Wave exposure calculations for the Baltic Sea

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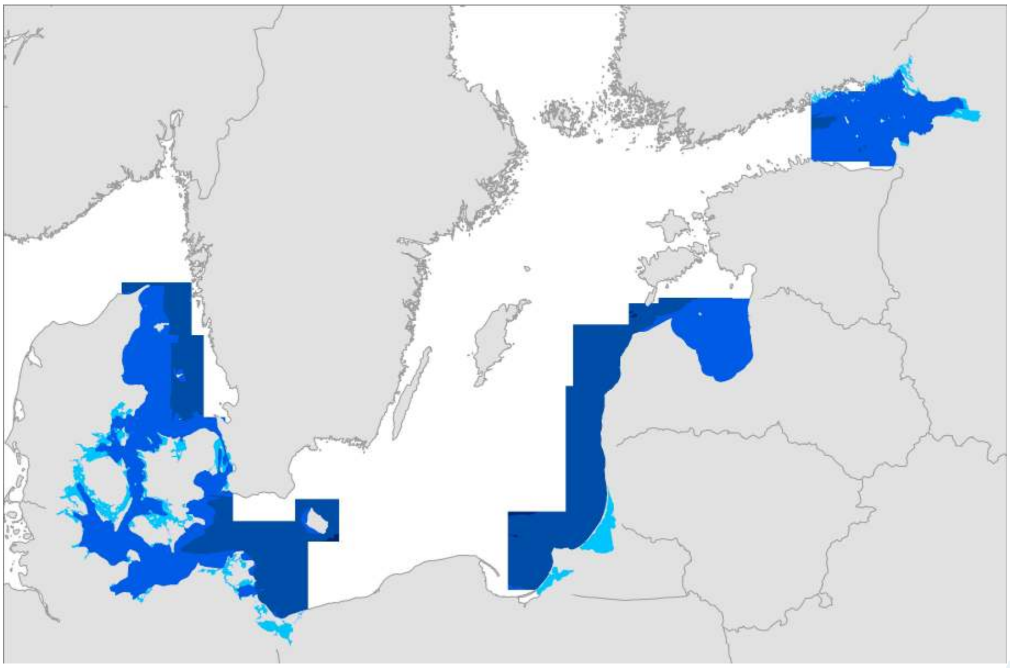
AquaBiota Water Research



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SUMMARY

SUMMARY

Wave exposure is one of the major factors structuring the coastal environment, and is an important parameter in both coastal research and management.

The aim of this project was to
1. construct wave exposure grids covering the Baltic Sea coasts of Russia, Latvia, Lithuania, Germany and Denmark using the Simplified Wave Model method SWM (Isæus 2004). These grids will complete grids earlier calculated for Sweden, Finland, Estonia and Poland, resulting in a seamless SWM-coverage for the Baltic Sea coasts.
2. merge the national SWM grids with a grid on off-shore significant wave height modelled using MIKE 21(DHI 2010) in order to produce a coherent wave exposure grid covering the entire Baltic Sea. The reason for combining grids modelled by two different methods is to utilize the benefits from high resolution wave grids in complex coastal areas, and well established wave theory in open areas.

The SWM wave exposure was calculated for mean wind conditions represented by the five-year period between September 1, 2002 and August 31, 2007. A nested-grids technique was used to ensure long distance effects on the local wave exposure regime, and the resulting grids have a resolution of 25 m. The methods used and described in this report incorporate the division of the shoreline into suitable calculation areas, the selection of wind stations and processing of wind data, the calculation of 27 fetch and wave exposure grids, and subsequently the integration of the separate grids into three seamless descriptions of wave exposure along the coasts of Russia, Latvia, Lithuania, Germany and Denmark.

Significant Wave Height was calculated by DHI using the MIKE 21 SW (where SW stands for Spectral Wave) modelling system (DHI 2010). The model was run for a three years period from January 1, 2007 to December 31, 2009. During the simulation period, significant wave height was saved for every hour.

The digital version of the grid was delivered to the EU SeaMAP lead partner JNCC in May 2010, and a printed version is found in Appendix of this report.

INTRODUCTION

1. INTRODUCTION

Geographic Information systems (GIS) have become an important tool for management as well as for research. This development has raised a demand for maps or models describing the environment to be used as input layers for the GIS analyses. Wave exposure is one of the major factors structuring the coastal environment, and information on wave exposure is therefore highly desired in the modelling process.

Wave exposure can be estimated in many ways. The method chosen for this project was the Simplified Wave Model (SWM), calculated with the software WaveImpact 1.0, which is fully described in the thesis by Isæus (2004). The method is called 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 validated successfully in the Stockholm archipelago and it was also found to be the most ecologically relevant method in a comparison with three other wave exposure methods along the Norwegian coast (FWM, STWAVE, Norsk Standard; Bekkby et al., in prep). SWM values have proved ecologically relevant in more than 20 scientific publications (i.e. Bekkby et al. 2008 and 2009, Eriksson et al. 2004, Florin et al. 2009, Härmä et al. 2008, Kersen et al. 2009, Kotta and Möller 2009, Norderhaug and Christie 2009, Sandman et al. 2005, sandström et al. 2005, Snickars et al. 2010, Soldal et al. 2009) and a large number of reports.

SWM has earlier been used for wave exposure calculations of the entire Swedish, Finnish, Norwegian, Estonian and Polish coasts. The use of the same method for describing the physical environment facilitates the comparison between all these coasts, and the implementation of common classification systems, such as EUNIS.

Oceanographic numerical wave modelling has become increasingly useful as a result of both software development and improved computation capacity. Still, it is too demanding to run high-resolution simulations (2-300 m) in areas as large as the Baltic Sea. The complex coastlines in large parts ofthe Baltic Sea make wave modelling in low resolution less accurate and hence less useful. However, in open areas, where the spatial variation is low, spatial resolution is less critical and the numerical wave-model results should be more reliable than a fetch-based method like SWM.

The aim of this project was to:

1. Construct wave exposure grids covering the Baltic Sea coasts of Russia, Latvia, Lithuania, Germany and Denmark using the Simplified Wave Model method SWM . These grids will complete grids earlier calculated for Sweden, Finland, Estonia and Poland, resulting in a seamless SWM-coverage for the Baltic Sea coasts.

2. Produce a coherent wave exposure grid covering the entire Baltic Sea by merging the national SWM grids with a grid on offshore significant wave height as modelled by the DHI MIKE 21 SW wave model (referens) . The reason for combining grids modelled by two different methods is to utilize the benefits from high resolution wave grids in complex coastal areas, and well established wave theory in open areas.

METHODS AND MATERIALS

2. METHODS AND MATERIALS

2.1. Land/Sea grids

In order to include large areas in the model, but still deliver high-resolution grids, SWM uses a nested-grids technique. 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 values on fetch, see**Figure 1**. These 100 m grids further provided input values for the final 25 m grids. The extent of the 25 m grids in each area was set to fulfil the criteria:

1. Include coastline features that affect the fetch locally.
2. Together cover the coastline in the area with an overlap between each grid pair.
3. Be of a manageable size, set by computation capacity.

This resulted in 27 grids (see the red rectangles in **Figure 1**).

Further, 10 coarser grids with 100 m cell size were created with an extent large enough to include a few 25 m grids together with surrounding coastline features of importance for the fetch calculations, see the blue rectangles in **Figure 1**. The extent of the coarse 500 m grid was set to include all land shapes that possibly could affect the fetch measured from the coasts included in this project. Since this grid was not limited by computation capacity it was created to include most of the Baltic Sea (green rectangle in **Figure 1**).

The land/sea grids were constructed from a coastline map from ESRI 2006. The map projection for the project was UTM (Universal Transversal Mercator), zone 34 N.

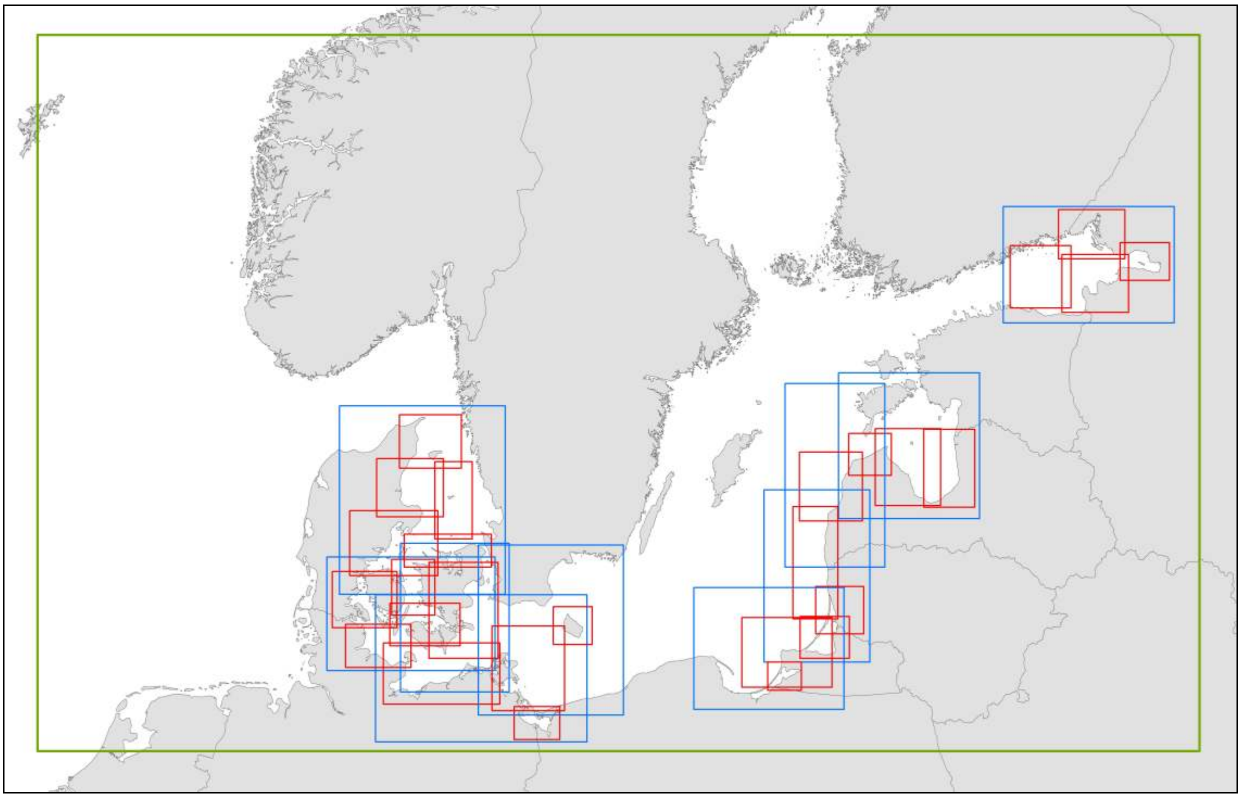

Figure 1. *The extent of grids used for the nested wave exposure calculations. The green rectangle shows the grid with 500 m resolution, the blue rectangles the 100 m grids, and the red rectangles the 25 m grids.*

Since some of the Danish fjords are not included in the coastline map, SWM values have not been calculated for these areas. Examples are Limfjorden, Odense Fjord and Roskilde Fjord.

