania
Torre Paola	Lazio
S. Lorenzo	Liguria
Porto Maurizio	Liguria
S. Stefano Sud	Liguria
Capo Berta	Liguria
Capo Cervo	Liguria
Ospedaletti - Capo Nero	Liguria
P.ta S.Martino-Capo Verde	Liguria
Alghero	Sardinia
Arbatax	Sardinia
S. Antioco	Sardinia
Olbia	Sardinia
Asinara	Sardinia
Capo Carbonara	Sardinia
Maraone - AMP Isole Egadi	Sicily
Antignano	Tuscany
Foce Tirso	Tuscany
Carbonifera	Tuscany

Meadow location	Region
Bega de Mar	Alicante
Cap de La Nao	Alicante
Santa Pola	Alicante
El Oasis	Alicante
West Parc National Calbarque	Murcia
East Parc National Calbarque	Murcia
Calabardina	Murcia
Ibiza	Balearic Is.
Maiorca	Balearic Is.
Menorca	Balearic Is.
South Alicante	Alicante

The distribution of the obtained values and the statistical parameters of the resulting light dataset are indicated in table 2 and figure 3. These values (mean of 2.17% and median of 1.52%) are generally higher than what would be expected from bibliographic references. A closer look at a specific site in Port-Cros (Figure 4) shows the difficulty of choosing the lower boundary, due to the very high variability of light values (up to 8%) and associated depth (from 24 to 46 m), which shows either that many points are not on the lower boundary or that there are other factors besides light limiting the deeper extension of the plants (sediment type, human pressure, cartographic error, etc.). Based on the above-mentioned argumentation, it was decided that this validation approach would not be considered for the purpose of defining the infralittoral zone limit.

Table 2 Statistics of the observed light values associated with the French and Italian Posidonia meadow lower limits

	Valid N	Mean	Geometric	Median	Minimum	Maximum	Percentile	Percentile	Std.Dev.
Fr_Light	979.00	2.17	1.64	1.52	0.20	9.86	0.69	4.80	1.82

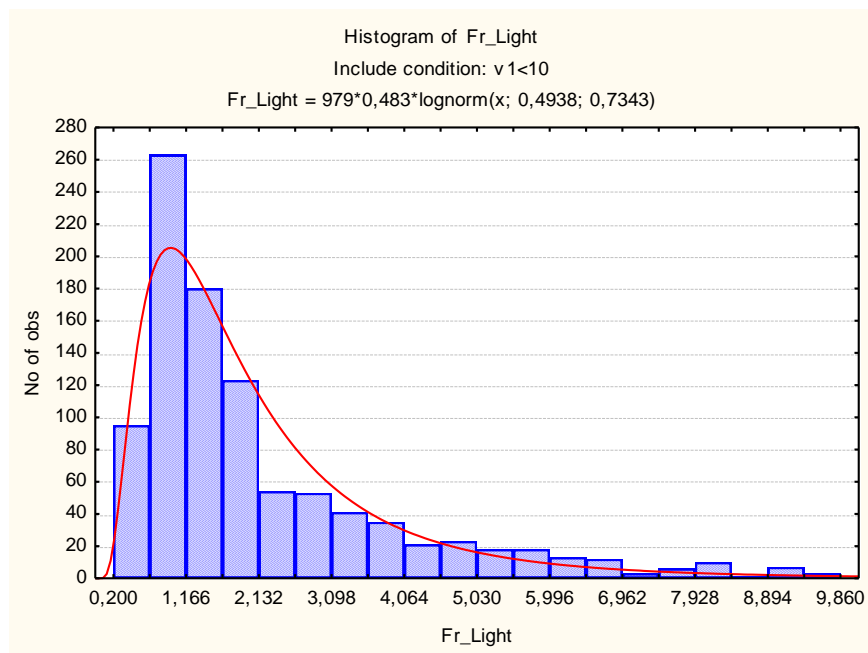


Figure 2 Histogram of the observed light values associated with the French and Italian Posidonia meadow lower limits

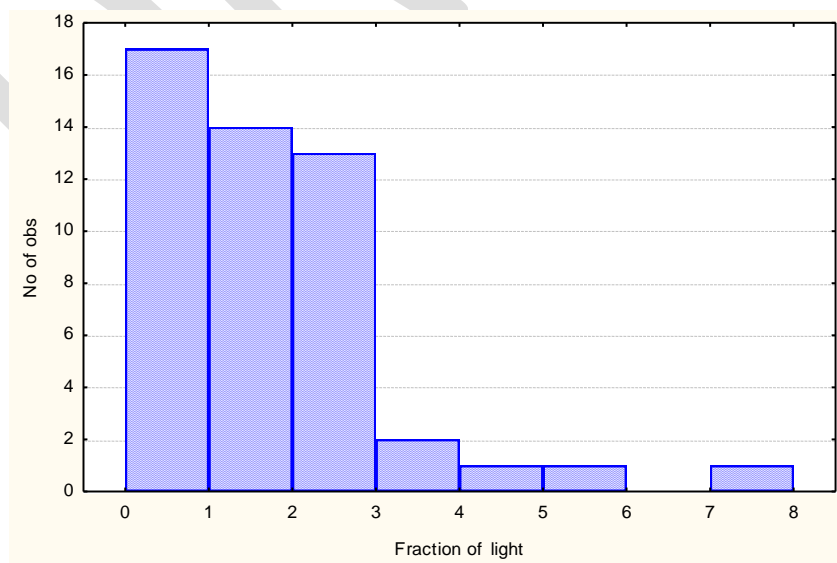


Figure 3 Histogram of light fraction values observed for the Port Cros Posidonia meadow lower limit.

2.5.4 Minimum light values observed in Posidonia meadows

The second approach consisted in selecting the lowest pixel value in each of the 40 Posidonia meadows located in Italian, French and Spanish waters and considered as having good conservation status. The statistics of this data set are listed below (see table 3 and figure 5). Both the mean and median values observed on the overall lie very close to the expected hypothesised minimum value of light (1%) that is expected to allow the photosynthesis of Posidonia. In view of the log-normal distribution the median value of 0.82 % was therefore considered a valid threshold value for the hard limit of the infralittoral/circalittoral boundary and the lower quartile (0.34%) and upper quartile (1.6%) were instead considered as valid fuzzy values to be used in the creation of a confidence map for this limit. Refer to the fuzziness section to visualise the resulting buffer.

Table 3 Statistics of the minimum light values observed in Italian, French and Spanish Posidonia meadow polygons.

Descriptive Statistics (Statistica_luce_final.sta) Include condition: v24 > 20 Exclude condition: v18 < 40 or v24 = 41 or v24 = 46 or v24 = 48											
	Valid N	Mean	MG	Median	Min	Max	LQ	UQ	Pct10	Pct90	Std.Dev.
Min_%	40	1.136	0.751	0.821	0.165	3.623	0.340	1.609	0.188	2.535	0.997

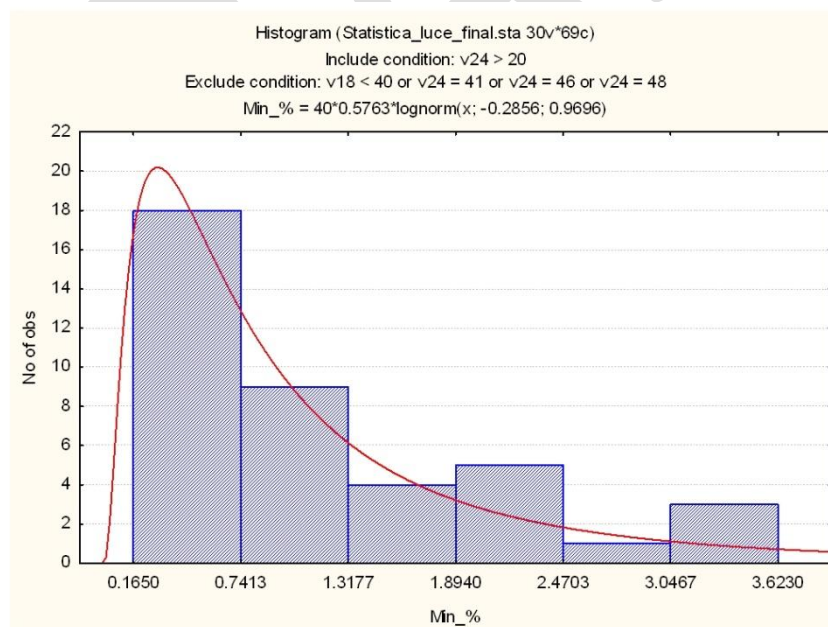


Figure 4 Histogram of the observed minimum light values associated with 40 Italian, French and Spanish Posidonia meadow polygons.

The quality of the fit between the photic zone and Posidonia meadow extension is shown in Figure 5. This fit was actually computed with the 1% value (prior to adopting 0.82%), however the difference is negligible. It should be noted that the quality of the underlying bathymetry is crucial in this

validation. However good our field data may be, if the Zeu computation is jeopardised by approximate bathymetry, then the validation process is meaningless. In the Lavezzi Islands area, the DTM comes from unbiased soundings and the error of the kriged DTM remains within the 1-5m range.

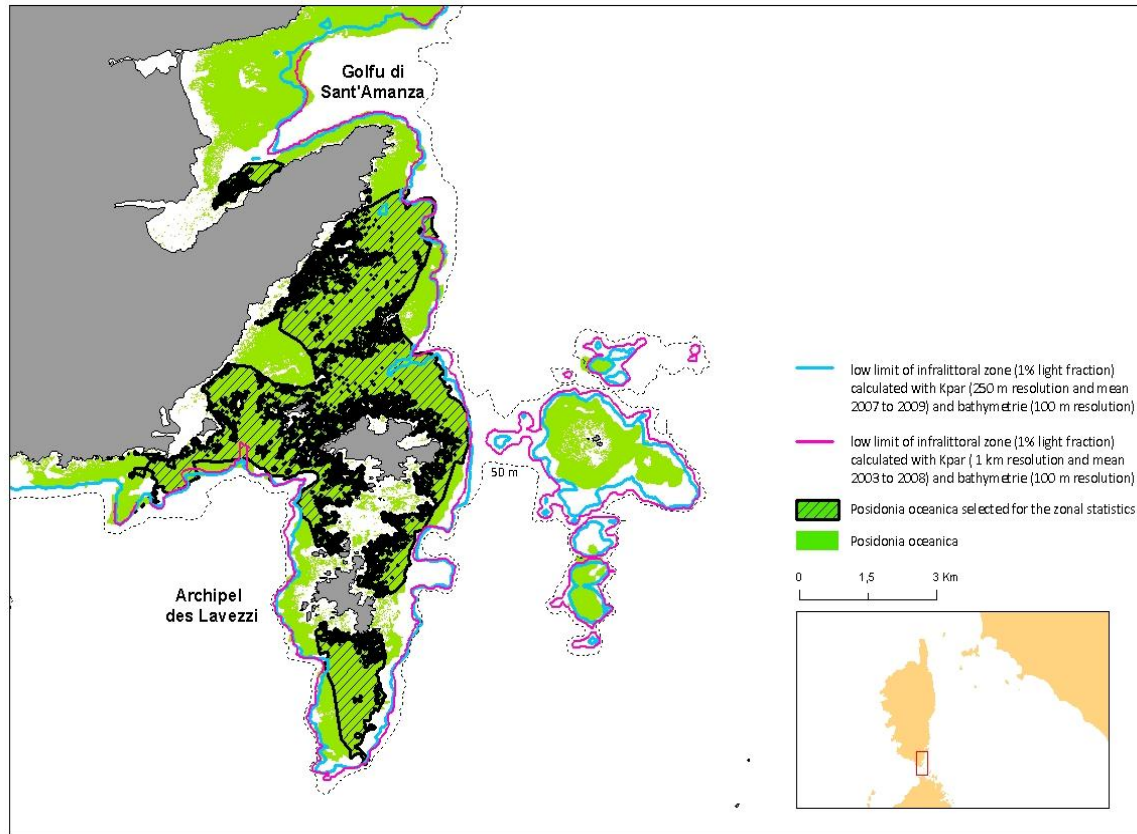


Figure 5 Visual comparison between satellite-derived photic depth Z_{eu} computed from 1km and 250 m MERIS imagery respectively in red and blue, and lower limit of *Posidonia* beds in Corsica (Lavezzi Archipelago).

2.5.5 Definition and validation of the upper / lower circalittoral boundary

The lower limit of the upper Circalittoral zone is defined by the limit of the deepest extension of sciaphilic algae photosynthesis (brown algae *Cystoseira*, *Sargassum*, *Laminaria*). According to bibliographic literature, this is defined as 0.01% surface light reaching the sea bottom. However, the distribution of these sciaphilic algae is not only poorly known and mapped but also limited in spatial extension and is far too fine scale with respect to the broad scale 250 pixel resolution of the model. A validation of the modelled 0.01% light layer with respect to these assemblages is therefore not possible, since our previous experience with the validation of 1% light-*Posidonia* indicated that fine scale point data are not useful for validation of interpolated variable values reported on large size pixels such as those used in the present project. The conclusion is that the 0.01% light layer cannot be validated using the very same assemblages that are presumed from literature to be indicative of the change in this variable threshold.

In an attempt to express the uncertainty of the latter limit and give proper warning to users, it was decided to derive fuzzy limits for this boundary. As fuzzy limits could not be based on statistical quartiles data as was the case for the photic zone, the project opted for a range using the same proportion of the central value [0.005 to 0.015%]. Refer to the fuzziness section to visualise the resulting buffer.