2.2. Fetch calculations

The wave exposure estimates were computed in a geographic information system (GIS) with the software WaveImpact 1.0, which has been particularly developed for this purpose. Grids with only two classes, *Land* and *Sea*, were used for the calculations. WaveImpact uses ASCII grids (text files) of the format that can be exported and imported into the GIS softwares ArcView and ArcMap.

The wave exposure values are based on fetch, i.e. the distance of open water over which the wind can act upon the sea surface and waves can develop. The fetch is calculated for every sea grid cell of the map. Basically, this is done by starting at the map edge of the incident – wind direction and increasing the grid cell values by the size of one cell (in meters) for each sea grid cell in the propagation direction, until land is reached (**Figure 2a**). The procedure starts over again from zero if there are more sea cells on the other side of the land cells.

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. Instead of adding the cell size to the source-cell value straight behind, the cells behind-to-the-right and behind-to-the-left were used. The procedure is illustrated by an example for a southerly wind in **Figure 2b-c**.

The formula used for calculating a southerly wind/wave direction, when no land pixels obstructed (**Figure 2b**), was:

Formula 1.

OutputMatrix(i, J) =
OutputMatrix(i + 1, J - 1) * (0.5 - Ref)
+ OutputMatrix(i + 1, J + 1) * (0.5 - Ref)
+ OutputMatrix(i + 1, J - 2) * Ref
+ OutputMatrix(i + 1, J + 2) * Ref
+ Cell size,

where *OutputMatrxs(i, J)* is the current cell position in the grid, *i* is increased downwards (southwards) in the grid relative to the current position, *J* is increased to the right (eastwards) in the same way, *Ref* is the calibration value of the refraction/diffraction effect (set to 0.35), and *Cellsize* is the cell size in meters.

In the case when the adjacent grid cell on the left (western) side of the current grid cell was *Land* only cell values from behind and from behind-to-the-right were used (**Figure 2c**):

Formula 2.

OutputMatrix(i, J) =
OutputMatrix(i + 1, J) * (0.5 - Ref)
+ OutputMatrix(i + 1, J + 1) * (0.5 + Ref)
+ Cellsize.

Corresponding formulas were used for land obstacles to the right (east), and for all sixteen wind directions (see **Section 2.2** below).

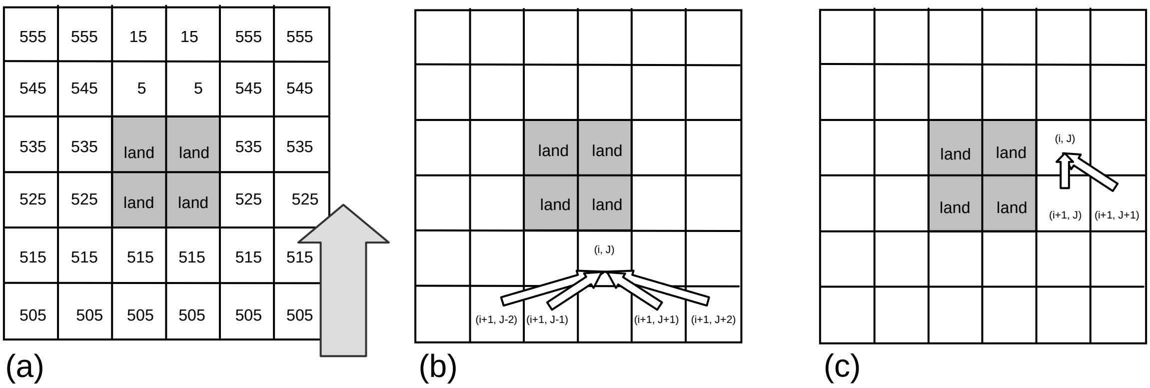

Figure 2. *Examples illustrating the calculation of the fetch values in a land/sea grid, for a southerly wind. a) The basic principle of increasing the fetch values by adding one cellsize (here 10 m) for each new cell. b) Values from the cells adjacent to the source cell are used instead of the source cell itself, in order to simulate refraction/diffraction patterns. c) Calculations when an island limits the use of values from all adjacent cells.*

This method results in a pattern where the fetch values are smoothed out to the sides, and around island and skerries, in the way waves get deflected by refraction and diffraction. Aerial photographs of wave crests deflected around islands were used to coarsely calibrate the simulation of refraction/diffraction during the construction of the method (Isaeus 2004).

The fetch values were calculated for each 25-m grid with input from the coarser grids in the nested procedure described above (see Section 2.1).

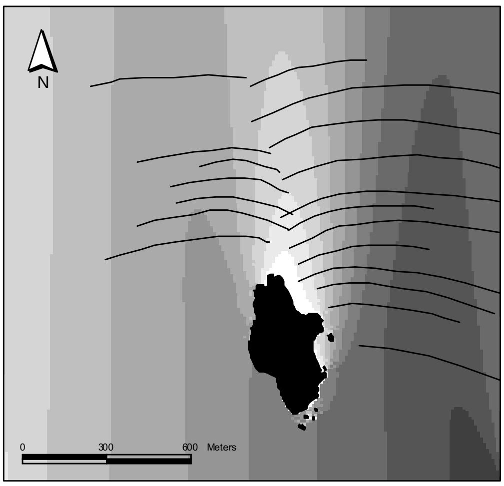

Figure 3. *Aerial photographs of wave crests (black lines) were used to calibrate the refraction/diffraction simulation during construction of SWM.*

2.3. Wind Data

The used wind data were retrieved from the British Met Office Unified Model, by the Interdisciplinary Centre for Mathematical and Computational Modelling, University of Warsaw. Archived hourly wind data were extracted for the five-year period between September 1, 2002 and August 31, 2007. A total of 26 locations (**Table 1**) were used. For some grids there were several wind stations available. For those grids, the most representative wind station was selected. One station (W25) is associated with two wave-exposure grids.

For the calculations, the wind data were divided in sixteen compass directions (N, NNE, NE, ENE etc.), each representing an angular sector of 22.5°. For each sector the mean value of all available wind-velocity measurements were calculated for further use in the exposure calculations.

Locations of utilized wind stations are shown in **Figure 4-6**.

Table 1. *The utilized wind stations with positions and the number of the associated land/sea grid. The wind was measured at 10 m height at all locations.*

Wind Station	Latitude (dg, WGS84)	Longitude (dg, WGS84)	Grid
W1	60.266879	26.446906	1_A25a
W10	55.431788	21.241252	2_C25b
W11	55.007888	21.223949	2_C25c
W12	54.957046	19.963878	2_D25a
W13	54.602437	20.162788	2_D25b
W14	55.988547	11.322688	3_A25a
W15	56.239533	10.790875	3_A25b
W16	56.726102	11.567913	3_A25c
W17	56.805585	10.275369	3_A25d
W18	57.348390	10.520584	3_A25e
W19	55.276034	12.461676	3_B25a
W2	60.350912	28.431404	1_A25b
W20	55.125372	10.889313	3_C25a
W21	54.729844	10.734908	3_C25b
W22	55.589205	10.657787	3_C25c
W23	54.969565	10.022656	3_C25d
W24	53.738150	14.134215	3_D25a
W25	54.592147	13.570689	3_D25b and 3_E25a
W26	54.540348	11.094197	3_D25c
W3	59.682043	28.008268	1_A25c
W4	60.203831	28.990740	1_A25d
W5	57.719137	24.337691	2_A25a
W6	57.366654	23.123312	2_A25b
W7	57.634256	22.074749	2_A25c
W8	57.450996	21.587188	2_B25a
W9	56.384347	20.969643	2_C25a

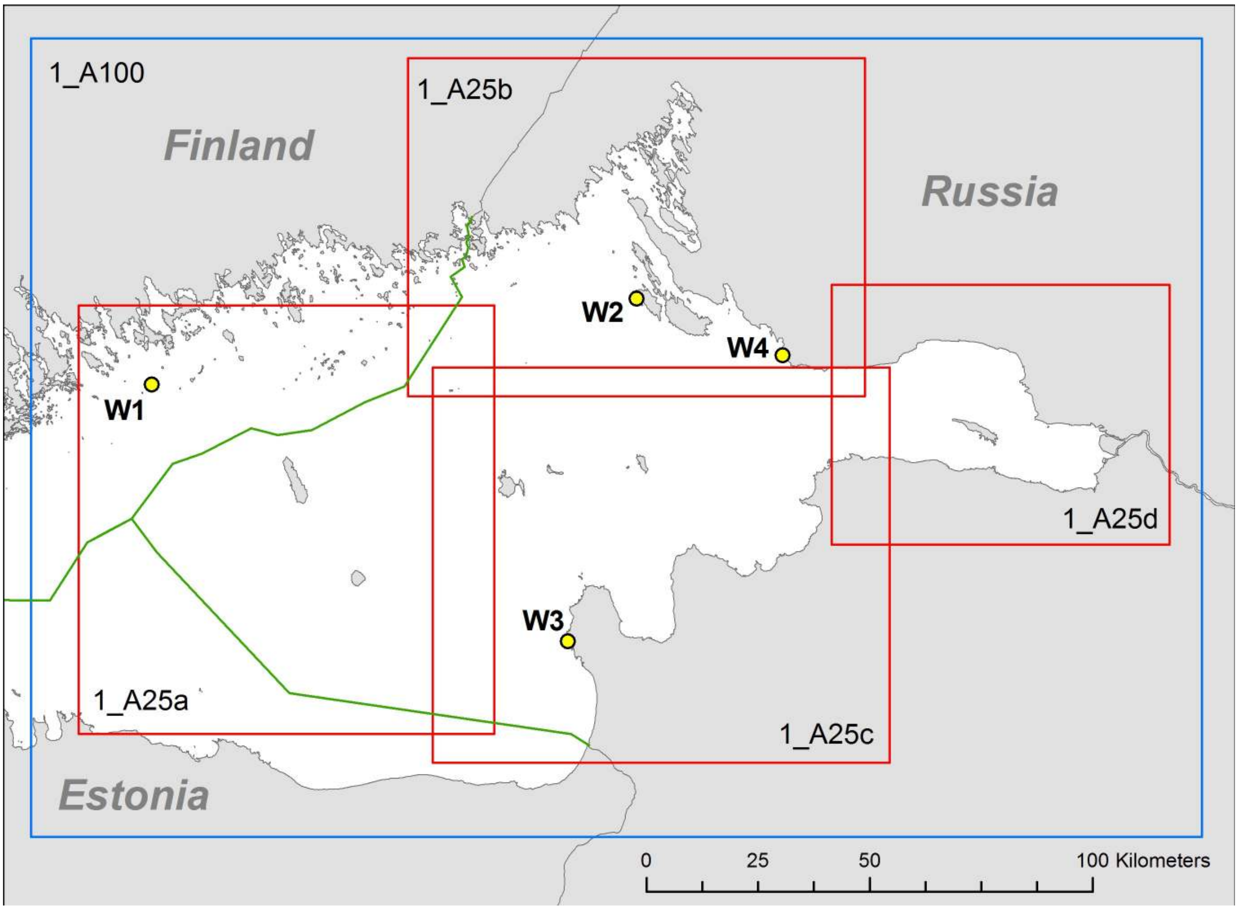

Figure 4. *The location of the utilized wind stations in the inner (Russian) parts of Gulf of Finland (marked by yellow dots and their names) and the extent of the land/sea grids with a grid resolution of 100 m (blue) and 25 m (red), respectively. The green line represents the EEZ border.*

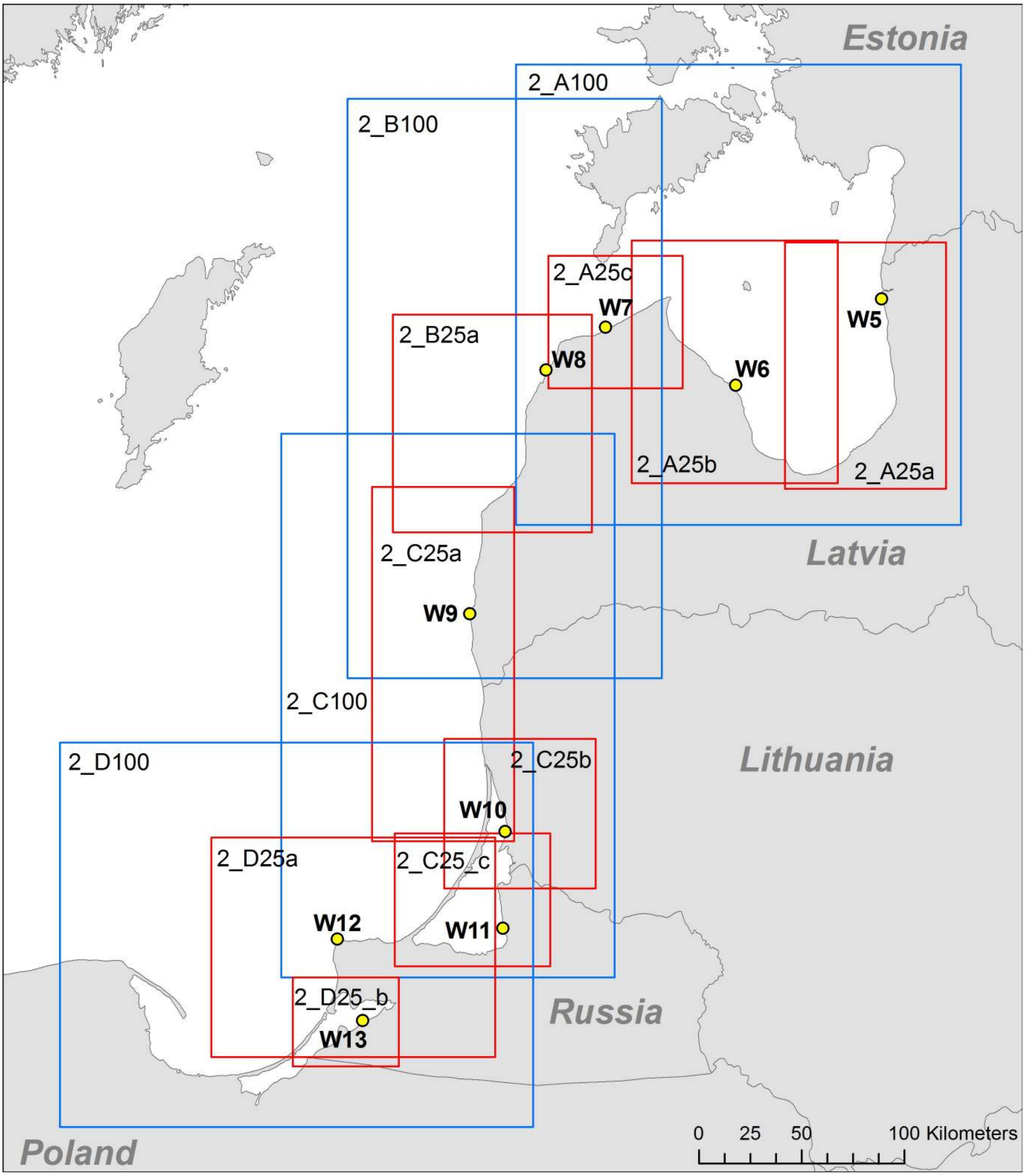

Figure 5. *The location of the utilized wind stations for Latvia, Lithuania and Kaliningrad (Russia), marked by yellow dots and their names and the extent of the land/sea grids with a grid resolution of 100 m (blue) and 25 m (red), respectively.*

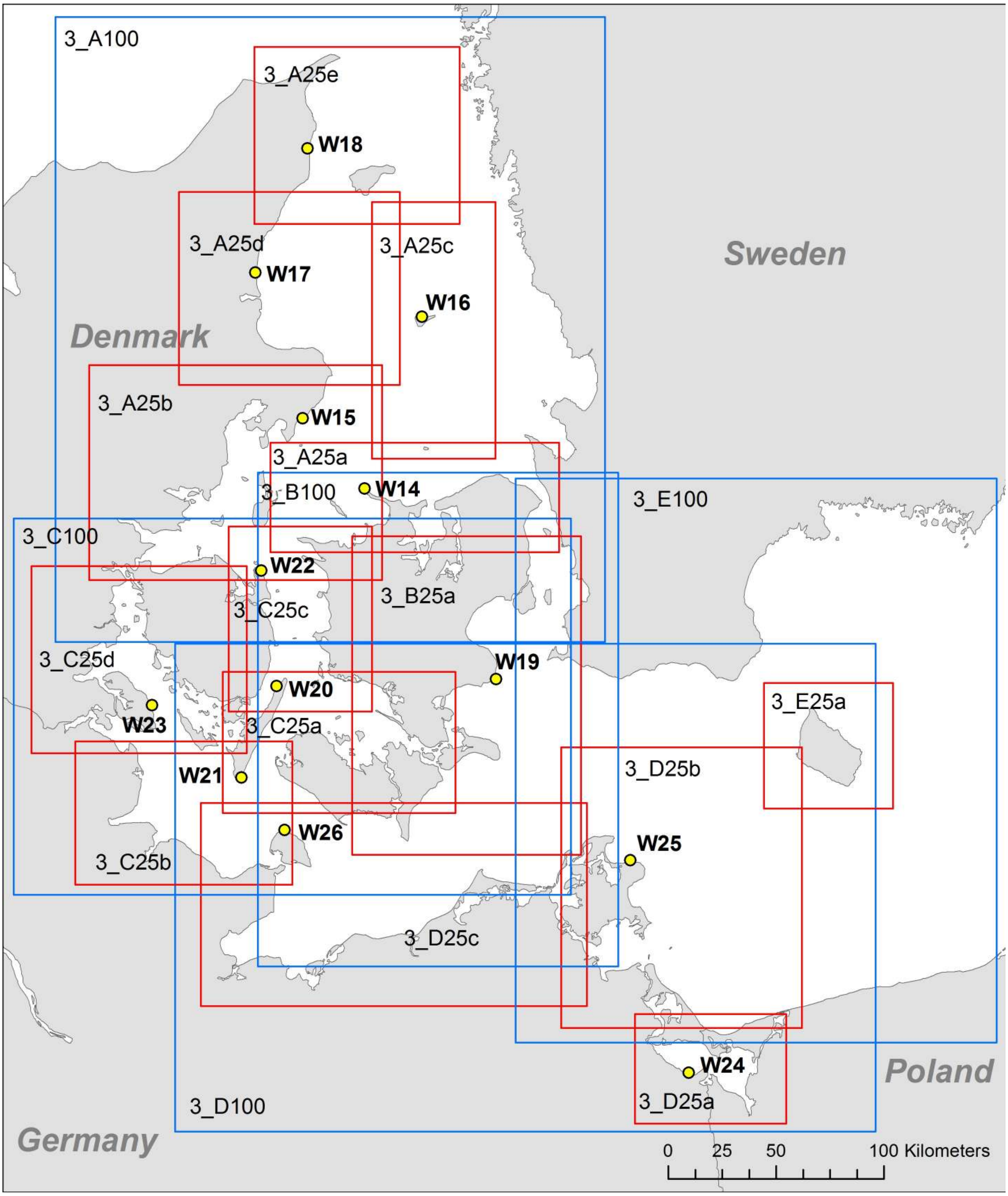

Figure 6. *The location of utilized wind stations for the Danish and German coasts (marked by yellow dots and their names) and the extent of the land/sea grids with a grid resolution of 100 m (blue) and 25 m (red), respectively.*

2.4. Wave exposure calculations

For each wind sector the value of each cell in the corresponding fetch grid was multiplied by the mean wind speed. In this case this resulted in sixteen new grids. The mean value of all grids was calculated in an overlay analysis, which can be summarized by the formula:

Formula 3.

$$SWM = \frac{\sum_{i=1}^{16}(F_i * W_i)}{16},$$

Where SWM is the wave exposure value, F_i is the adjusted fetch value for the direction i, and W_i is the mean wind speed in direction i.

This was repeated for each grid of the 27 sub regions along the coasts (the red rectangles in **Figure 4**, **5** and **6**).

2.5. Creation of a coherent wave exposure grid for the Baltic Sea

Since SWM layers only cover coastal areas, open sea areas have to be complemented with another kind of wave exposure in order to create a wave exposure grid covering the entire Baltic Sea. For this purpose mean significant wave height was selected, as calculated by DHI using the MIKE 21 SW (where SW stands for Spectral Wave) modelling system (DHI 2010).

The average value of the mean significant wave height for the years 2007, 2008 and 2009 was calculated and a GIS layer was created. In order to transform the mean significant wave height to SWM a regression (**Figure 7**) was performed using data points in overlapping areas (Formula 4). Data points with SWM values under 100,000 m^2/s (corresponding to a relatively low degree of exposure) were not included since SWM and mean significant wave height differ drastically in such unexposed areas. Totally 22,639 overlapping points were included in the regression.

Formula 4.

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

where Y = SWM and X = mean significant wave height.