2.6 Light thresholds in the Baltic Sea

2.6.1 Computing Baltic light levels

Due to high amounts of coloured dissolved organic matter, frequent cloud cover and a lack of optical field data for sea-truthing, remote sensing of the optical properties of Baltic waters at a regional scale is difficult (Kratzer *et al.* 2003). An alternative approach, which was successfully applied earlier (Al-Hamdani & Reker 2007, HELCOM 2009), is using Secchi depth data. The method described in Al-Hamdani and Reker (2007) was refined, and additional data were incorporated, to produce a euphotic zone depth raster for the Baltic Sea.

Secchi depth data were obtained via the International Council for the Exploration of the Sea (ICES): Aarup's collection (Aarup 2002) covering 1902 to 1998 and additional data covering 1999 to 2008. Also the Finnish Environment Institute (SYKE) provided further data points for the years 2000 to 2008. For the interpolation of the light layer, only data from 1980 or later and covering months from which a reliable estimate of the growing season (March to October) mean could be derived were used. In total, the interpolation was based on data for 5738 locations.

At many of these locations, Secchi depths had been measured repeatedly, and monthly means were calculated. The main growing season from March to October was covered with at least one measurement per month at 277 locations. For these, "growing season means" were calculated, which were strongly correlated to the monthly means from April to October. Thus, a linear regression function was determined for each of these months (R^2 ranging from 0.77 to 0.86; Figure 7). For the locations where data were not available for the whole March to October period, but at least for one of the months between April and October, the growing season mean was estimated based on the month with the best-fitting regression line.

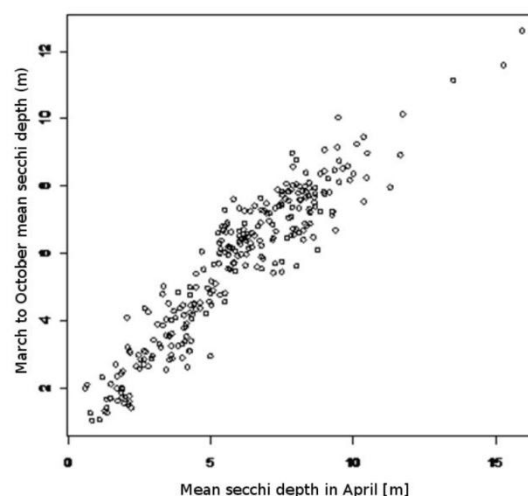


Figure 6 Scatter plot of April mean secchi depths vs. growing season (March to October) mean secchi depths, $n=277$.

However, this approach neglects inter-annual variability, and the density of data points was spatially very variable. To avoid pseudo-patchiness, the study area was subdivided into squares with a side length of 10km. For each square, the growing season means of all data points within were averaged and assigned to the points' mean centre. A secchi depth raster with a spatial resolution of 200m was then interpolated from the mean centres based on local trend surfaces. Cross-validation showed a mean error caused by the interpolation of below 1m and without a clear spatial pattern. Finally, a low pass filter was applied.

To derive euphotic zone depths from secchi depths, conversion factors ranging from 1.7 to 3.5 have been suggested in literature (Al-Hamdani and Reker, 2007, and references therein; Holmes 1970). For the Skagerrak and Kattegat, the secchi depths were compared to euphotic zone depths derived from Aqua-MODIS satellite imagery at 1km resolution. A factor of three gave the best fit. This is backed up by Holmes (1970). Figure 8 shows the final euphotic zone depth raster.

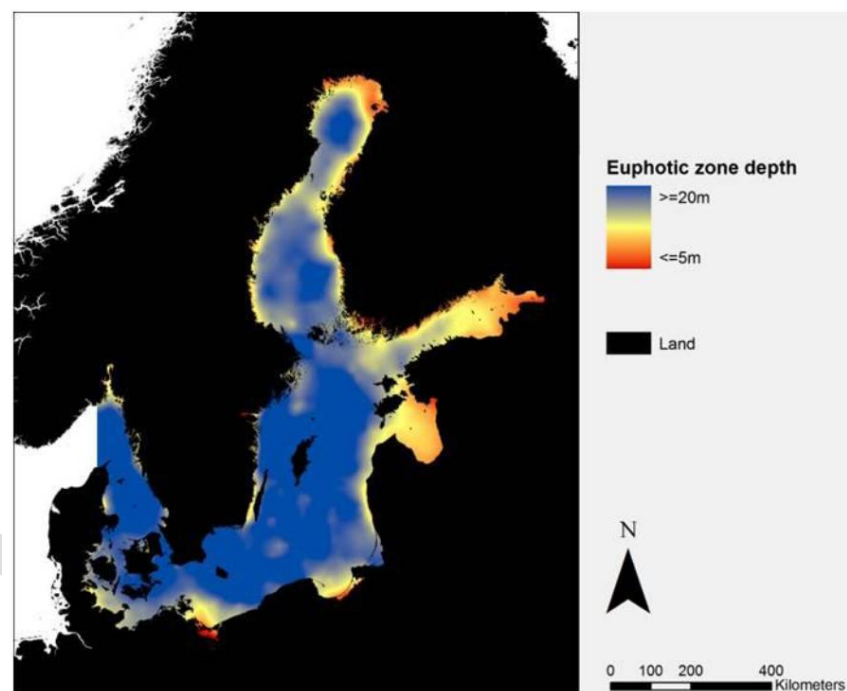


Figure 7 Euphotic zone depths for the Baltic Sea derived from secchi data.

The analyses of thresholds for light were done separately for (1) oligohaline, (2) mesohaline and (3) polyhaline and fully marine zones, since the biological communities used to define the thresholds differ greatly between the salinity zones. In the oligo- and mesohaline parts of the Baltic Sea proper (inside Öresund and the Danish Belts), the ratio between Secchi depth and depth was instead used to map the thresholds. In the polyhaline and fully marine parts of the Baltic Sea area (Kattegat and Skagerrak), the $K_{d_{PAR}}$ layer produced from MERIS data was used to map the thresholds between infralittoral and circalittoral and between upper and lower circalittoral.

2.6.2 Oligohaline and mesohaline zones

The oligohaline and mesohaline zones lack kelp communities, which are used to define the lower threshold of the infralittoral in the Atlantic EUNIS. Instead, the threshold was defined by the deepest occurrence of algal-dominated biotopes.

The field data set used to set the threshold values came from a total of 902 diving transects from the Swedish and Finnish coasts, 70 from the oligo- and 832 from the mesohaline salinity zones. The data was compiled from a number of different studies, using a standard method for monitoring of phytobenthic communities in the Baltic Sea (Kautsky 1992; HELCOM 1999). In short, diving transects were placed perpendicular to the shoreline, from the shore to the deepest occurrence of macroalgae or plants and the substratum type and surface cover of all algae, plants and sessile animals were noted within depth sections in a 6-10 m wide corridor along the transect line. The transect method is designed to monitor depth distribution of organisms and the data were therefore expected to be well suited to defining the light-related thresholds.

For threshold analyses, each transect section from the diving transects was classified into preliminary EUNIS classes using the BalMar tool (reference) and the deepest finding of biotopes dominated by macroalgae was recorded for each transect and used in the analyses. The depth/Secchi depth ratio for the deepest recording was calculated as the ratio between the depth recorded during the inventory and the Secchi depth taken from the interpolated data layer (data ref code?).

The results from the analyses are shown in Figure 8 and Table 4. The analyses identified a large variation in the largest depth/Secchi depth ratio. Part of this variation is likely to come from the fact that the depth distribution of algae at a certain site can be set by substrate limitation instead of light limitation. This is likely the case for a large part of the recordings of depth limit at a depth/Secchi depth ratio much below 2. However, part of the variation is likely due to errors in the Secchi depth layer.

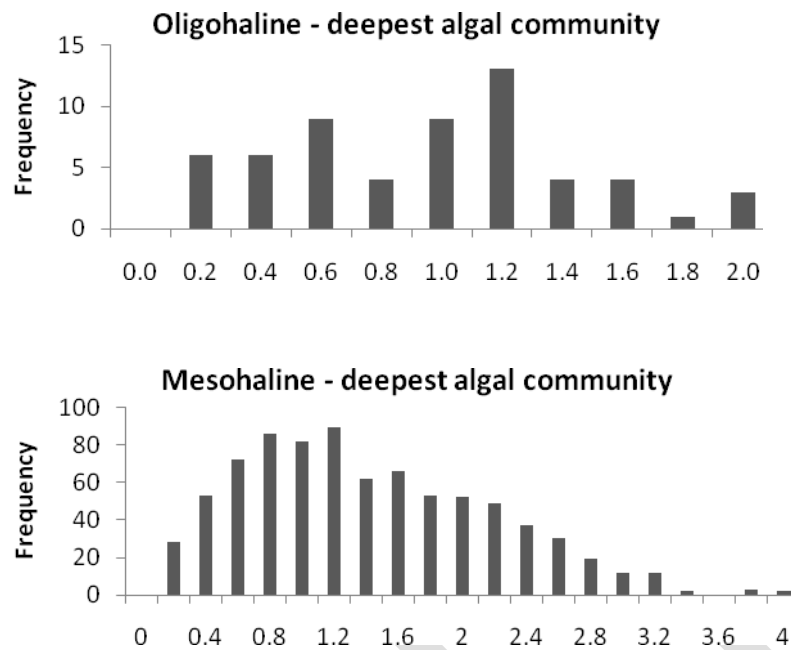


Figure 8 Histograms of depth distribution of the deepest location found of algae-dominated communities in transects.

Table 4 The thresholds defined for the oligo- and mesohaline salinity zones. The values are depth/Secchi depth ratio.

	Fuzzy threshold	Definition	Statistica	Value (D/SD)
Oligohaline				
Infralittoral/circalittoral	upper	Depth of algal domination	75 percentile	1.2
Infralittoral/circalittoral	lower	Depth of algal domination	max	2.0
Mesohaline				
Infralittoral/circalittoral	upper	Depth of algal domination	75 percentile	1.8
Infralittoral/circalittoral	lower	Depth of algal domination	max	3.2

The maximum depth/Secchi depth ratio recorded was used as the lower limit of the fuzzy threshold, after removing one or a few extreme outliers apparently resulting from errors in the Secchi depth layer. The 75 percentile was used as the upper limit of the fuzzy threshold for the transect data. The percentile levels were chosen as the expected fraction of the data that is likely to show the deepest occurrence of macroalgae and the resulting threshold values were examined and judged to give a reasonable result.

The wide fuzzy threshold results in a large uncertainty around the light thresholds derived from the Secchi depth layer. It was also clear from the analyses that the defined thresholds tend to overestimate the depth distribution in some regions while underestimating it in other regions. For instance, the depth of the infralittoral is underestimated in offshore areas of the Baltic Proper, in some parts of the Eastern Baltic Proper and some coastal areas in the Bothnian Bay. This means that the mapping of the biological zones in the Baltic Sea could be greatly improved by a better light layer for the Baltic Sea, for instance produced from MERIS data.

2.6.3 Polyhaline and fully marine zones

In the polyhaline and fully marine zones, the lower threshold of the infralittoral was mapped using the threshold developed for the North and Celtic Seas. The relevance of this threshold in the Kattegat and Skagerrak was tested using the depth limit of kelp (*Saccharina latissima*, *Laminaria digitata* and *L. hyperborea*) in 198 diving transects collected with the method described above and in most transects the maximum depth. Only three of the transects (<2%) had presence of kelp below 1% light from the $K_{d_{PAR}}$ layer, indicating that this threshold is relevant in the polyhaline and euhaline salinity zone as well in the Kattegat and Skagerrak..

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EUSeaMap

Technical Report No. X

Modelling

DRAFT

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1 Introduction

The objective of the EUSeaMap project was not only to produce habitat maps but also to deliver a model that would allow repeatability, i.e. a model that could be rerun by persons with moderate expertise in geographic information system and no experience in computer programming.

After a recap of the different concepts used in the EUSeaMap modelling project (triplet approach and fuzzy logic), this document describes how modelling has been carried out, what models are composed of, what they need to run and what they produce.

2 Methodology: the 'triplet' approach

EUSeaMap modelling methodology builds on the MESH project 'triplet' approach, which involves the combination of three information layers (Coltman et al., 2008):

- Seabed substrate (e.g. mud, sand, rock)
- Biological zone (e.g. infralittoral, circalittoral), based on bathymetry and light variables
- Energy (e.g. low energy, moderate energy), based on variables describing wave action and tidal currents

Each of these three layers contains codes. The final habitat map is the result of a simple addition of these codes. Different units are used in each layer so that the background information is not lost when layers are combined. These units are 1's for energy codes (e.g. 2 is 'moderate energy'), 10's for seabed substrate codes (e.g. 10 is 'rock') and 100's for biological zone codes (e.g. 300 is 'deep circalittoral'). Therefore the addition of the three layers results in a layer with a 3 digits code that is quite easy to decrypt (in the above examples we would have 312, which means 'deep circalittoral' + 'rock' + 'moderate energy').

Such a 'triplet' term was relevant for the MESH study area. Within the EUSeamap project, it is relevant for the North/Celtic Seas, but it is not for the Baltic Sea, where a salinity parameter needs to be taken into account, and the Mediterranean Sea, where energy variable cannot be used.