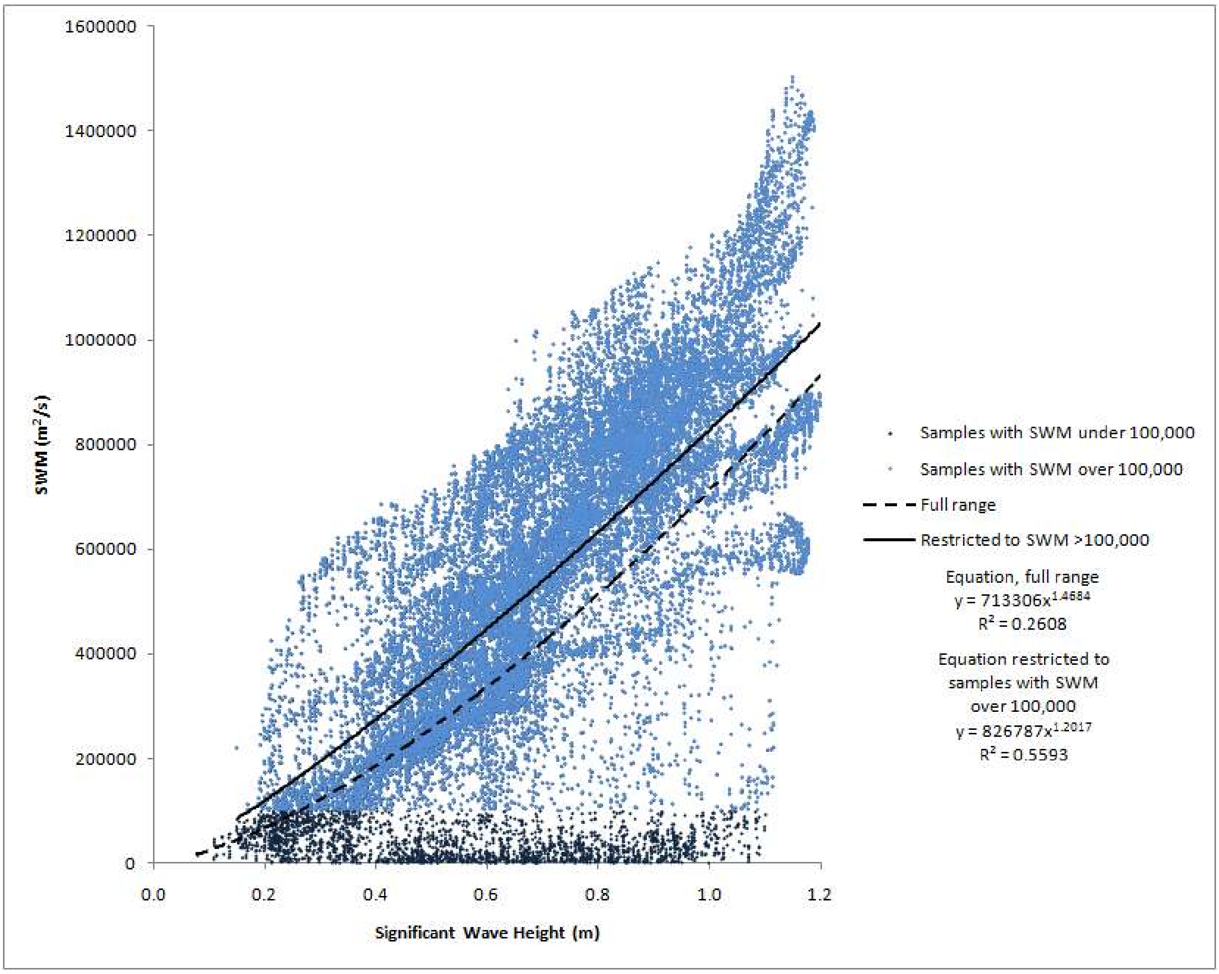

Figure 7. *Plot of SWM and significant wave height in overlapping areas. Dark blue dots represent SWM samples that were not included in the final regression (SWM values under 100,000 m^2/s).*

RESULTS AND DISCUSSION

3. RESULTS AND DISCUSSION

Since the separate wave exposure (SWM) grids are calculated from different wind data and wind period, it leads to somewhat different wave exposure values in areas where the grids overlap. To avoid this artifact, and to level out the differences between adjacent grids, the grids were merged while giving overlapping cells the mean value of the corresponding input cells. This merging into a rather seamless grid was done using the script *MosaicToNewRaster*, within the ESRI ArcGIS 9.3.1 Data Management toolbox, with mosaic method set to *Mean*. The merged grids were then clipped again into 27 separate grids to get grids of manageable sizes. The same method was used also when merging these newly produced grids with the earlier results for Sweden, Finland, Estonia and Poland.

For some grids, the wind regime in parts of the overlapping areas was expected to be better represented by the wind regime of one of the overlapping grids. In such areas values were taken exclusively from one of the grids (mosaic method set to *First* or *Last* depending on layer order). This was the case for the lagoons of the Southern Baltic Sea (Szczecin, Vistula and Curonian lagoon), where SWM inside the lagoons were calculated with wind data from locations at the inner shores of the lagoons, and SWM for the shores outside the lagoons were calculated with wind data from the outer coasts (**Figure 8-10**).

For areas in the Kattegat and Skagerrak seas, where Swedish and Danish wave exposure grids overlap, values were taken from the Swedish grids since the associated wind data are more representative for the mid areas of these straits than wind data from the Danish east coast. This resulted in a distinct line in the middle of Kattegat (visible in **figure 12-14**).

At the Polish borders with Germany and with the Russian Kaliningrad enclave, SWM values from Russian grids were used on the Russian side, whereas values from German grids were used on the German side and Polish grids were used on the Polish sides of the borders (**Figure 8 and 9**).

For the Russian part of the Gulf of Finland, were Finnish and Russian SWM grids overlap, the Finnish SWM values were used since the Finnish SWM grids were calculated with a more detailed coastline map. In areas where Russian and Estonian SWM grids overlap, Russian SWM values were used on the Russian side of the EEZ and Estonian values were used on the Estonian side. This approach was chosen since the coastline of the Estonian grid was more detailed on the Estonian side of the border and vice versa (**Figure 11**).

All SWM grids created in this project are shown in **2** whereas **Figure 13** provides an overview of all SWM grids for the Baltic Sea (including grids created earlier). The colours indicate preliminary EUNIS classes according to the legend. The grids are shown in more detail in Appendix.

The SWM layers were merged with the transformed significant wave height layer in GIS (ESRI ArcGIS 9.3.1) creating a seamless wave exposure layer for the entire Baltic Sea (**Figure 14**). 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. 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 m^2/s, 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. This layer was created according to the EU SeaMAP standard grid for the Baltic Sea in WGS84 and a spatial resolution of 0,003 degrees (200-300 m). All grids were converted from UTM34N to WGS84 prior to analysis and merging.

The gridcell resolution of 25 m was a compromise between the need for high resolution and manageable amounts of data.

However, in a study by the Swedish Board of Fisheries (Göran Sundblad, pers. comm.) on the effects of scale on SWM values it was concluded that the results for a 25 m resolution differed only little from those of finer resolution. However, for resolutions of 50 m and coarser the results differed significantly.

The 25 m resolution then seems to be an acceptable compromise even though studies of the narrowest bays might benefit from resolution even higher than so.

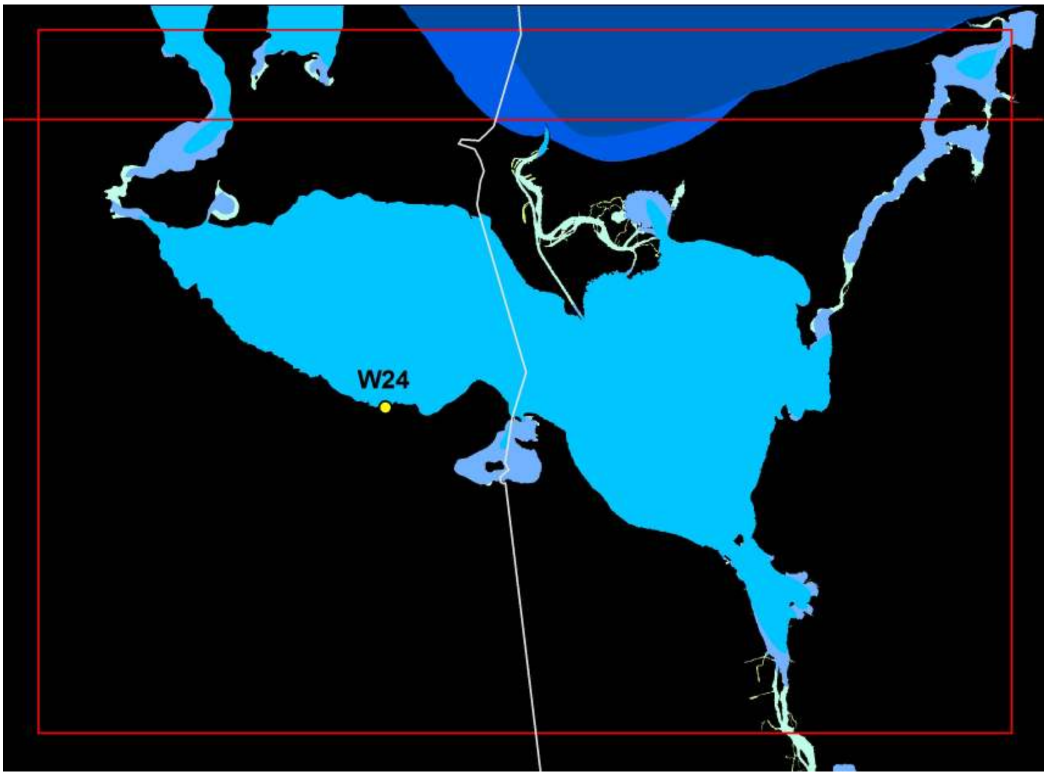

Figure 8. *Wave exposure grid 3_D25a (red rectangle) covering the Szczecin Lagoon area. SWM values were calculated using wind data from station W24. 3_D25a was merged with 3_D25b (extending to the north from the red line in the upper part of the map) using the mosaic method Mean. SWM for the grid 3_D25b was calculated with wind data from station W25. SWM values on the Polish side of the border (grey line) are taken from Polish grids.*

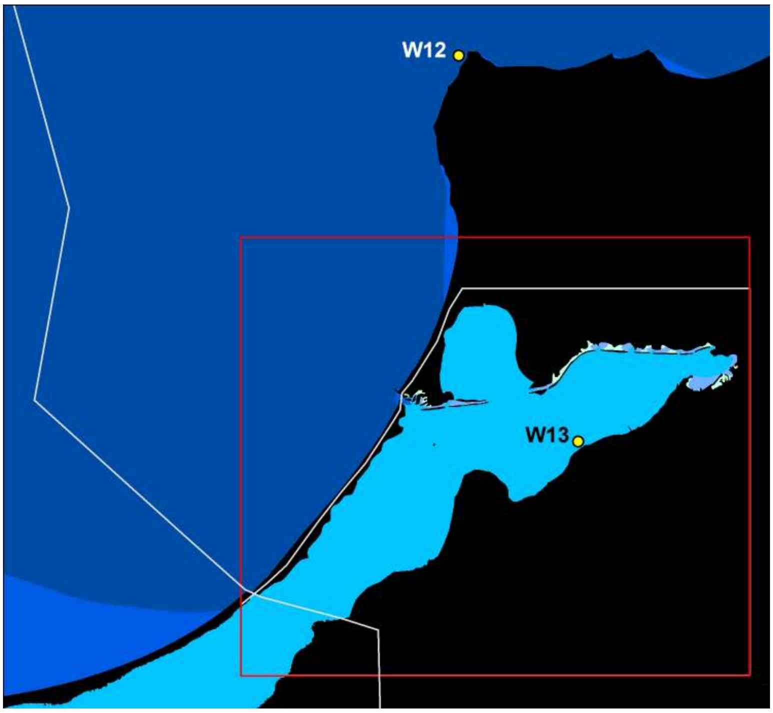

Figure 9. *Wave exposure grid 2_D25b (red rectangle) covering the Russian part of the Vistula lagoon area. SWM values for the lagoon were calculated using wind data from station W13. SWM values for the outer coast are taken from grid 2_D25a, calculated with wind data from station W12. On the Polish side of the border (grey line crossing the lagoon) values are taken from Polish grids.*

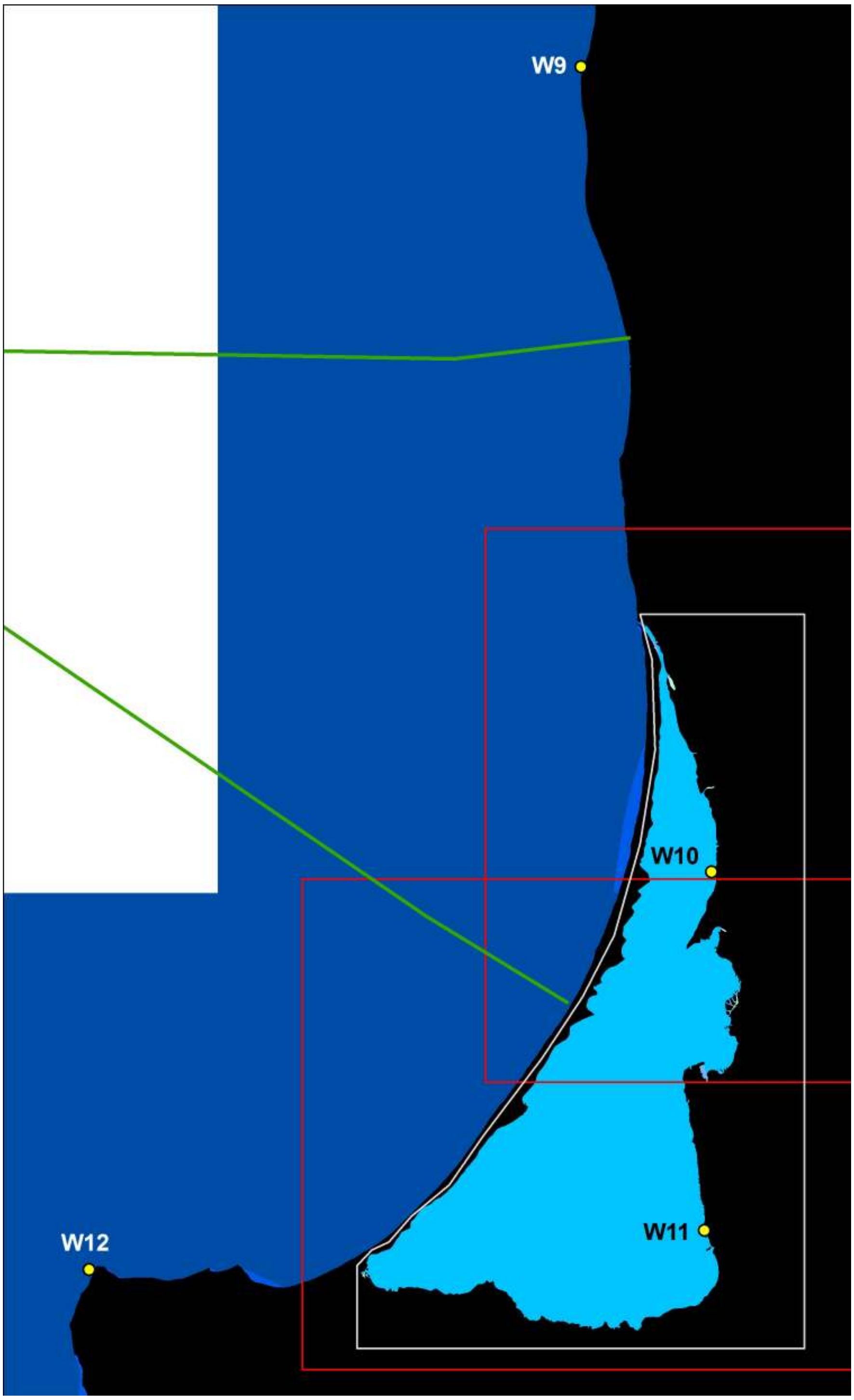

Figure 10. *Wave exposure grids 2_C25b and 2_C25c (red rectangles) covering the Curonian lagoon area. SWM values for the lagoon were calculated using wind data from stations W10 and W11. SWM values for the outer coast are taken from the grids 2_D25a and 2_C25a, calculated with wind data from stations W9 and W12. The green lines represent EEZ borders.*

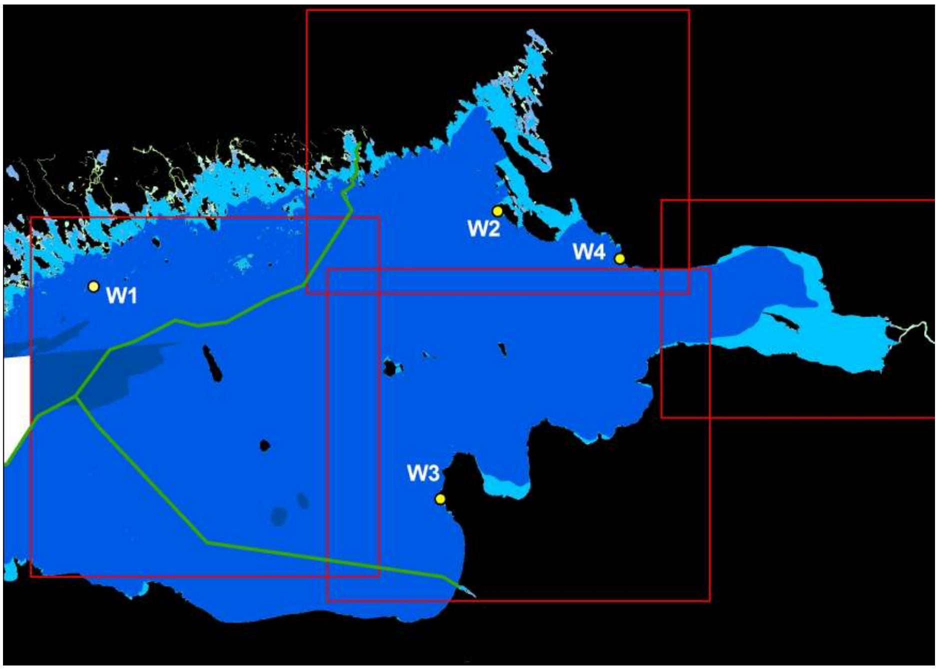

Figure 11. *Wave exposure grids 1_A25a to 1_A25d (red rectangles) covering the Russian parts of the Gulf of Finland. Wind stations are marked by yellow dots and their numbers. The grids were merged using the mosaic method Mean. Where Estonian grids overlap, values from Estonian grids are used on the Estonian side of the EEZ border (green line), and values from Russian grids used on the Russian side. Where Finnish grids overlap, values from Finnish grids are used*

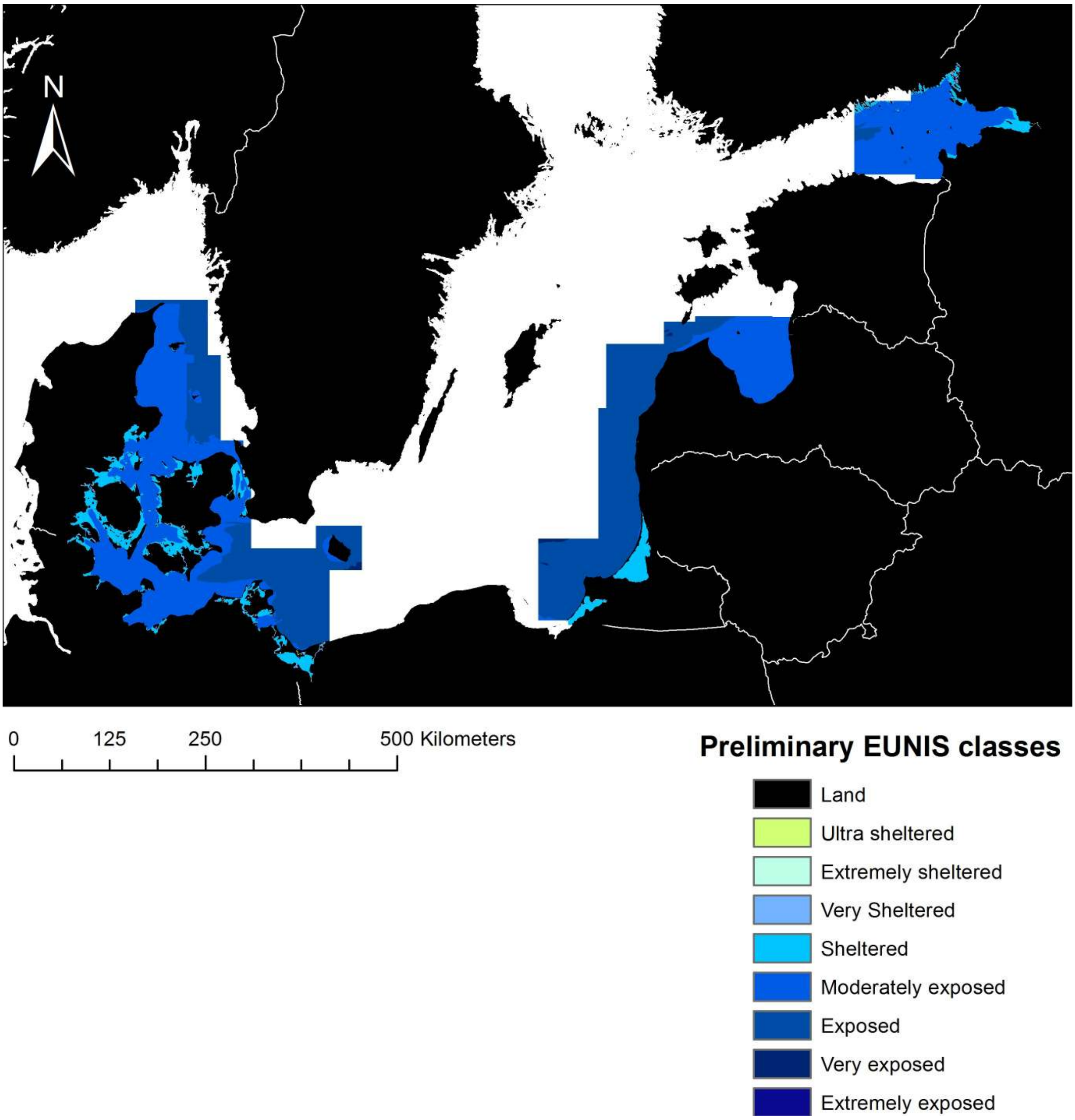

Figure 12. *An overview of the coasts included in this project, showing a mosaic of the calculated wave exposure grids. The colours indicate preliminary EUNIS classes according to the legend. Each grid is shown separately in Appendix.*