3 Thresholds and Fuzzy logic

Computing categorical maps, for example biological zones (infralittoral, circalittoral and so on), from continuous variables, implies that a set of thresholds have to be determined. For example, in the Mediterranean Sea the threshold for infralittoral – circalittoral delimitation is 1% of light reaching the seabed, because it is considered that below this value seagrasses do no longer have light enough to grow. Above this limit the probability of being in infralittoral zone is 1, below it is 0. Symmetrically above this limit probability of being in circalittoral zone is 0, below it is 1.

But trying to classify in this way has limitations. Obviously nature is not as simple; boundaries between two habitats are not that sharp. A way to show some of the flexibility seen in real world is to use fuzzy boundaries instead of sharp ones.

Fuzzy logic involves calculations of probability derived not merely from Boolean laws, as described above, but through a fuzzy membership function. The shape of this function is governed by four control points (Roberson et al., 2004). Figure 1 illustrates the fuzzy membership function of a class, e.g. "Upper circalittoral" biological zone. In abscissa is the variable value (e.g. percentage of light at the seabed). In ordinate is the degree of membership, i.e. the probability of being in the class. Control points are a, b, c and d. Their abscissa is, respectively, ULMin (Upper Limit Minimum abscissa), ULMax (Upper Limit Maximum abscissa), LLMin (Lower Limit Minimum abscissa), and LLMax (Lower Limit Maximum abscissa).

Point 'a' indicates where the membership function begins to increase above 0. 'b' is the point where the membership degree reaches its plateau, i.e. 1. Point 'c' marks the location where the membership function begins to drop below 1 and 'd' indicates where the membership degree again is 0. In other words before point 'a' and after point 'd', there is no doubt that we are out of the class; between points 'b' and 'c', there is no doubt that we are within the class; and between points 'a' and 'b' on the one hand (upper limit of the class) between points 'c' and 'd' on the other hand (lower limit of the class) it is "fuzzy", fuzziness being expressed through an equation. This equation can be a simple straight line, as shown in figure 1, or a more complex function. In EUSeaMap, a straight line was used to model fuzziness.

A fuzzy membership function is not always composed of four points. If a class has only one limit because there is not any other class either above it (e.g. infralittoral zone) or below it (e.g. abyssal zone) the function will have only 2 points.

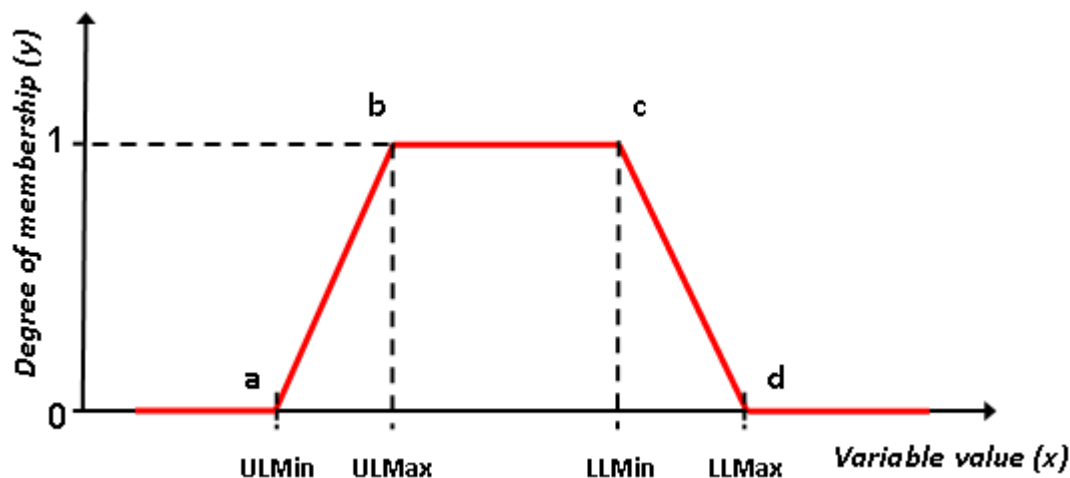


Figure 1 Fuzzy memberships function of a class (e.g. upper circalittoral biological zone). Controls points are 'a', 'b', 'c' and 'd'. From left to right, before 'a' and after 'd', likelihood is 0; between 'b' and 'c', it is 1; between 'a' and 'b' is the upper boundary of the class. There likelihood goes up from 0 to 1; between 'c' and 'd' is the lower boundary of the class. There likelihood drops from 1 to 0.

In terms of thresholds, by comparison with a Boolean classifier a fuzzy one needs more than one threshold to define a class boundary; it needs a range of values, corresponding to [ULMin, ULMax] and [LLMin, LLMax] in figure 1. These fuzzy limits are defined either from literature and expert judgment (rarely), or through testing against field data.

Having established these values, the appropriate membership fuzzy function to assign a value between 0 and 1 to each grid cell in a fuzzy membership 'score' layer is the following one.

When $x \leq UL_{Min}$ or $x \geq LL_{Max}$, $y = 0$

When $x \geq UL_{Max}$ and $x \leq LL_{Min}$, $y = 1$

When $x > UL_{Min}$ and $x < UL_{Max}$, $y = x / (UL_{Max} - UL_{Min}) - UL_{Min} / (UL_{Max} - UL_{Min})$

When $x > LL_{Min}$ and $x < LL_{Max}$, $y = x / (LL_{Min} - LL_{Max}) - LL_{Max} / (LL_{Min} - LL_{Max})$

This function has to be run for each class that comprises a given variable. Hence the result is one membership 'score' layer per class. For example for biological zones in Mediterranean Sea we will have five membership 'score' layers ('infralittoral', 'upper circalittoral', 'deep circalittoral', 'bathyal', 'abyssal'). Obviously this does not constitute a final product. It has to be simplified.

Two products can be derived from the class membership 'score' layers (figure 2):

- A 'membership' categorical layer (figure 2a) indicating to which class a given pixel belongs. This layer is obtained by picking up in the class membership 'score' layers, for each pixel, the identifier of the class which has the greatest score.
- A global 'membership score' layer (figure 2b) within which the value of a pixel is the membership score of the class which has the greatest score.

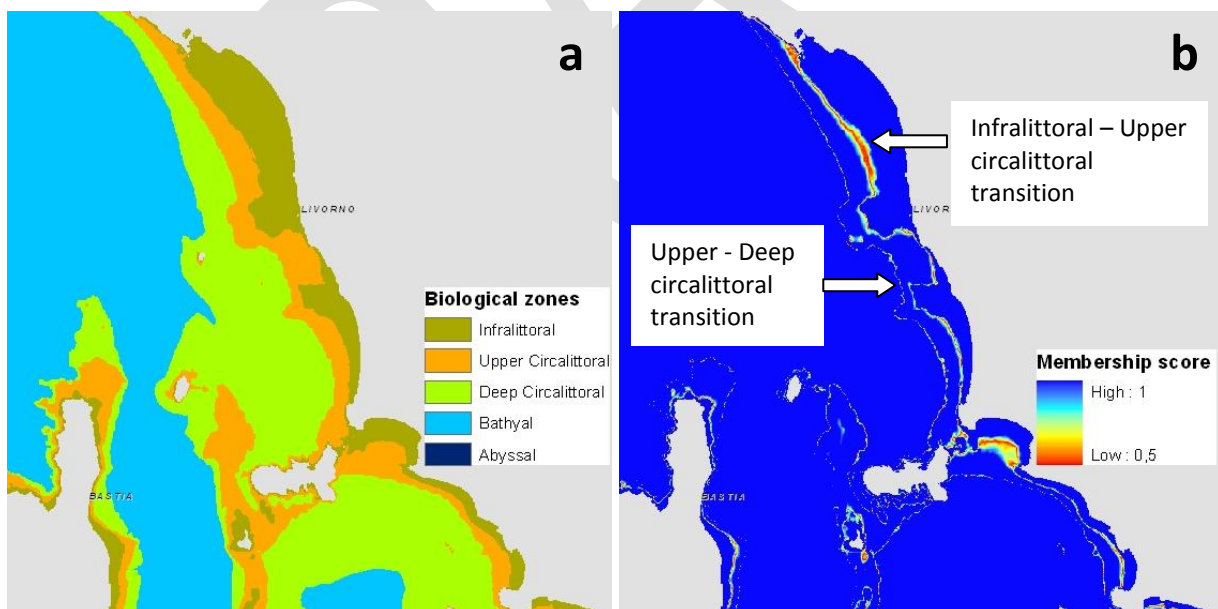


Figure 2 Products provided by a fuzzy classification (example of biological zones scheme). (a) The 'membership' layer, where the value of a pixel is the identifier of the class which has the greatest score; (b) The 'membership score' layer within which the value of a pixel is the membership score of the class which has the greatest score. While 'a' is classical categorical map, easy to understand, 'b' provides a supplemental information when clicking on a pixel in a GIS software : the likelihood of occurrence of a class; it also visually presents the transitional zones where we move from one environment to another (non-blue coloured 'ribbons')

These two products are complementary. The former one is a classical easy-to-use categorical map. The latter one provides the user with additional information. For each pixel it indicates the likelihood of occurrence of a class, and reflects visually the transition zones where we move from one environment to another (e.g. from infralittoral to circalittoral or from low to high energy).

4 Technical considerations

Modelling within EUSeaMap Project has been carried out in raster mode, which is the most convenient and the most efficient way to combine multiple continuous variables. ESRI® ArcGIS™ 9.3 and Spatial Analyst have been used. ArcGIS™ is a GIS software. One of its modules is ModelBuilder, which allows one to design models, i.e. graphically chain together ArcGIS™ tools using the output of one tool as the input to another tool. Models designed through ModelBuilder can be saved and executed multiple times. Spatial Analyst™ is an extension of ArcGIS™, in which raster combination through the concept of ‘map algebra’ can be performed.

4.1 Model settings

One of the key requirements of the EUSeaMap project was that it had to be done at 300m resolution, and that the outputs had to be in geographic coordinates (latitude/longitude). As longitude length strongly varies with latitude (e.g. 1° of longitude in Madrid = 85km, whereas 1° of longitude in London = 69km) it was not possible to have the same resolution for the whole project study area. Therefore one of the main objectives was to find, for each basin covered by the project, a resolution not equal to but globally compatible with the expected 300m resolution. Partners finally agreed on a 0.0027 decimal degrees resolution in the Mediterranean Sea (which equates to a cell of 230x300m) and a 0.003 decimal degrees resolution in Celtic, North and Baltic seas (which equates to a cell of 167x333m).

For the above reason, for storage considerations and also because each basin has its own specificities (e.g. only Baltic Sea takes account of salinity) one model has been developed for each basin: one for Baltic Sea, one for North/Celtic Seas, and one for Mediterranean Sea.

The following ArcGIS environment settings were used, applied to the individual models for the basins:

Cartography settings > Cartographic coordinate system > **WGS84** (geographic coordinate system)

General settings > Extent > Specified basin lat long limits (see table 1)

Raster Analysis settings > Cell Size > Specified basin cell size (**0.003 dd** for Baltic, Celtic and North Sea, **0.0027 dd** for Mediterranean Sea)

The limits of the regions used in the modelling are set out in Table 1. A region of overlap between 8 and 13 degrees east was run for the Kattegat Sea marking the transitional area between the Baltic and North Sea. The North and Celtic areas were treated as contiguous areas; run within the same model with the same thresholds, settings and rules.

Table 1 – Latitudinal and longitudinal limits of the models. Figures are given in decimal degrees, WGS84 horizontal datum.

Region	Lat. Min.	Lat. Max.	Long. Min.	Long. Max.
Baltic Sea	53.592700	65.907700	9.418402	30.244402
North and Celtic Seas	46.836332	63.885332	-24.997816	12.997184
Western Mediterranean Sea	34.741792	44.720992	-6.1166584	16.328442

The exact areas covered by the models were limited by the spatial coverage of input datasets. The extent of the substrate layer dictates the extent of the final habitat map.

4.2 EUSeaMap toolbox

As mentioned in the introduction, one of the main challenges of the projects was to build reusable models, i.e. models that could be run repeatedly by persons with little experience in computer programming or in the use of ArcGIS™ ModelBuilder.

Thus an ArcGIS™ toolbox, called 'EUSeaMap', was built (figure 3). This toolbox is composed of three toolsets (one toolset per basin), with each toolset containing at least one main model that has to be run to build the habitat map. The toolset can also contain other models which are either called by the main model or have to be run by the user before running the main model.

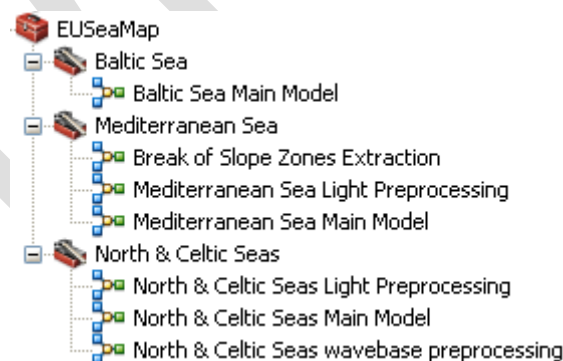


Figure 3 EUSeaMap Toolbox. It contains three toolsets (one per region), and each toolset contains at least one model, the main one. For example in Mediterranean the main model is 'Mediterranean Sea Main Model'. The other models are either loaded by the main one (e.g. 'Break of Slope Zones Extraction'), or are tools that have to be loaded by the user before launching the main model (e.g. 'Mediterranean Sea Light Preprocessing').