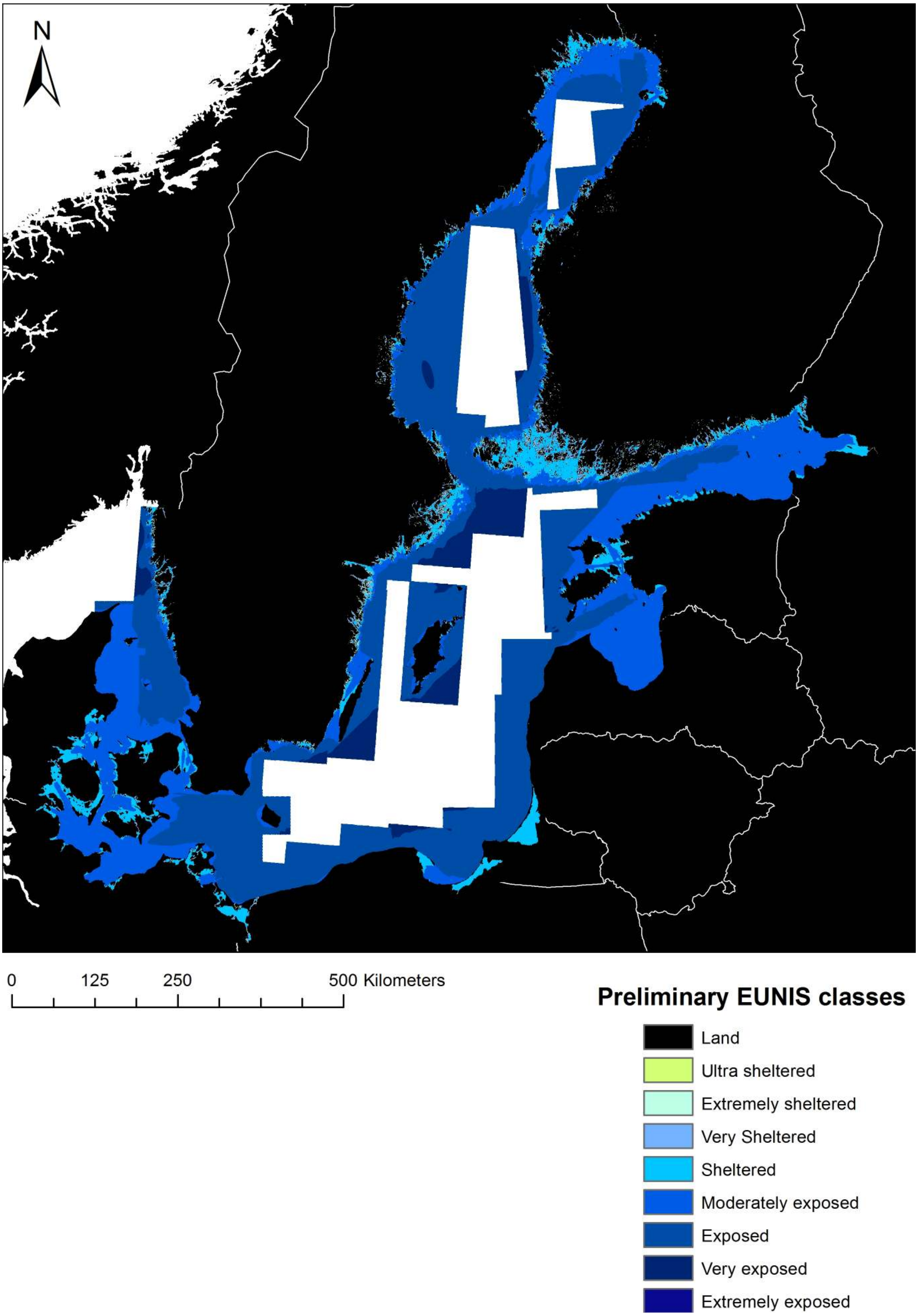

Figure 13. *An overview of all wave exposure grids for the Baltic Sea, calculated in this and earlier projects. The colours indicate preliminary EUNIS classes according to the legend.*

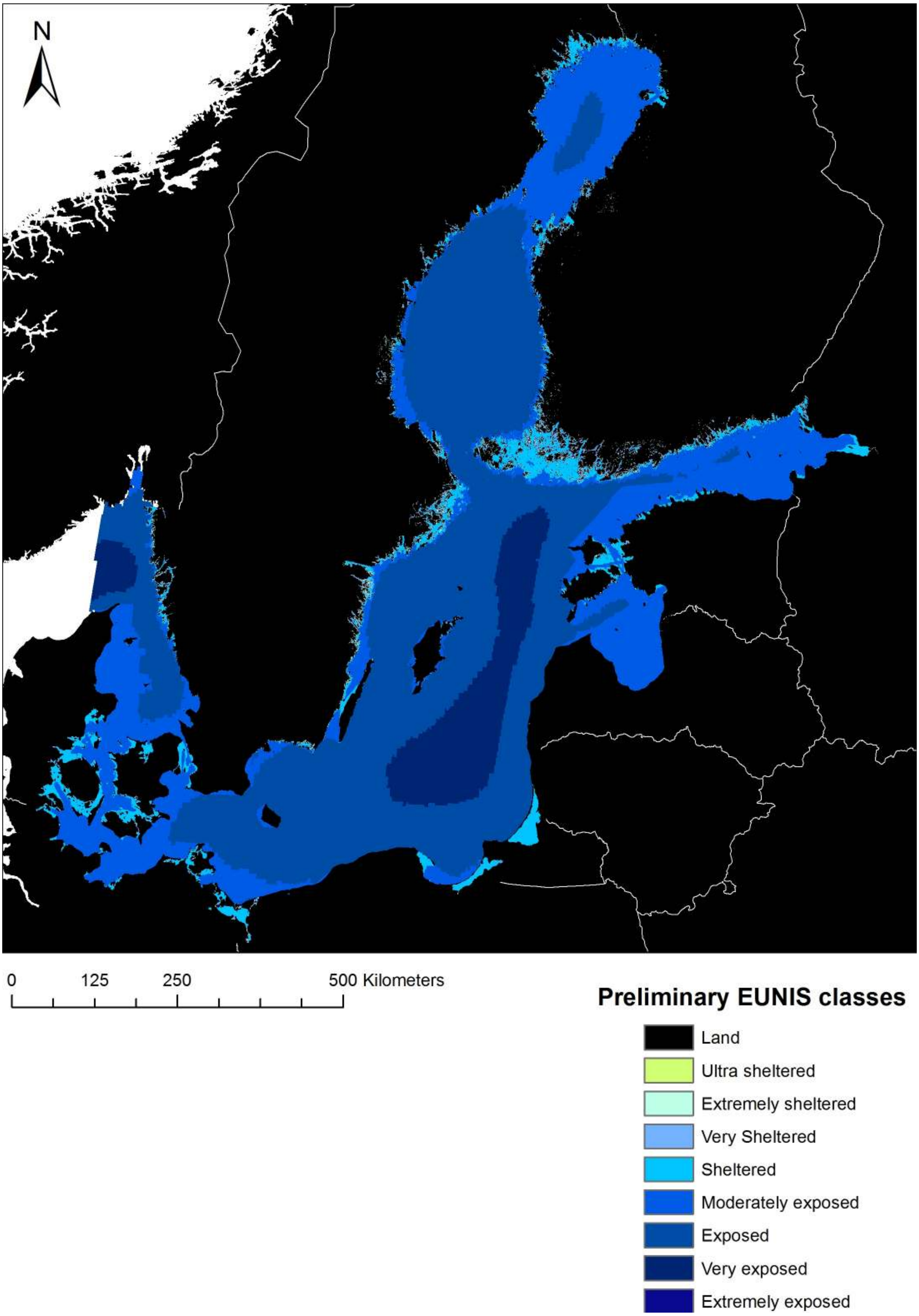

Figure 14. *SWM for the Baltic Sea where the coastal grids (Figure 12) have been merged with significant wave height recalculated to SWM values. The colours indicate preliminary EUNIS classes according to the legend.*

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APPENDIX

APPENDIX: WAVE EXPOSURE GRIDS

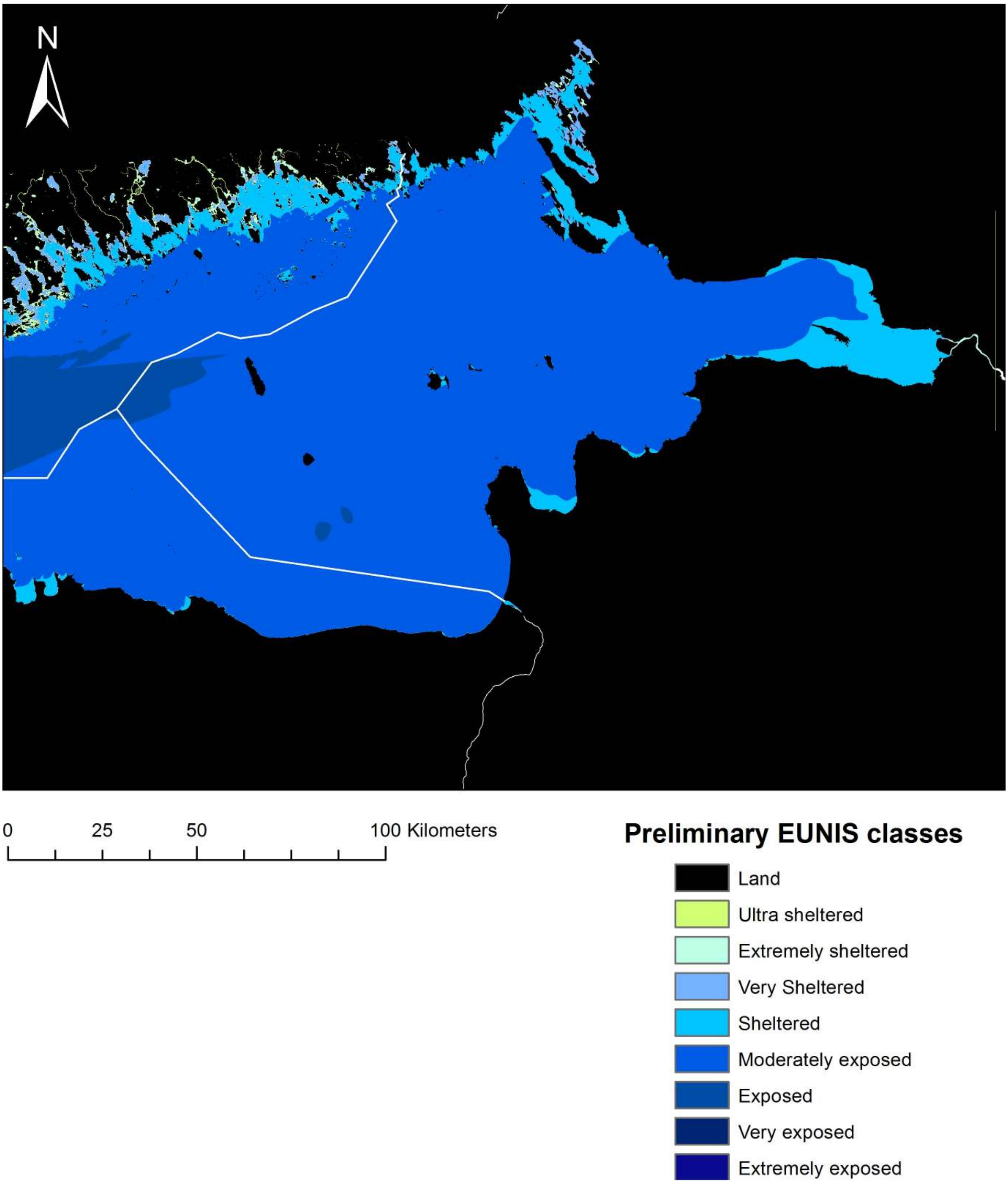

Figure 1. *A mosaic of the wave exposure grids for the inner parts of the Gulf of Finland. The colours indicate preliminary EUNIS classes according to the legend. The mosaic is composed from four wave exposure grids (1_A25a to 1_A25b) as well as wave exposure grids for Finland and Estonia (calculated in earlier projects).*