4.3 EUSeaMap file structure

Models and data are stored according to the following hierarchical file structure (figure 4): in the first level there are four directories, one for each model plus one named 'toolbox', which contains 'EUSeaMap.tbx' file, which is the ArcGIS™ toolbox file corresponding to the EUSeaMap toolbox described above. Within each model directory, there are four sub-directories: 'inputs' containing the data that feeds the model; 'output' into which the model writes the data it produces; 'temp' which stores the temporary data created by the model while running and 'translation_table' which contains the excel file that enables translation of the triplet codes found in the habitat map computed by the model into corresponding Eunis codes (see 'habitat translation table' section above for more details).

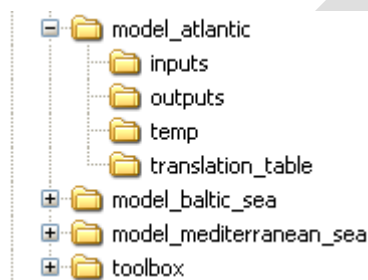


Figure 4 Modelling file structure. 'toolbox' is the directory that contains the EUSeaMap toolbox file. The other directories contain information consumed or produced by each regional model. Each of these model directories (e.g. 'model_atlantic' directory, opened here) contain 4 sub-directories. 'inputs' contains the input data consumed by the model, 'outputs' contains the outputs of the model, 'temp' holds the temporary files that the model creates and in 'translation_table' directory there is the excel file that enables translation of the triplet codes into corresponding Eunis codes.

4.4 How to use the EUSeaMap toolbox

To install the EUSeaMap toolbox in an ArcMap™ document (i.e. a mxd file), right-click the 'ArcToolBox' entry in the ArcToolBox window, and click 'Add Toolbox'. Browse to the location containing the 'EUSeaMap.tbx' file ('toolbox' directory, as mentioned in the previous section), and select the file.

To launch a model in ArcMap™ ArcToolbox window one has to double click on the name of the model. This will open a dialog box allowing one to parameter the model (figure 5). The parameters are the thresholds and the input files. They are specific to a given basin. Default values are proposed for each parameter. These values are those that have been used in the scope of the project. For more details on what each parameter correspond to for a given basin see 'Regional model description' section.

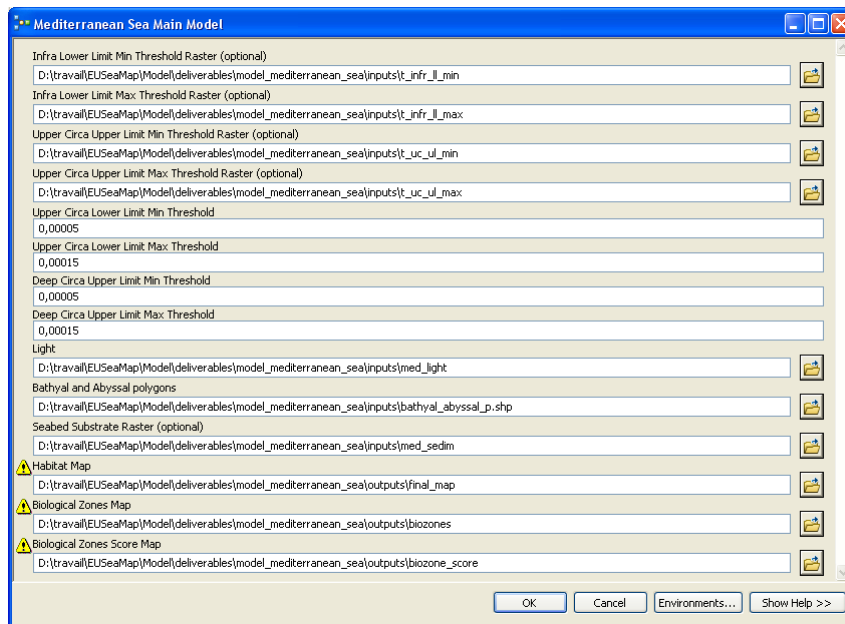


Figure 5 Example of a dialog box used to parameter a model, here the Mediterranean Sea model

4.5 Habitat translation tables

As mentioned in chapter 2, models produce habitat maps identified through triplet codes. These codes have then to be translated in Eunis. This can be done thanks to a translation table, which is in an excel file located, as seen in 'EUSeaMap file structure' section, in 'translation_table' directories.

Model code combinations were translated to EUNIS habitat types where possible. This exercise requires careful examination of the EUNIS classification system in the context of the possible combinations of physical variables that are used in the EUSeaMap models. Model code combinations were matched to EUNIS codes at level 3 and in some cases down to level 4. For the Baltic the model outputs were used to develop a proposal for the level structure of EUNIS for the Baltic region, and so the translation table relates it to proposed EUNIS habitat types, with dummy EUNIS codes.

In addition to the full detail EUNIS habitats that were predicted, the tables were adapted to include information on parent EUNIS classes, and additional aggregation classification schemes. This allows users to display the final outputs in aggregations that are suitable for different purposes.

5 Regional model descriptions

The goal of this chapter is to describe how to reuse a model if updates need to be applied (update of a layer, i.e. bathymetry, or of a threshold). In other words this section provides assistance for filling in the dialog box seen above. Therefore it describes each input the model requires and the output it produces. It also gives a short description of how the model proceeds, without going into further details.

5.1 Baltic model

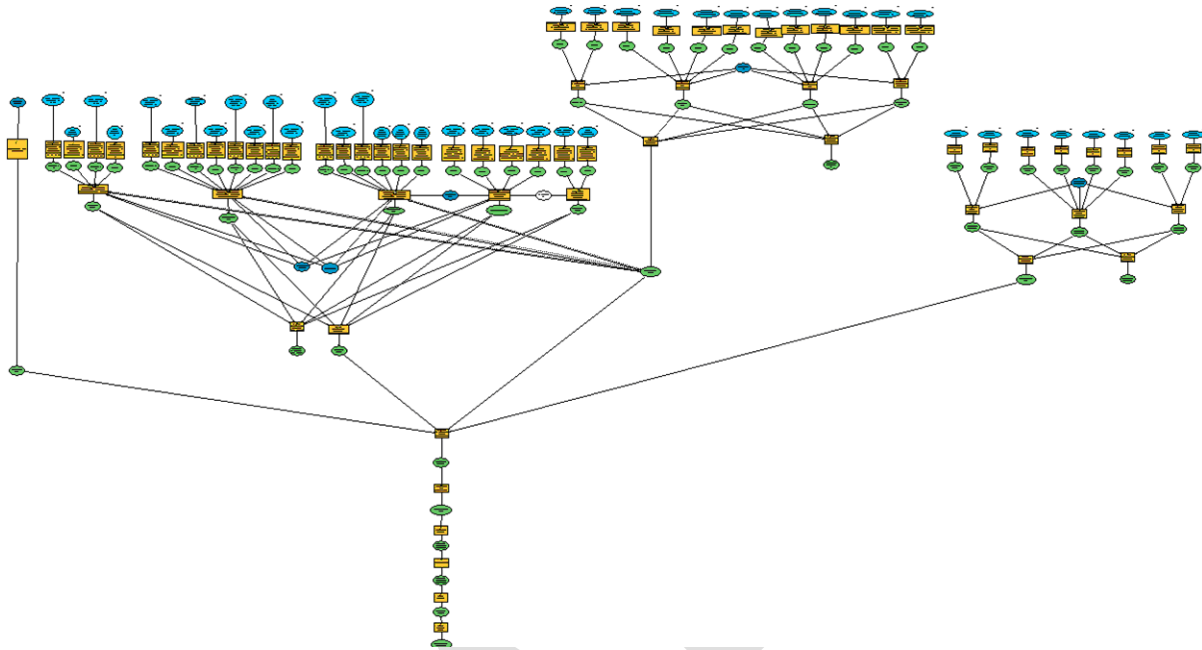


Figure 6 Screen capture of the Baltic Sea region habitat model

4.1.1. Baltic model inputs

The input layers for the Baltic basin are as follows:

Substrate

The data source was the 1:1,000,000 vector substrate map produced by the EMODNET Geology group (August 2010 release). The original map is stored in a personal GeoDatabase. The process to convert the map to a raster grid is within the main model. In order for the model to work properly the table of the layer must contain a field named 'substcode'. This is a key field because it holds the codes that the model needs to compute the triplet code. These codes are listed in table 2. For more details on the substrate layer see the Substrate technical appendix.

Table 2 – Seabed substrates of Baltic, North and Celtic Seas. and corresponding codes

Substrate	substcode
Seabed	0
Mud to Sandy Mud	1
Sand to Muddy Sand	2
Coarse Sediment	3
Mixed Sediment	4
Till	5
Rock or Reef	6

Bathymetry

The bathymetry used was that also used in the BALANCE project. For more details on the bathymetry layer see the Bathymetry technical appendix.

Light

The ratio of water depth to secchi depth. In addition a light (% at seabed) layer based on MERIS satellite data was used for polyhaline and euhaline areas as classified using the salinity layer. For more details on the light layer see the Light technical appendix.

Wavebase ratio

The wavebase ratio is the product of a preprocessing model, which implements a series of calculations (based on Soulsby, 1997) to derive the ratio of wavelength to depth, using peak wave periods across the study region. It is only used for euhaline areas as classified using the salinity layer. For more details on the wavebase ratio layer see the Energy technical appendix.

Salinity

The salinity layer is the mean value (psu). It has been estimated using calibrated and validated hydrodynamic model data averaged over several years (2000 – 2008), at a scale of ~5.5km. For more details on the salinity layer see the Salinity technical appendix.

Energy

In the Baltic model a single energy layer is used: wave energy exposure layer, pre-prepared using a high resolution fetch-based wave exposure model, amalgamated with coarse resolution oceanographic modelled data. For more details on the energy layer see the Energy technical appendix.

In addition to the above input data layers, the thresholds used in the model are requested as input parameters by the model to construct constant rasters for each threshold used in the model. All threshold parameters were specified as Data Type double, and are listed in summary Table 4. Details of the thresholds are in the corresponding Technical Appendices for the relevant variable.

4.1.2. Baltic model Outputs

The main outputs layers for the North/Celtic region are as follows:

Biological Zones Score Map – Gridded raster layer. The fuzzy membership scores associated with the final Biological Zone classification produced by the model per grid cell.

Biological Zones Map – Gridded raster layer. The final Biological Zone classification produced by the model per grid cell.

Combined Score Map – Gridded raster layer. The combined fuzzy membership scores per grid cell associated with the final classifications of energy and biological zone.

Energy Classification Map - Gridded raster layer. The energy classification (High, Medium or Low) based on energy due to waves at the seabed.

Energy Score Map - Gridded raster layer. The fuzzy membership score associated with the wave energy classification per grid cell.

Salinity Classification Map - Gridded raster layer. The salinity classification (oligohalinen, mesohaline, polyhaline or euhaline) based on energy due to currents at the seabed

Salinity Score Map - Gridded raster layer. The fuzzy membership score associated with the salinity classification per grid cell.

Seabed Substrate Raster Layer – Gridded raster layer. This is the raster conversion of the input polygon substrate map.

Habitat Map Raster Layer - Gridded raster layer. The final habitat output map with ModelCode built from a combination of the Biological zone, energy, salinity and substrate class codes.

Habitat Map Polygon Layer – Polygon shapefile. The final habitat output map, to which habitat types are translated using join with the habitat translation table (based on the ModelGrid code).

In addition to these layers, the contributing fuzzy membership classes for each individual class are stored within the folder Outputs>Classes

4.1.3. Baltic model Geoprocessing

As shown in figure 2 the Baltic toolset contains only the main habitat model: all input data was pre-prepared, with the exception of the light layer that is used in Polyhaline and Euhaline regions as delineated by the model using the salinity data layer.

The Baltic model runs the geoprocessing to establish the salinity regime first, as a precondition on the biological zones and energy classification. If the salinity class is either Polyhaline or Euhaline, the model rules implemented then for the Biological and energy classes are those that are used in the North & Celtic model. The model also switches input data layers to the same as those used for the North Sea, and as a result the outputs are identical to those predicted by the North & Celtic Seas model in the area of overlap that includes much of the Kattegat and Skagerrak Seas.