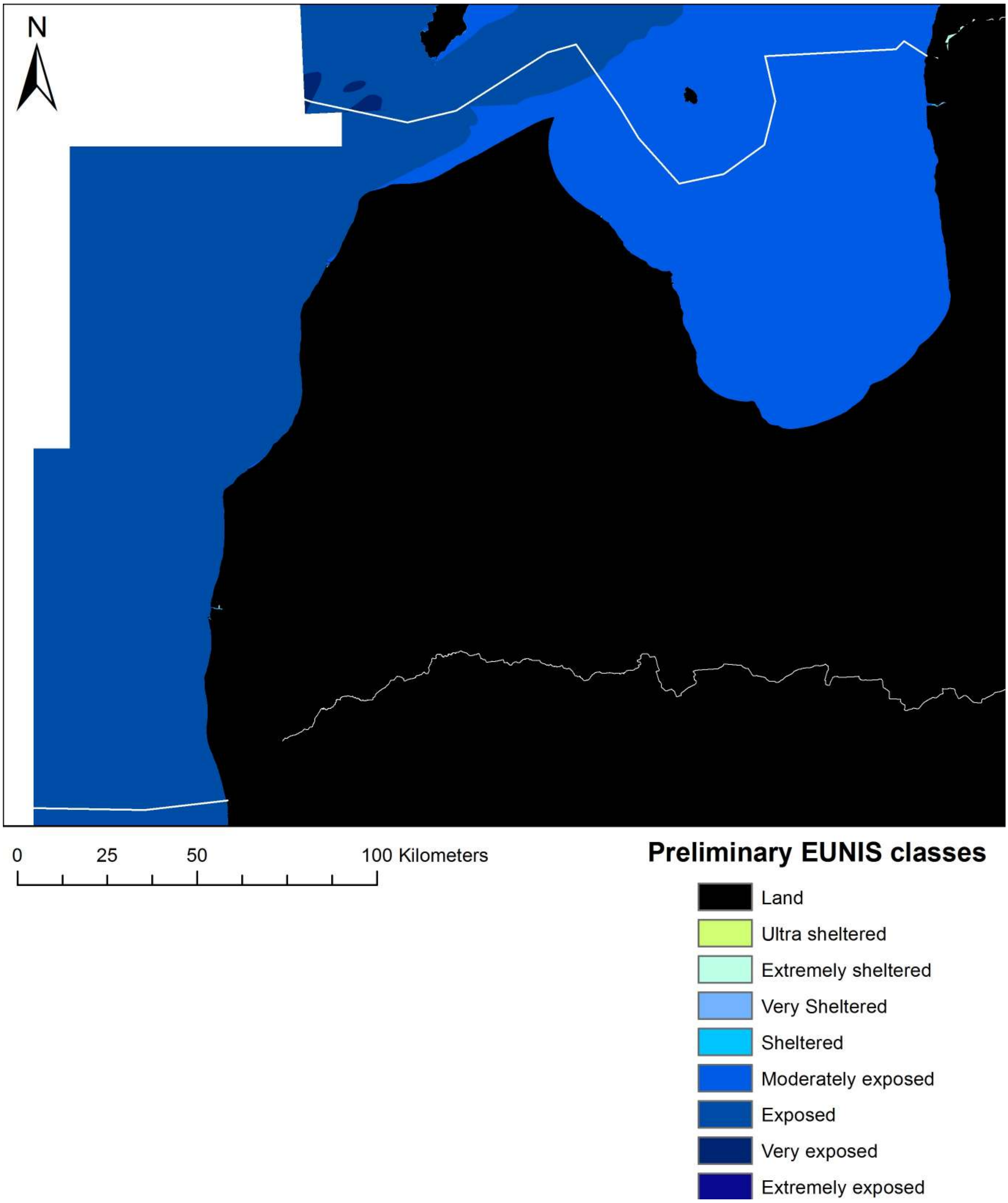

Figure 2. *A mosaic of the wave exposure grids for Latvia. The colours indicate preliminary EUNIS classes according to the legend. The mosaic is composed from four wave exposure grids (2_A25a to 2_A25c and parts of 2_C25a) as well as wave exposure grids for Estonia (calculated in an earlier project).*

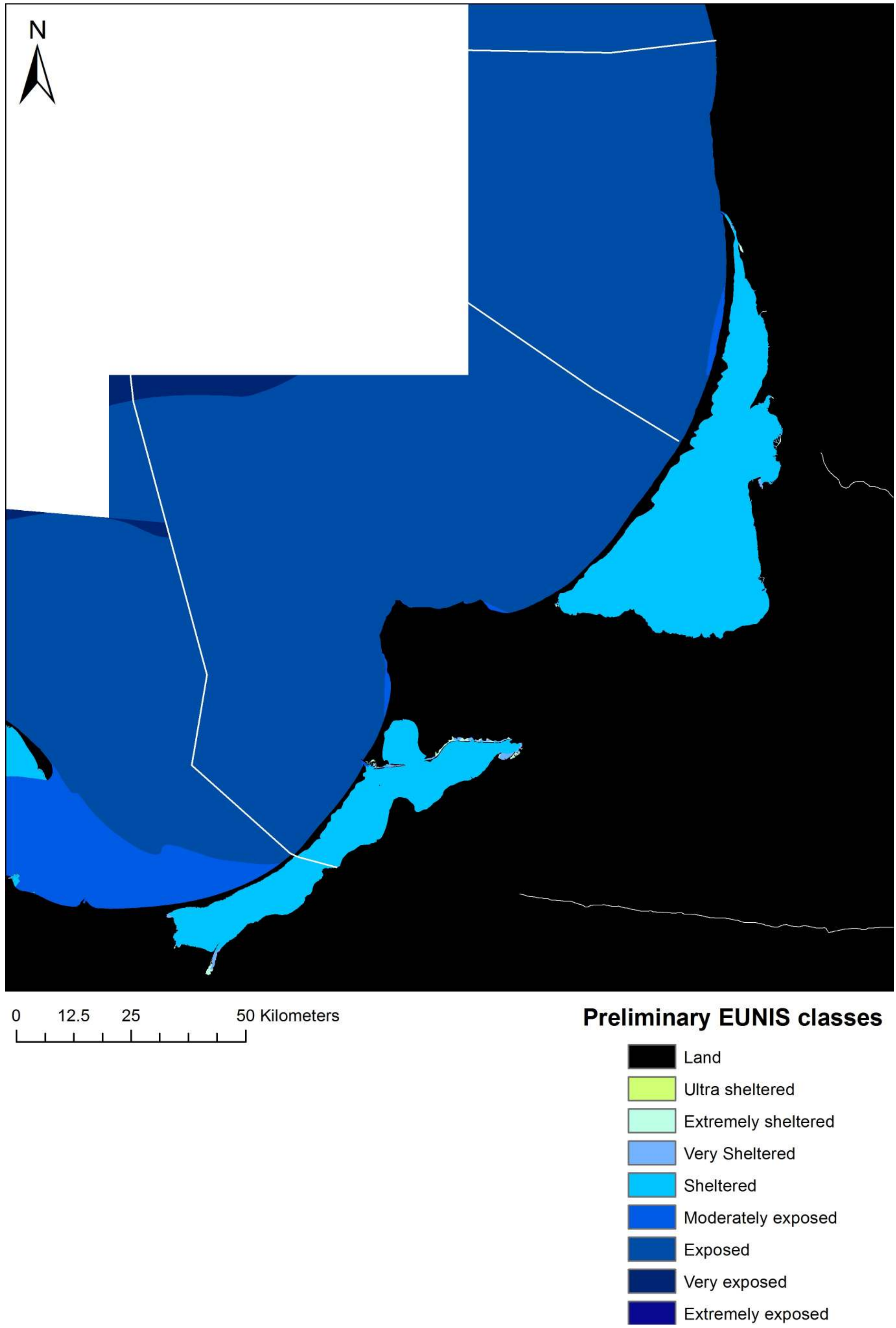

Figure 3. *A mosaic of the wave exposure grids for Lithuania and Russian enclave Kaliningrad with the Curonian and Vistula lagoons. The colours indicate preliminary EUNIS classes according to the legend. The mosaic is composed from five wave exposure grids (2_C25b to 2_D25b and parts of 2_C25a) as well as wave exposure grids for Poland (calculated in an earlier project).*