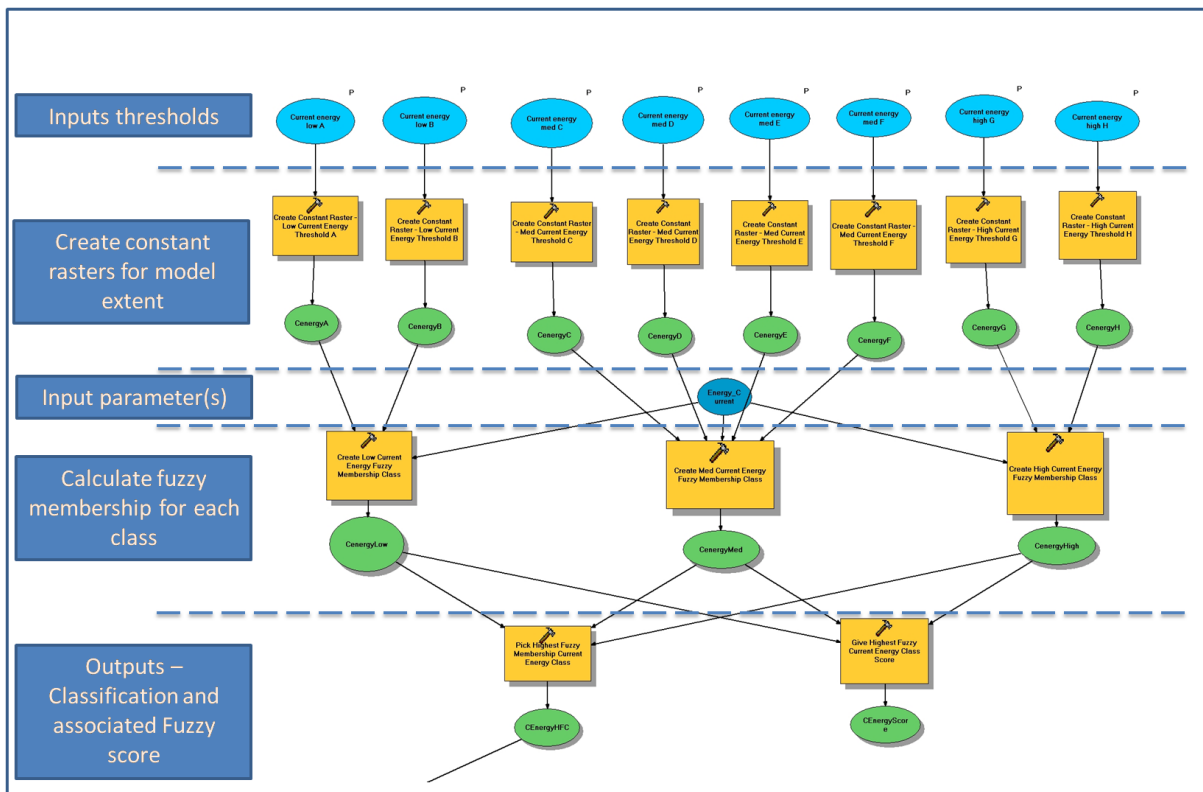


Figure 7 Annotated screen capture illustrating the geoprocessing to construct fuzzy membership values for each grid cell for each class.

Figure illustrates how the geoprocesses within the model convert the input thresholds into constant rasters which are in turn used to derive fuzzy membership functions for each grid cell. An example of the Map Algebra used to calculate these functions is given below for the infralittoral and circalittoral biological zones. The same principles are applied in the North, Celtic and Western Mediterranean models.

INFRALITTORAL

Threshold Raster name	BioCOLi	BioC	BioDOLi	BioD	BioEPoly	BioE	BioFPoly	BioF
Variable Raster name	n/a	Bathy	n/a	Bathy	Light	Light	Light	Light
Value	n/a	-1	n/a	1	0.011	0.0033	0.009	0.0027

con(salinityHFC == 4,con(Bathy >= 0 & Light > BioE,1,con(Light <= BioE & Light > BioF,(Light - BioF) / (BioE - BioF),0)),con(Bathy >= 0 & Light > BioEPoly, 1,con(Light <= BioEPoly & Light > BioFPoly,(Light - BioFPoly) / (BioEPoly - BioFPoly),0)))

con(salinityHFC == 3,con(Bathy >= 0 & Light > BioEPoly, 1,con(Light <= BioEPoly & Light > BioFPoly,(Light - BioFPoly) / (BioEPoly - BioFPoly),0)),con(Bathy >= 0 & Light > BioE,1,con(Light <= BioE & Light > BioF,(Light - BioF) / (BioE - BioF),0)))

CIRCALITTORAL

Threshold Raster name	BioGPoly	BioG	BioHPoly	BioH	BioIPoly	BioI	BioJPoly	BioJ
Variable Raster name	Light	Light	Light	Light	Light	Wbase	Light	Wbase
Value	0.011	0.0033	0.009	0.0027	0.0011	2.05	0.0009	1.95

con(salinityHFC == 4,con(Light > BioG,0,con(Light <= BioG & Light > BioH,(BioG - Light) / (BioG - BioH),con(Light <= BioH & Wbase > BioI,1,con(Wbase <= BioI & Wbase > BioJ,(Wbase - BioJ) / (BioI - BioJ),0))))),con(Light > BioG,0,con(Light <= BioGPoly & Light > BioHPoly,(BioGPoly - Light) / (BioGPoly - BioHPoly),con(Light <= BioHPoly & Light > BioIPoly,1,con(Light <= BioIPoly & Light > BioJPoly,(Light - BioJPoly) / (BioIPoly - BioJPoly),0))))))

con(salinityHFC == 3,con(Light > BioG,0,con(Light <= BioGPoly & Light > BioHPoly,(BioGPoly - Light) / (BioGPoly - BioHPoly),con(Light <= BioHPoly & Light > BioIPoly,1,con(Light <= BioIPoly & Light > BioJPoly,(Light - BioJPoly) / (BioIPoly - BioJPoly),0))))),con(Light > BioG,0,con(Light <= BioG & Light > BioH,(BioG - Light) / (BioG - BioH),con(Light <= BioH & Wbase > BioI,1,con(Wbase <= BioI & Wbase > BioJ,(Wbase - BioJ) / (BioI - BioJ),0))))))

5.2 North/Celtic model

4.2.1. North and Celtic model inputs

The input layers for the North/Celtic basin are as follows:

Substrate

The data source was the 1:1,000,000 vector substrate map produced by the EMODNET Geology group (August 2010 release). The original map is stored in a personal GeoDatabase. The process to convert the map to a raster grid is within the main model. The layer must contain a field named 'substcode' and this field must contain the values listed in table 2. For more details on the substrate layer see the Substrate technical appendix.

Bathymetry

Bathymetry was preprepared for the model, using the EMODNET Hydrography DEM (... release), replaced with the SeaZone Hydrospatial DEM in shallow UK waters. For more details on the bathymetry layer see the Bathymetry technical appendix.

Light

The light (% at seabed) layer is based on MERIS satellite data and used in both the polyhaline and euhaline areas as classified using the salinity layer. For more details on the light layer see the Light technical appendix.

Wavebase ratio

The wavebase ratio is the product of a preprocessing model, which implements a series of calculations (based on Soulsby, 1997) to derive the ratio of wavelength to depth, using peak wave periods across the study region. For more details on the wavebase ratio layer see the Energy technical appendix.

Salinity

The salinity layer is the mean value (psu). Salinity has been estimated using calibrated and validated hydrodynamic model data averaged over several years (2000 – 2008), at a scale of ~5.5km. For more details on the salinity ratio layer see the Salinity technical appendix.

Energy

In the North and Celtic Seas model, two energy layers are used. Kinetic energy at the seabed due to waves, and kinetic energy at the seabed due to tidal currents. For more details on the energy layers see the energy technical appendix.

In addition to the above input data layers, the thresholds used in the model are requested as input parameters by the model to construct constant rasters for each threshold used in the model. All threshold parameters were specified as Data Type double, and are listed in summary Table 4. Details of the thresholds are in the corresponding Technical Appendices for the relevant variable.

4.2.2. North and Celtic model outputs

The main outputs layers for the North/Celtic basin are as follows:

Biological Zones Score Map – Gridded raster layer. The fuzzy membership scores associated with the final Biological Zone classification produced by the model per grid cell.

Biological Zones Map – Gridded raster layer. The final Biological Zone classification produced by the model per grid cell.

Currents Energy Classification Map - Gridded raster layer. The energy classification (High, Medium or Low) based on energy due to currents at the seabed.

Currents Energy Score Map – Gridded raster layer . The fuzzy membership score associated with the current energy classification per grid cell.

Combined Score Map – Gridded raster layer. The combined fuzzy membership scores per grid cell associated with the final classifications of energy and biological zone.

Salinity Classification Map - Gridded raster layer. The salinity classification (oligohalinen, mesohaline, polyhaline or euhaline) based on energy due to currents at the seabed

Salinity Score Map - Gridded raster layer. The fuzzy membership score associated with the salinity classification per grid cell.

Seabed Substrate Raster Layer – Gridded raster layer. This is the raster conversion of the input polygon substrate map.

Wave Energy Classification Map - Gridded raster layer. The energy classification (High, Medium or Low) based on energy due to waves at the seabed.

Wave Energy Score Map - Gridded raster layer. The fuzzy membership score associated with the wave energy classification per grid cell.

Habitat Map Raster Layer - Gridded raster layer. The final habitat output map with ModelCode built from a combination of the Biological zone, energy, salinity and substrate class codes.

Habitat Map Polygon Layer – Polygon shapefile. The final habitat output map, to which habitat types are translated using join with the habitat translation table (based on the ModelGrid code).

In addition to these layers, the contributing fuzzy membership classes for each individual class are stored within the folder Outputs>Classes

4.2.3. North and Celtic model geoprocessing

As shown in figure 2, the North/Celtic toolset contains three models: the sub-routine to derive wave base ratios from peak wave periods across the study region, the sub-routine to compute the percentage of light at seabed from kpar, and the main model. The subroutines have to be launched before running the main model, as they produce the required inputs. These processes are described more fully in respectively energy and light technical appendices.

The North and Celtic Seas model also runs the geoprocessing to establish the salinity regime first, as a precondition on the biological zones. This allows the model to implement different rules for the polyhaline region in the Skagerrak and Kattegat Seas. The salinity regime effectively becomes the dividing line; the switch between North/Celtic model and the Baltic model happens at the interface between Mesohaline and Polyhaline.

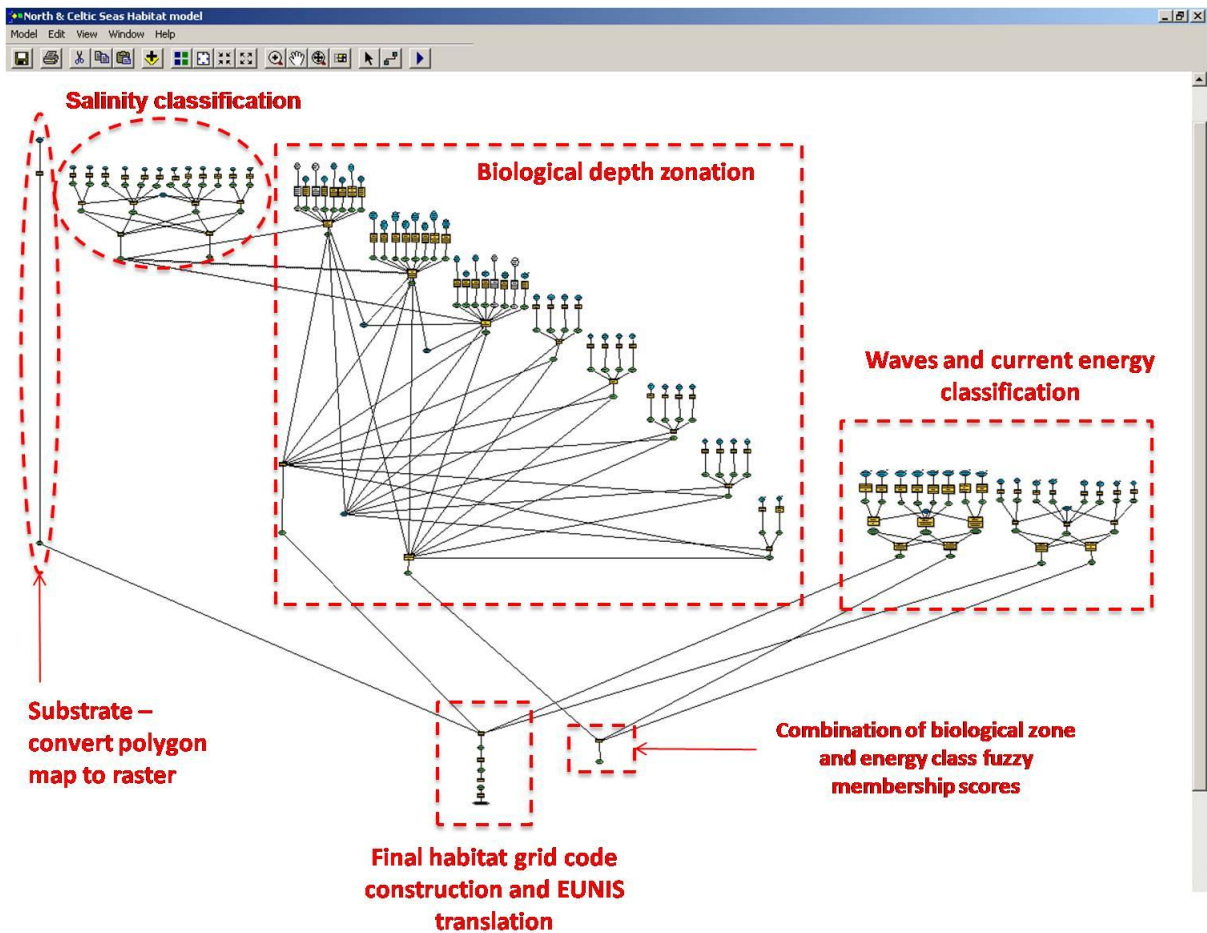


Figure 8 Screen capture of the North and Celtic sea basins' habitat model

5.3 Western Mediterranean model

One particularity of western Mediterranean basin is that only one physical variable is used in the model: percentage of light at seabed. Hence only one classification layer, the biological zones, has to be computed, and the final calculation, which performs the addition of these biological zones and the seabed substrates, results in a 'doublet' code. Another particularity is that because of Mediterranean Sea exceptional geomorphology (abrupt break of slopes) both circalittoral/bathyal and bathyal/abyssal delimitations are not derived from bathymetry thresholds, but were manually interpreted from the bathymetry layer.

The input layers for the Mediterranean basin are as follows:

Substrate

For copyright reasons the original substrate polygon layer can not be delivered. Thus the input of the Mediterranean model is a raster layer with a 0.0027 dd pixel size. The pixel

values must be those listed in table 3. For more details on the substrate layer see the Substrate technical appendix.

Table 3 – Seabed substrates of Mediterranean Sea and corresponding codes

Substrate	value
Rock	10
Coarse & mixed sediment	20
Sand	30
Sandy Mud	40
Muddy Sand	50
Sand	60
Posidonia oceanica	70
Cymodocea nodosa	80

Bathymetry

Bathymetry layer is multisource. For more details on the bathymetry layer see the Bathymetry technical appendix.

Light

The light input layer is the percentage at seabed. For more details on the light layer see the Light technical appendix.

Bathyal and Abyssal polygon layer

This polygon layer contains two polygons corresponding to the bathyal and the abyssal zones. In the 'CODE' field of the attribute table the bathyal polygon is given '1' value and the abyssal polygon is given '2' value. For more details on the how the limits of these polygons were elaborated see the bathymetry technical appendix.

In addition to the above input data layers, the thresholds used in the model are requested as input parameters. These threshold values are required to construct constant rasters for each model, except for the infralittoral lower limit and upper circalittoral upper limit. For these two limits, rather than providing a single value for each fuzzy membership function

control point (see fuzzy logic section), thresholds raster layers have to be provided because the value corresponding to these control points is not spatially constant. For example the percentage of light value corresponding to the 'a' control point of the upper circalittoral upper limit is 6.0 in gulf of Lion, while it is 1.1 elsewhere. Hence a raster layer containing two values (6.0 in gulf of Lion, 1.1 elsewhere) is provided to the model through the 'Upper Circa Upper Limit Max Threshold Raster' parameter of the dialog box.

All threshold parameters were specified as Data Type double, and are listed in summary Table 4. Details of the thresholds are in the corresponding Technical Appendices for the relevant variable.

4.2.4. Mediterranean model outputs

The main outputs layers for the Mediterranean basin are as follows:

Biological Zones Score Map – Gridded raster layer. The fuzzy membership scores associated with the final Biological Zone classification produced by the model per grid cell.

Biological Zones Map – Gridded raster layer. The final Biological Zone classification produced by the model per grid cell.

Habitat Map Raster Layer - Gridded raster layer. The final habitat output map with ModelCode built from a combination of the Biological zone and substrate class codes.

Habitat Map Polygon Layer – Polygon shapefile. The final habitat output map, to which habitat types are translated using join with the habitat translation table (based on the ModelGrid code).

4.2.5. Mediterranean model geoprocessing

As shown in figure 2, the Mediterranean toolset contains three models: the sub-routine to compute the percentage of light at seabed from kpar, the subroutine to extract biological zones that depend on the break of slope limits, and the main model. The first subroutine has to be launched before running the main model, as it produces the required light input. The subroutine that extracts biological zones depending on the break of slope limits is not stand-alone. It is launched by the main model.

Figure 9 illustrates the key steps of the model. It first converts the input thresholds into constant rasters which are in turn used to derive fuzzy membership functions for each grid cell. Then it transforms the bathyal and abyssal polygon layer into three raster layers ('shelf', 'bathyal zone' and 'abyssal zone'), calculates the fuzzy membership for each biological zone, computes the global fuzzy score layer and the biological zones, and finally performs the habitat map calculation.

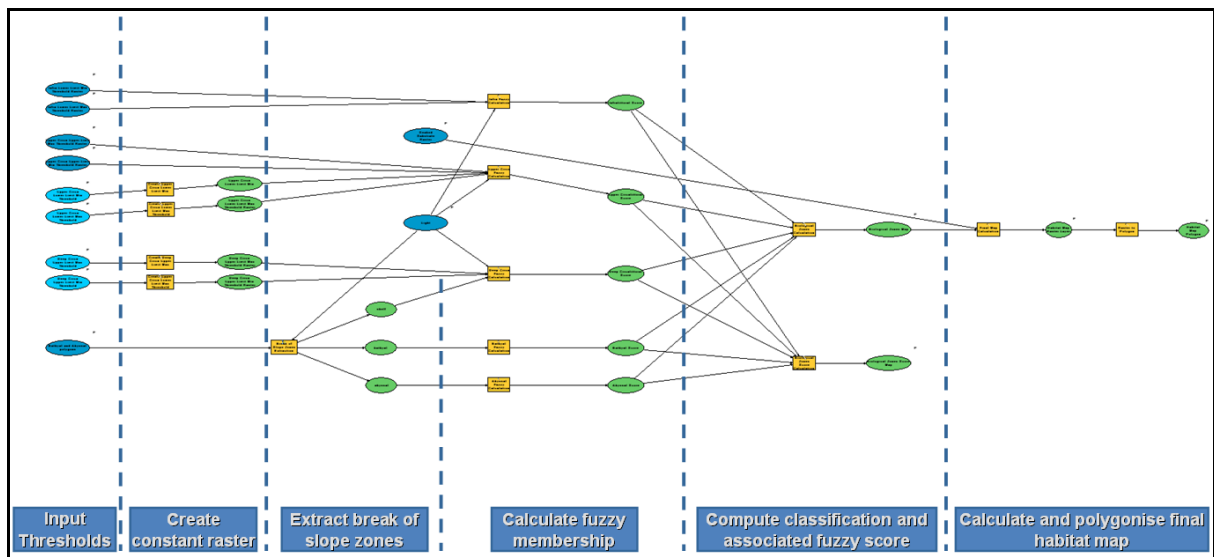


Figure 9 Screen capture of Mediterranean Sea basin's habitat model

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DRAFT

EUSeaMap

Technical Report No. X

Substrate data and thresholds

DRAFT

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DRAFT

1 Introduction

The task for producing a unified substrate map for the Baltic, North Sea, Celtic and the Mediterranean seas was not easy. Maps has to be compiled and integrated together where each individual map has its own classification standard and was presented in a particular format which need not to be the same as the others. Some maps are quite old and on paper which need digitization and georeferencing, other do not have metadata with which makes the judgment of its accuracy very difficult. Due to the low resolution background maps and the existence of gaps at many areas, the final product is not homogeneous in accuracy. Some parts are highly accurate with high confidence scores while others lack information and hence accuracy. Expert judgment was used in areas where there is little or no information.

2 Data layer preparation

Two main substrate maps were produced in the EUSeaMap project; one for the Baltic, North and Celtic Seas and the other for the Western Mediterranean Sea. The former required 200 maps to compile while the latter was produced from enormous amount of source maps and information as well as a lot of expert judgment and interpolation.

Folk classification system was adopted for the sediment classification, but it was modified according to the required outcome of the project which is the habitat map. The two modified Folk systems were not similar but follow the special characteristics of the two geographic regions.

2.1 Baltic, North and Celtic Seas

2.1.1 EMODNET sediment map

The first draft of EMODNET sediment map was delivered to EUSeaMap by June 2010. The map was a result of integration and harmonisation of data from 17 organisations from all partner's countries (Fig. 1). Each partner submitted a substrate map of their national waters including the EEZ. The submitted shape file contains attribute table containing information about the metadata.

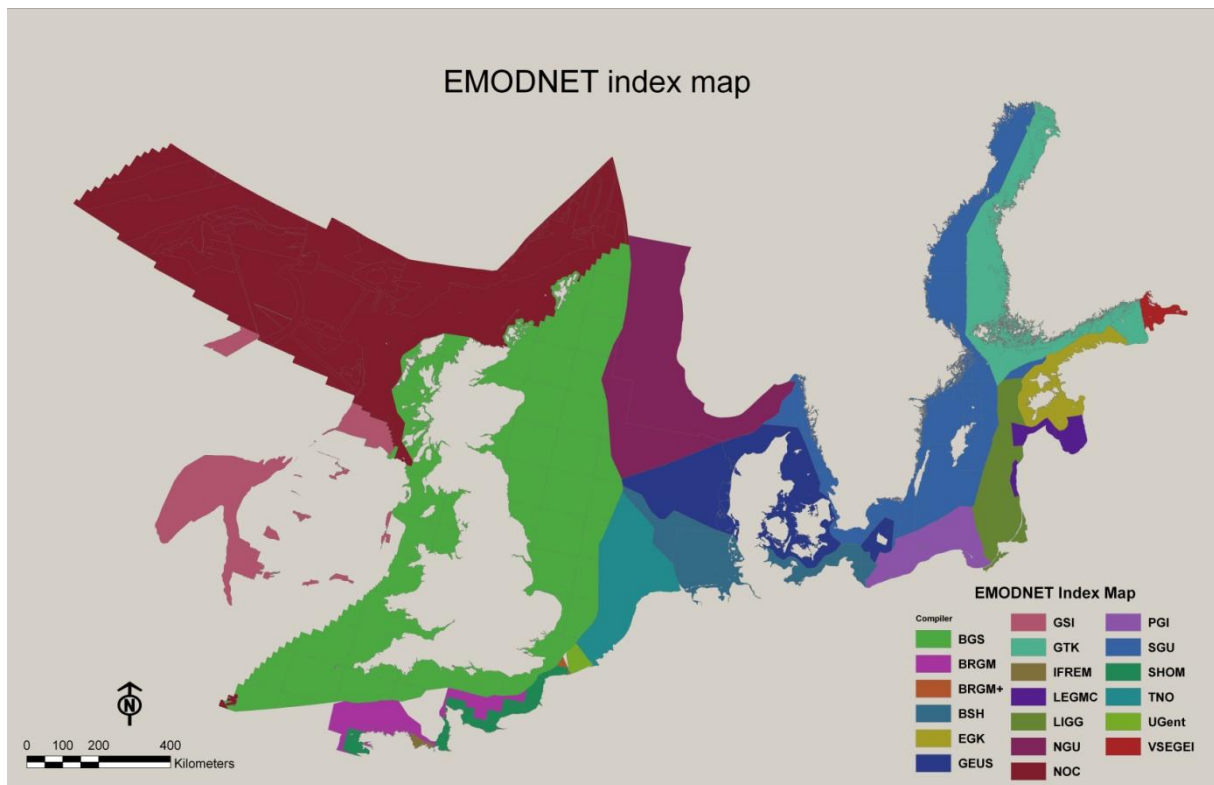


Figure 1 EMODNET index map

More than 200 maps were harmonised to a one continuous map. Methodologies used for producing these maps divers enormously, remote sensing method can varies from poor to full coverage and positioning systems ranges from advanced systems with 0-5m accuracy to Nautical Charts with over 100m accuracy. Gaps were found in few areas such as the Channel and the Celtic Sea.

One of the aims of the EMODNET - Geology project is to highlight data gaps and deficiencies, for example the low - resolution data on which many of the national geological interpretations are based. The attribute table was created in order to stress the importance of the metadata; even though the resulting substrate map would look continuous, the datasets behind include variable methodologies, sediment classification and confidence. The confidence of the map is not uniform and so areas are not always comparable. This information is necessary for users and decision - makers to allow them to realize the limitations of the maps.

Harmonisation

Each partner harmonised their available sea - bed substrate data. Like the index shape file, the sea - bed substrate shape file includes an attribute table that contains information related to the reclassification.

The current sea - bed substrate map was produced on the basis of EUSeaMap requirements. Due to the challenging timeline, the substrate reclassification scheme is simplified and provides an estimate of the substrate from the uppermost 30 cm of the sediment column. The BALANCE approach was adapted to reclassification due to its simplicity and transparency (Al - Hamdani et al. 2007). The approach is based on surface material (that is sometimes predicted). At the kick - off meeting in

Edinburgh it was decided to include 4 substrate classes on the basis of the modified Folk triangle (mud to sandy mud; sand to muddy sand; coarse sediment; mixed sediment) and take into account 3 additional classes (boulder, till/diamicton, bedrock) (Figure 2). The aim was to compile one sea - bed substrate map that includes all seven classes. Only two boulder fields were defined from the study area. Due to their small coverage and feedback from the EUSeaMap project, boulders were merged with bedrock.

The numerous European national and international sediment datasets are very diverse. Traditionally, European countries have conducted their marine geological surveys according to their own national survey and interpretation standards.

Substrate classifications also vary as different nations have interpreted their data according to national classification schemes. The seabed surface sediment maps that were not originally in the Folk classification system were reclassified. The first step in the reclassification was to analyze the surface material. In ideal cases the substrate content was examined from the actual surface samples and grain - size analysis. If this was not possible, an expert - based prediction of the surface sediments was made.