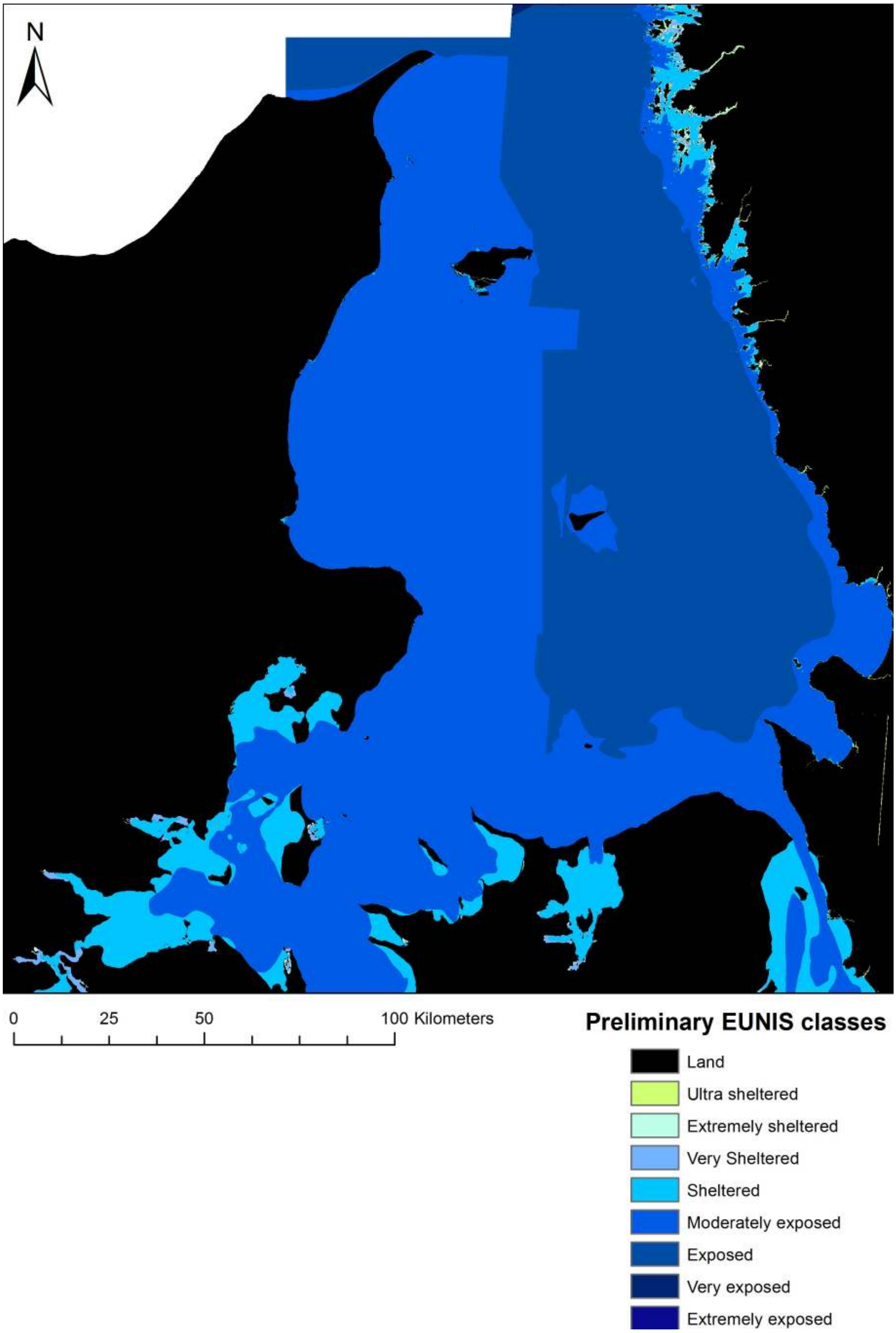

Figure 4. *A mosaic of the wave exposure grids for the Baltic coasts of northern Denmark. The colours indicate preliminary EUNIS classes according to the legend. The mosaic is composed from wave exposure grids calculated within this project as well as wave exposure grids for Sweden (calculated in earlier project). Where Swedish grids overlap, values from Swedish grids have been used.*

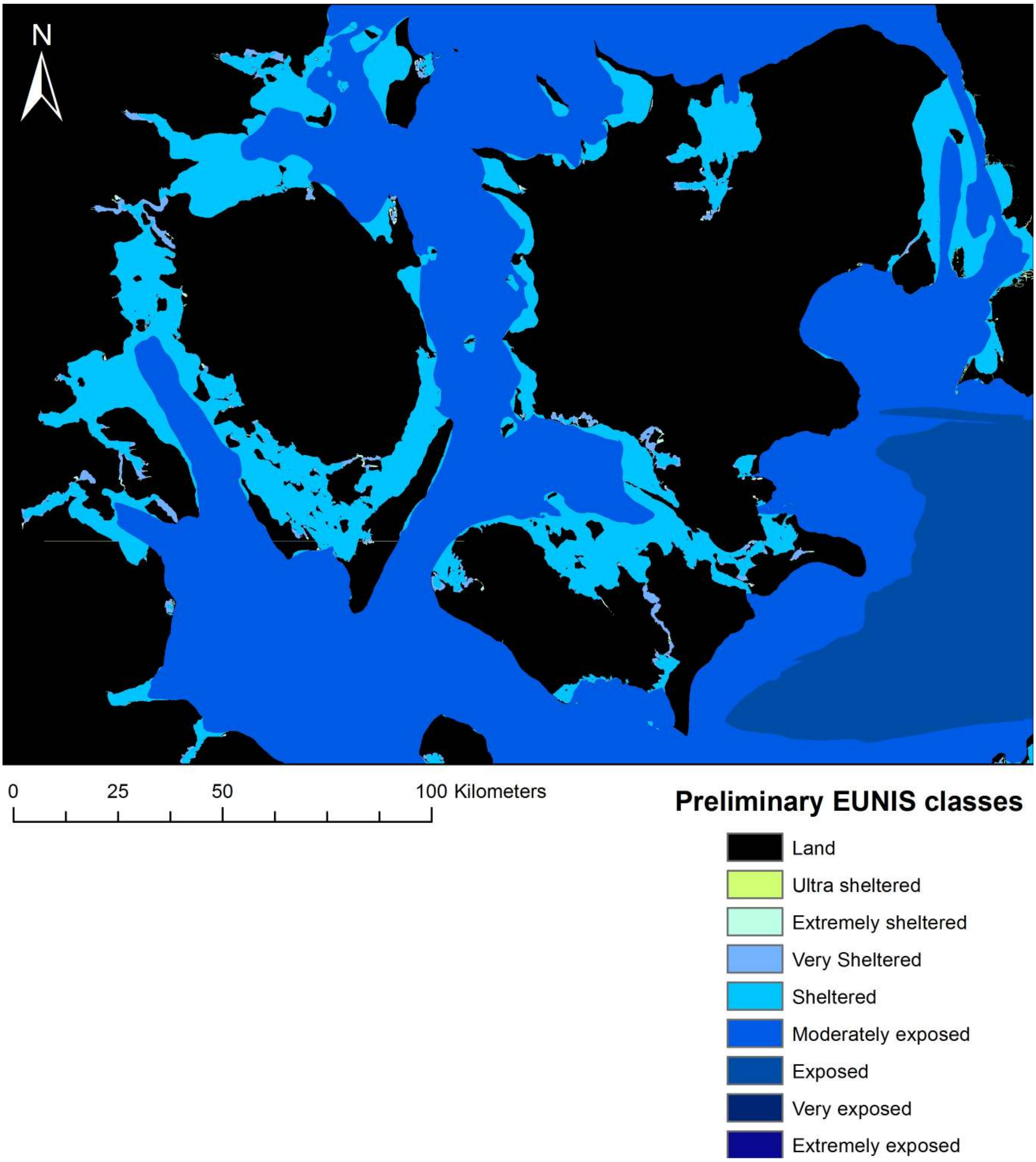

Figure 5. *A mosaic of the wave exposure grids for the Baltic coasts of southern Denmark and parts of the German coast. The colours indicate preliminary EUNIS classes according to the legend. The mosaic is composed from five wave exposure grids (2_C25b to 2_D25b and parts of 2_C25a) as well as wave exposure grids for Poland (calculated in an earlier project).*

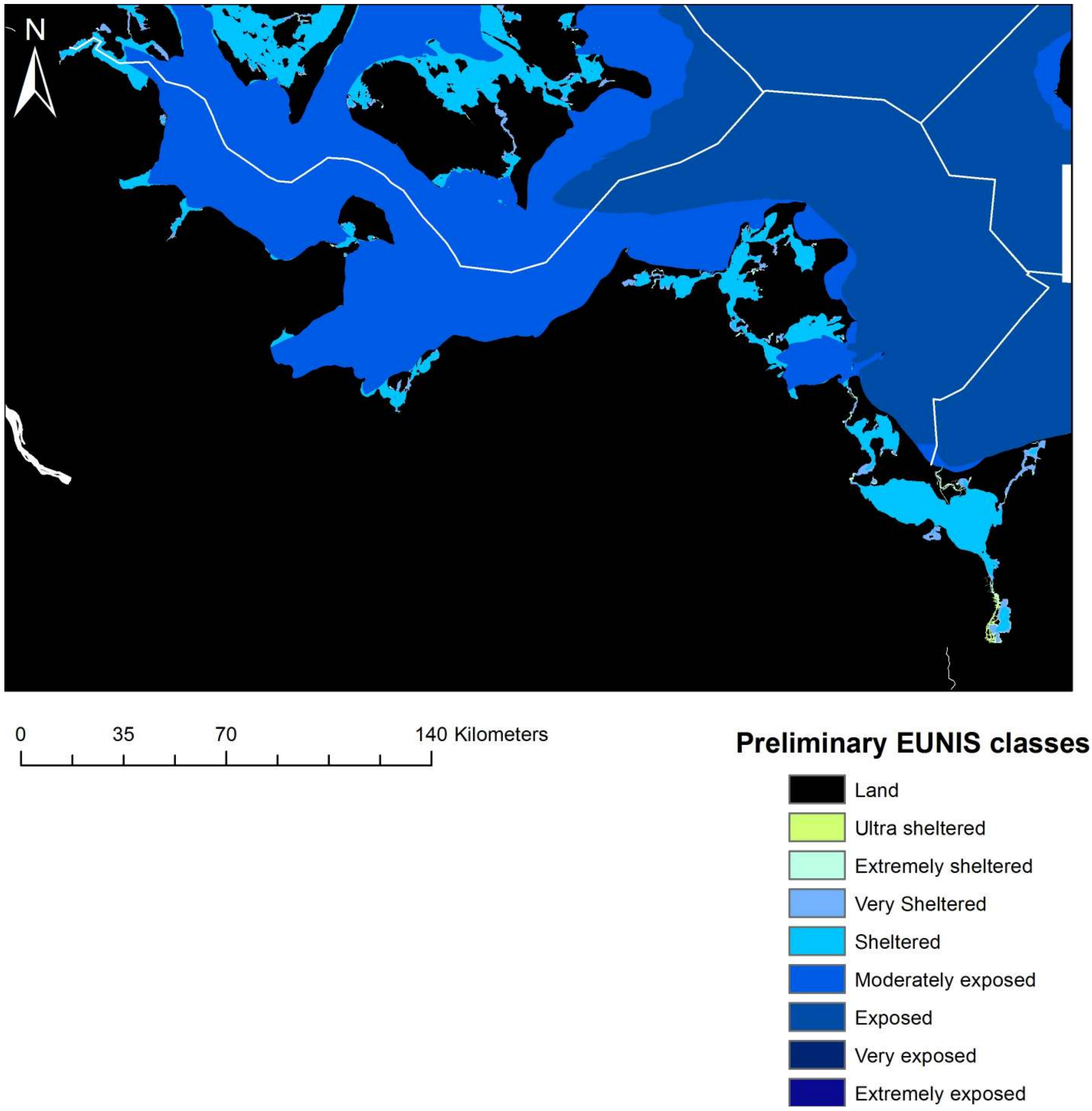

Figure 5. *A mosaic of the wave exposure grids for the Baltic coast of Germany. The colours indicate preliminary EUNIS classes according to the legend. The white line represents the EEZ border.*

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