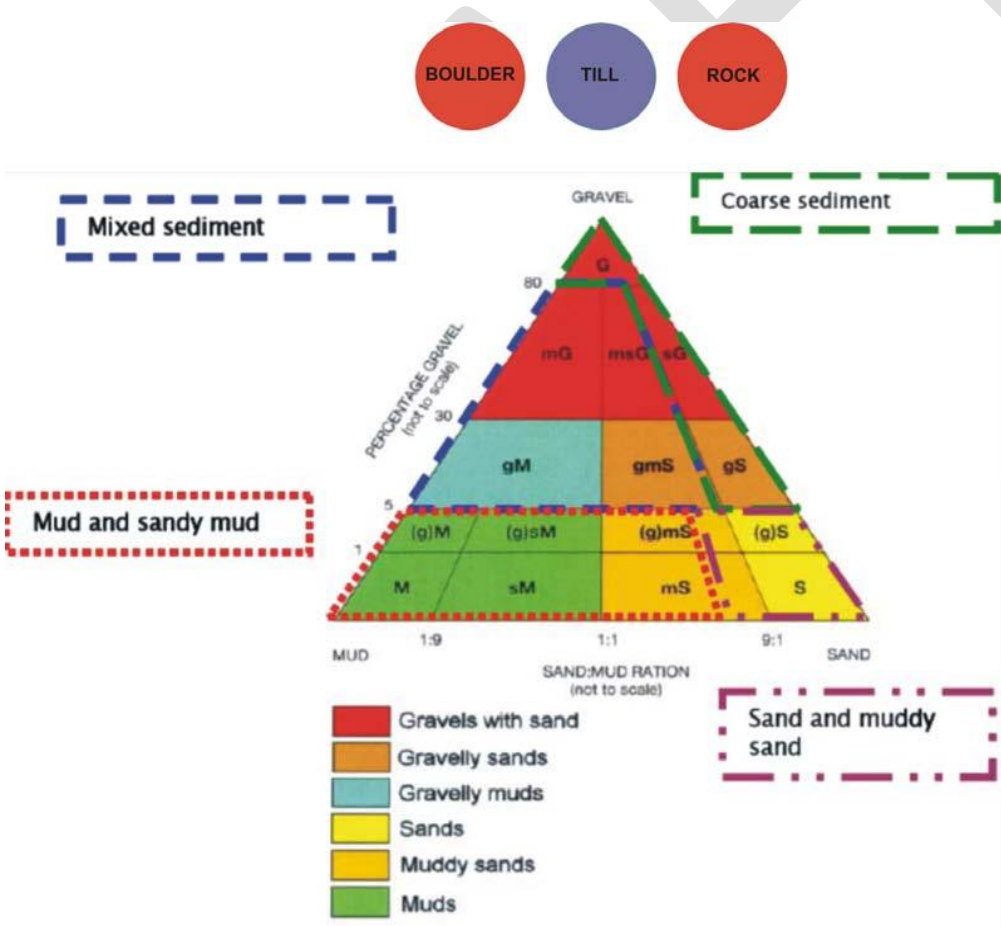


Figure 2 The modified Folk classification system.

The predicted surface sediments were then compared with the modified Folk classification system to find the best fit. In addition, differences in national grain-size classification schemes were identified.

Harmonization of national categories into one classification scheme is essential for interoperability. Unfortunately, the substrate reclassification is not unambiguous in every case. In particular, the definition of the mixed sediment class turned out to be somewhat "fuzzy". During the project meeting in Rovaniemi it was found that the term "mixed sediment" had been interpreted different by the partners during the harmonizing process. For example, the following seafloor types and sediments have been identified as "mixed sediment": patchy seafloor; glacial clay; bimodal grain size distribution.

The seabed substrate attribute table shows that large portion of the maps is reclassified to the modified Folk system based on expert-based prediction, especially in the Baltic Sea area.

Generalisation

The EMODNET Geology project provides data at 1:1 million scale. If not originally compiled at this scale, more detailed maps were generalized. The EMODNET project followed the cartographic principles established in MESH project (Foster - Smith, R. & al., 2007). Accordingly the smallest cartographic unit (polygon) on a map of the scale 1:1 million is about 4 km². Thus all sediment polygons less than 4 km² were eliminated.

The generalization procedure was implemented in ArcGIS environment and followed GTK's guidelines (Väänänen et al., 2007). This method raises the issue of the deletion of important information. It is important to be aware of these issues to try to improve the generalization methodology in future projects. For example, partners could generalize their data individually or could be separate layers that show heterogeneity and special features.

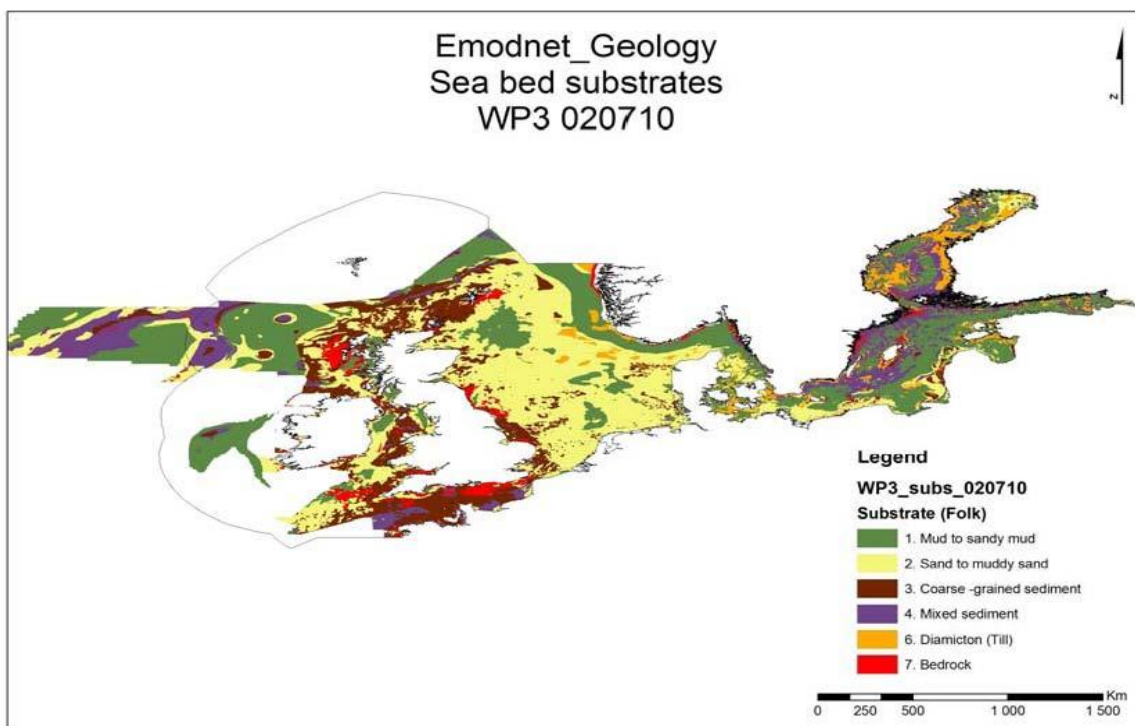


Figure 3 Sea-bed substrate map of the EMODNET geology study area.

2.2 Western Mediterranean Sea

EMODNET map was not extended to the Western Mediterranean basin; therefore the substrate map for the Mediterranean Basin was compiled separately. The only available map of the seabed substrate that covered the Mediterranean basin was the sediments map of the International Bathymetric Chart of the Mediterranean (IBCM) of the Intergovernmental Oceanographic Commission (IOC), but its scale was (1: 5000.000) and precision was not appropriate for the requirements of the EUSeaMap project.

In order to obtain substrate maps for the Mediterranean basin at a resolution appropriate to the grid analysis defined by the project (cells of 0,0027 degrees); it was necessary to carry out compilation, analysis and harmonization of different types and sources of information on seabed substrate of each country (geologic, bionomic and substrate maps or other documents or data)..

The seabed substrate map obtained for the Mediterranean Basin contains information on the superficial sediments, seagrass meadows and hard substrata. It has been prepared by EUSeaMap project directly using different cartographic sources derived by previous works compiled by all partners. Therefore, it must be kept in mind that, this represents an assemblage of different information collected at different scales and/or projections, with different methodologies, for different objectives and was available in different formats (shape files, images or printed maps).

Therefore much effort was put in standardizing the different sediment classifications used in the various maps, documents and projects.

Compilation and harmonization of the sub-bottom substrate information

The construction of the seabed substrate map went through the following stages:

1. Compilation of substrata, bionomic maps and other documents at national level.
2. Adoption of standards and common classification protocols for the substrate map.
3. Harmonization of the substrate maps to national level and generation of a unique map for the country.
4. Realization and evaluation of the first version of the harmonized map of the Mediterranean basin.
5. Gaps elimination and completion of information
6. Final seabed substrate map in vector and raster formats.

1. Compilation of substrata, bionomic maps and other documents at national level.

There is a lot of information on the Mediterranean bottom substrate, but it is multi-source, not systematic, without standards and at the same time there are wide areas without information.

Each partner carried out an inventory and compilation of information on the seabed substrate to national level, finding information that was at different scales and/or projections, classifications and formats.

The sources (original projects) used for the collection of the original data have showed that the cartographic projects identified had a quite local character and they were not harmonized. The bionomic maps have variable scales, ranging from 1:1.000.000 at 1:5.000.

For the French and the Italian substrate maps, the number information sources were few and quite homogeneous (they mainly were cartographic projects), but Spanish sources were much more numerous and complex of harmonizing.

For the areas outside of the EEZ of these countries it decided to use the sediments map of IBCM and to complete the information with documents compiled by the IEO as they are the available sources for completing the map of the seabed substrate.

2. Adoption of standards and common classification protocols for the substrate map.

The existing national and international substrate maps are numerous, but substrate classifications vary as different projects have interpreted their own data according to different objectives, local names and standards. For this reason it was essential to adopt a common classification that leads to the harmonization of different categories into one classification scheme. This is important for obtaining a unified substrate map that can be integrated with the biological, oceanographic and bathymetric datasets and modelled with GIS tools.

In Madrid meeting, November 2009, this issue was discussed keeping in mind the characteristics of main habitats substrate, results and experience of BALANCE, MESH and EMODNET geology projects. In the same way, it was considered that due to the variable and irregular boundaries and the variations of the different substratum classes, as well as the scale of the maps and the difficulty that it causes for the application of the EUNIS classification, that finished basic substrate map should be compiled, without reference samples in many cases and with a variable degree of accuracy. The reclassification of the substrates should be simple and comparable to the results obtained in the above mentioned projects.

Due to the important climatic, litological and geologic differences among the Northwester European Atlantic and the Western Mediterranean, it was not possible to use the same classification for the substrate, because till and boulders are associated mainly with periglacial sedimentation zones, and are not present in Western Mediterranean.

On the other hand, the *posidonia oceanica* and *cymodocea* represent a very significant habitat in Mediterranean basin and although they cover many zones, they don't form very extensive meadows and if they are not kept in mind, they can disappear of the final map of habitats.

For this reason there was the agreement to considerer *posidonia oceanica* and *cymodocea* as substrate classes. It was also agreed to do a unique class with all sediments bigger than sand size, since it adapted better to the characteristics of the Mediterranean substrate and habitats. The coarse and mixed sediment is a class that includes all sediment sizes larger than 2 mm (very coarse sand in Udden Wentworth classification).

Finally a “Modified Folk” classification which is similar to the NW Atlantic was adopted, but with some changes due to the Mediterranean characteristics. Then 5 substrate classes were suggested based on the modified Folk triangle (mud, sandy mud, muddy sand, sand and mixed sediment) and 3 additional classes (rock, posidonia oceanica and cymodocea) (Fig 4). The aim was to compile one seabed substrate map that includes all these eight classes.

The final substrate map was produced in ESRI shape file format showing polygon features, with the highest possible resolution and using the WGS84 geographical coordinate system (Lat/Lon).

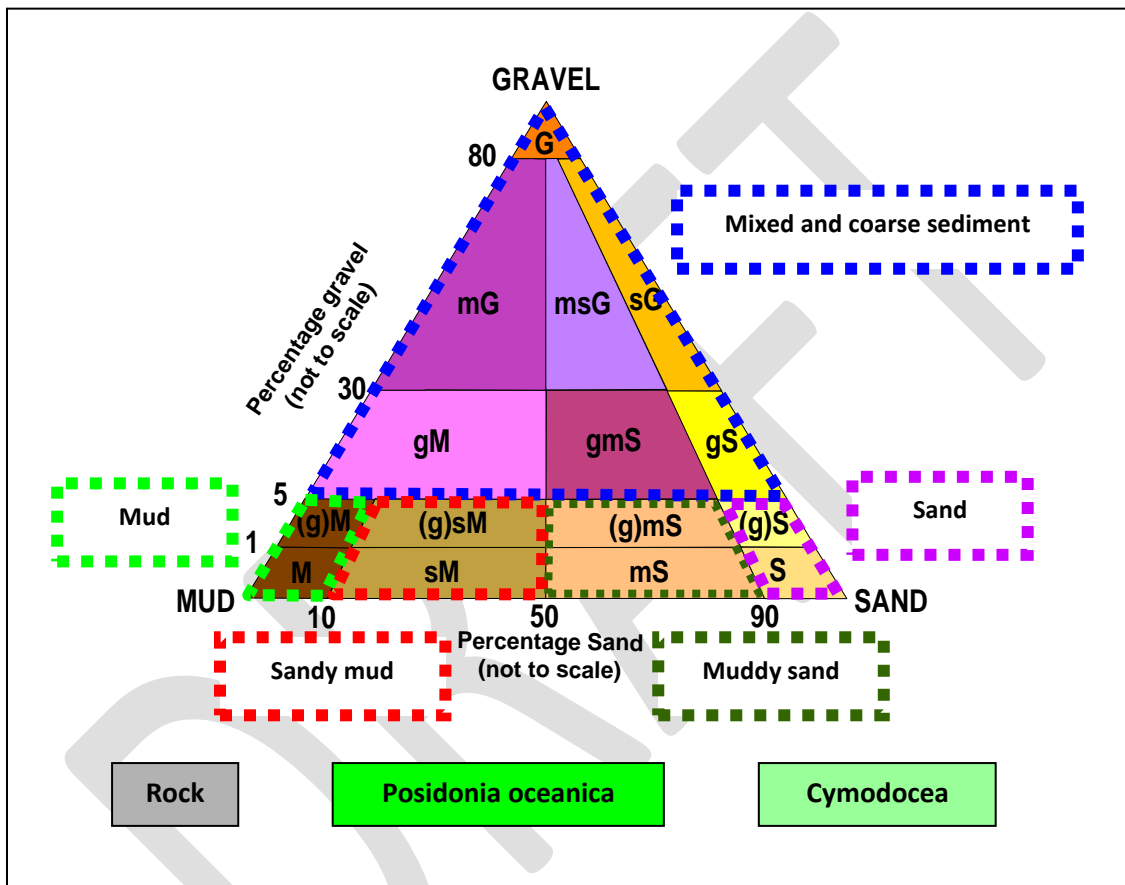


Figure 4. Mediterranean modified Folk classification system.

3. Map harmonization to national level

National substrate maps of each country were synthesis and harmonization at national level following the approved standards.

The maps were re-interpreted with the following criteria:

- On the basis of possible equivalence between grain size or class of old and new classification, grouping and renaming the old classes into new classes

- In case of prediction (interpolation or extrapolation) the modified Folk classification should be considered.

- The reclassification of the sediment map should be according to surface material correlation.

- Sediments maps of IBCM were used to fill blank zones outside national information of the EEZ. This information was adapted and reclassified by the IEO for making the map of the Mediterranean seabed substrate. The equivalence used is in Table 1.

IBCM classification	Modified Folk classification
Muddy sand	Muddy sand
Sandy mud	Sandy mud
Mud	Mud
Clayey sand	Muddy sand
Sandy clay	Sandy mud
Clay	Mud

Table 1. Equivalence between IBCM classes and Modified Folk System to Western Mediterranean.

- National maps ArcGIS polygon shape file was prepared with attributes shown in Table2.

Field name	Format	Description
FID	Short integer	Sequential ID provided by the software
Shape	Text	Description of the geometry
Area	Long integer	Area of the polygon (square meters)
Field 1	Text	Source
Field 2	Text	Classification of the polygon according to the EuSeaMap

Table 2. Main attributes considered in the national shape file of substrata layer.

An inventory was made with the main information about each source (Name, owner, year of the data, original projection, original scale, original Sediment Classification and other comments). This dataset was used later to make the confidence maps.

The gaps in the maps were filled by IEO with new information or by interpreting other data.

4. Realization of a harmonized map of the Mediterranean basin.

The national substrate harmonized and generalized maps were provided to IEO by partners in ArcGIS polygon shape file format. These files were unified by IEO, harmonizing inconsistencies encountered between maps, and fixing errors of topology, overlapping, etc. This was performed by contacting the map providers or by interpreting these areas with the following criteria:

- In boundary zones among different sources the most precise source in the original maps was considered and the boundaries were reshaped to become coherent with the geomorphologic characteristic.
- The geometry of boundaries between different substrata polygons should be coherent with geomorphology.
- The areas where rock sub-outcropping has been integrated in the rock category.

Most of the Mediterranean deep basin (continental slope and abyssal area) was compiled with sediment data of IBCM map.

In the continental shelf where more variety of habitats exists, but it is quite narrow in the Mediterranean basin and it is difficult to represent the variety of substrata and habitats, in consequence it has been necessary to look for maps of high resolution.

In the first version of substrate map (July 2010) was not complete and lacks information on the fanerogams meadows and it had incoherencies in some datasets boundaries.

Also there were four important gaps (figure 5), in the Algerian continental shelf, a great zone on the Italian shelf, western margin of Sardinia and Corsica and French margin.

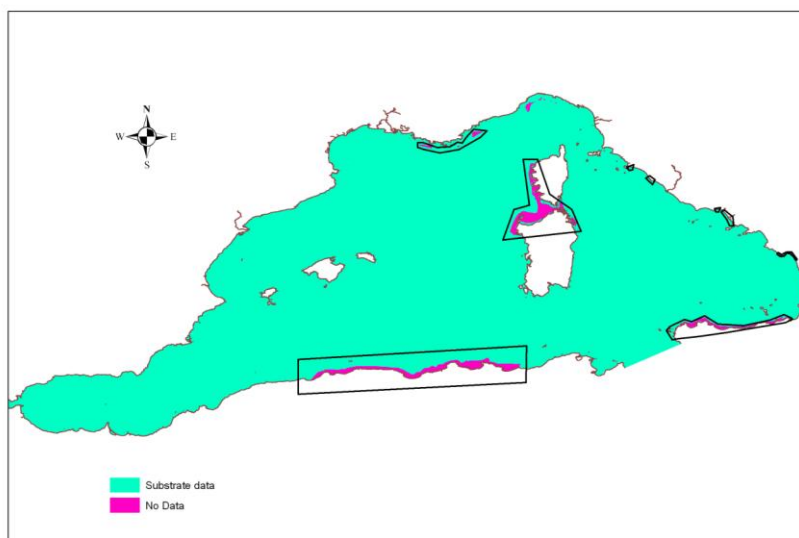


Figure 5. Gaps situation in the first map version (July2010). .

5. Gaps elimination and completed of the information

For gaps elimination, some substrate classes were extrapolated and/or polygons were expanded, keeping in mind that the areas of capes and abrupt coasts reflect certain continuation of shallow bottom due to the rocky outcropping. Likewise, the areas around the rocks and where the slope is high polygons of coarse sediment can be expanded.

The Algerian continental shelf:

The gap of substrate has been filled considering that it is possible to make a valid interpretation and model to wide scale using procedure given by Domzig et al. (2009), the geologic characteristics of the coastal area, as well as the following interpretation criteria:

- The areas where the coast is irregular and abrupt correspond to hard rock zones (this is supported in the geologic maps of the emerged zone) and therefore the adjacent seabed substrate should be constitutes of outcropping rocks.
- The main features of substrate should be very similar to those of the adjacent continental shelves surrounding the substrate.

Italian continental shelf:

- Since the available information was only on fanerogams meadows, the substrate information was completed with the data of ICBM.

Margin of Corsica and Sardinia:

- Geomorphologic characteristics of Corsica and Sardinia margin are very similar as well as the original data of internal shelf. Therefore the margin of Sardinia was assumed to have a similar evolution of that for Corsica, where there is very high resolution information. The geometry of substrate distribution in the continental shelf and upper part of slope of Corsica can be partially extrapolated from Corsica to Sardinia.

For this reason it has been considered that the gaps can be filled carrying out an interpretation (prediction) following a similar model using same geologic and geomorphologic criteria that exist for the nearest areas.

- In the continental slope of Corsica the turbidity activity has filled the canyons with sand and coarse sediments in the central part and base of slope; therefore, in the same zones, polygons with this type of sediments have been prolonged until the abyssal area using the geological information of the area. This has improved and completed the information of the western part of the islands and it has modified the data of ICBM.

The new interpretation of the nature of the substrate is based in Kenyon et al. (2002) and Mas et al. (2010), who extend the Var lobe to West of Corsica.

Kenyon et al. (2002) studied with high resolution geophysical techniques as well as cores samples the western margin of Corsica. They found that this margin is dissected by deep and straight canyons

that have steep axial gradients and that extend from land to deep sea. The axes have scour holes and trains of gravel or pebble waves.

In the lower part of canyons there were five separate depositional lobes extending beyond the canyon mouths. The lobes are constituted of stacked sedimentary sheets, whose core contain coarse to medium sand beds with some mud clasts in the middle. The sand bodies sampled are found where backscatter is relatively weak

- On the other hand, the data of the west margin of Corsica seems to support the hypothesis that all canyons of the east and west margins of Corsica and Sardinia present a similar structure and sedimentary distribution which exists in the west margin and upper part superior of the slope.

French continental margin:

New information from IFREMER (French Research Institute for Exploration of the Sea) was used to fill some small gaps and also to solve incoherencies in the information of the French margin and in that between Italy and France.

The deep area in front of Nice was mapped after modifying the data of GEBCO according to data on the evolution Var lobe presented in recent papers of Mas V. (2009) and Mas et al. (2010).

The zones where the data were modified or changed in last version are shown in figure 6.

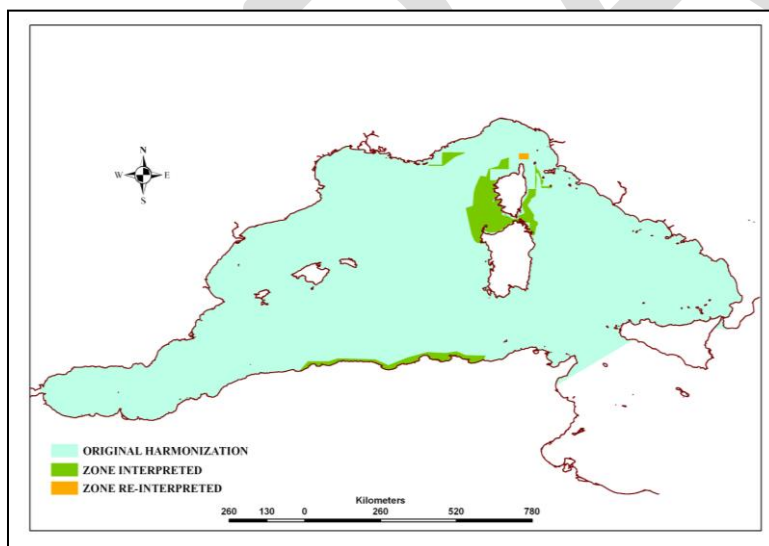


Figure 6 The modified Zones.

It has been very interesting, from habitats point of view, to discover that there are recent papers that show the existence of sands and coarse sediments in abyssal zones. It is possible that at west and east of Corsica Sardinia block new studies find more deposits with similar characteristics.

6. Final seabed substrate map in vector and raster formats.

As result of these processes a final substrate map was produced, unified and harmonized in an ArcGIS polygon shape file (Figure 7) as well as in raster format with a cell size of 0,0027 degrees (about 250 m)..

The substrate map of western Mediterranean is quite accurate in continental shelf and slope, but it is less accurate at deeper zone due to lack of information.

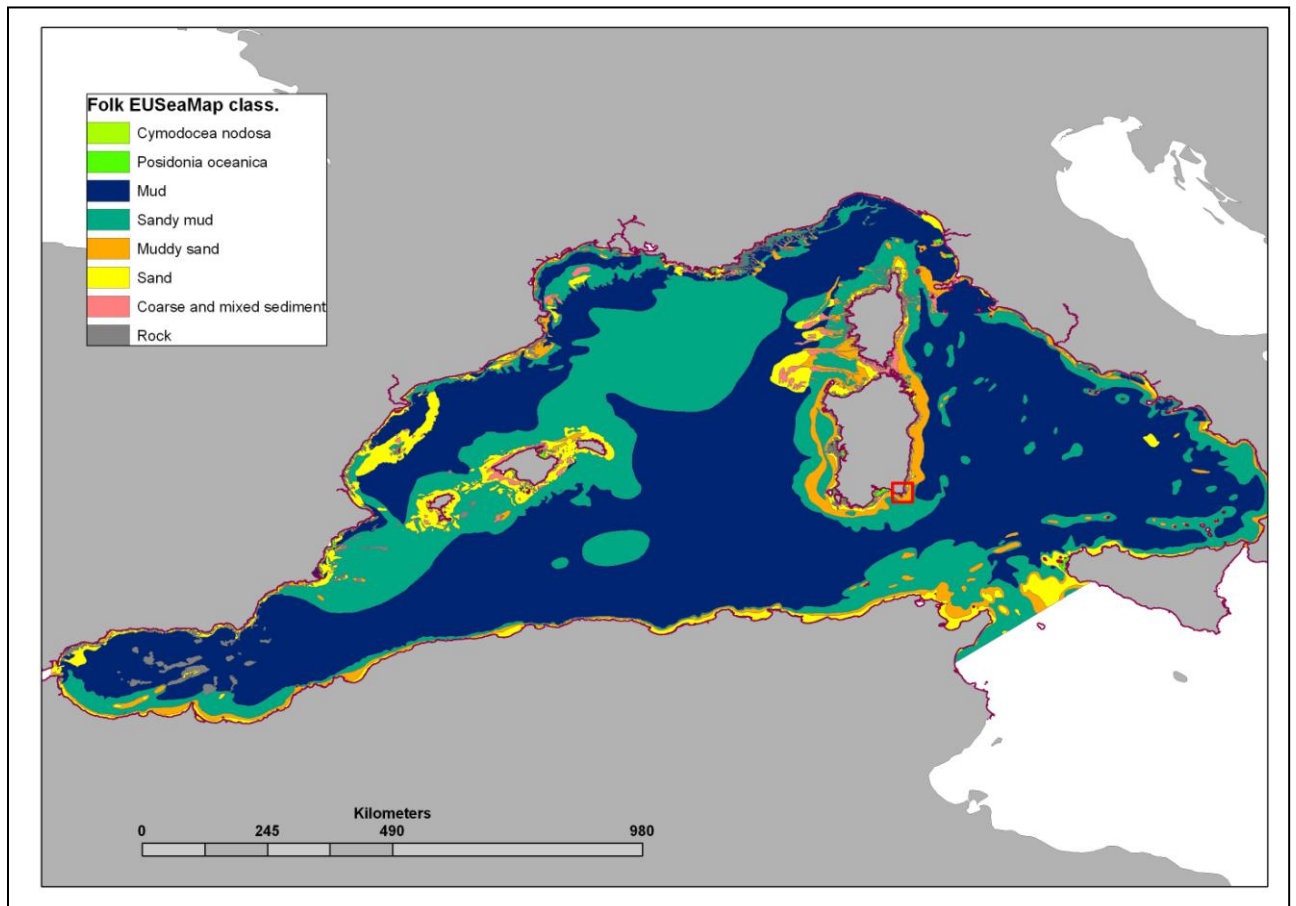


Figure 7. Final substrate map to Mediterranean basin

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