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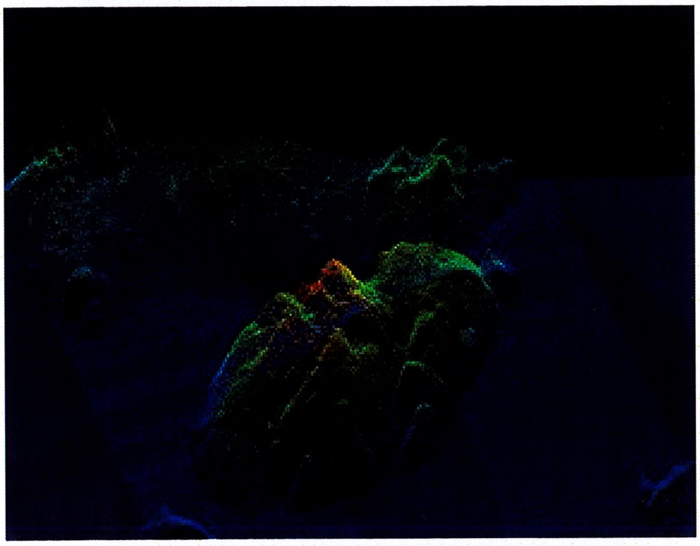
Modeling for survey priority and extended CATZOC classifications of Swedish territorial waters in the Baltic Sea



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Abstract

Hydrographic measurements and producing of sea charts are a vital part of safe navigations for vessels and ships. A request by the SMA in Norrkoping was made to extend CATZOC classifications in Swedish territorial waters by creating a model which could predict how fast the bathymetry would change at different locations. Models and maps were made in ArcMap GIS which would predict bathymetric changes of the seafloor in the Baltic Sea. Factors in the models include seabed type, the slope of the seafloor, and maritime transportation corridors. Survey priority maps were also made and include apart from the above-mentioned factors, the age of the latest FSIS-44 approved survey of Swedish territorial waters. These models and maps could be used to see where areas would have a need to be reclassed from A1 classification to a lower classification, or the need for the area to be re-measured. The results show a promising start where correlations between changes of the bathymetry over the years and predicted changes by the model could be made in small areas. This work opens a new way to assess changes in the bathymetry of Swedish territorial waters without the need to re-measure surfaces and helps to know which areas would be prioritized to be re-measured.

Sammanfattning

Hydrografiska mätningar och producering av sjökort är en viktig del inom säker navigering för båttrafik. En förfrågan från avdelningen källdata på Sjöfartsverket i Norrköping gjordes om att utöka CATZOC-klassificeringar av Sveriges territoriella hav genom att skapa en modell vilken kunde förutse hur snabbt förändringar av havsbotten på olika platser. För detta skapades modeller och kartor i ArcMap GIS med målet att förutse förändringar av batymetri på havsbotten i Östersjön. De faktorer som använts i modellen är sedimenttyp, lutning på havsbotten och sjöfartsleder. Modeller och kartor med sjömätningsprioritet har också gjorts. Där används tidigare nämnda faktorer tillsammans med ålder för senaste batymetriska mätningen med godkänd FSIS-44 standard för Sveriges territoriella vatten. Dessa kartor och modeller kan användas för att visa områden vilka behöver klassas ned från A1 till en lägre klass eller visa vilka områden som bör prioriteras för att mätas om. Resultaten från arbetet visar en lovande start hur korrelationer där förändringar över år av batymetrin mot modellens förväntade förändringar kunde göras på mindre områden. Arbetet är en start för hur man kan förutse förändringar i batymetrin, vilket i sin tur skulle minska behovet av att mäta om vissa områden men även göra en prioritet till vilka områden som bör mätas om.

List of acronyms used in the thesis

GIS – Geographical Information System

SMA – Swedish Maritime Administration

DIS – Depth Information System

MCDA – MultiCriteria Decision Analysis

CATZOC – Category Zone of Confidence

CHS – Canadian Hydrographic Service

CPPT – CHS Priority Planning Tool

HHM – Hydrographic Health Model

NOAA - The National Oceanographic and Atmospheric Administration

MTC – Maritime Transportation Corridors.

HELCOM – Helsinki Commission

BALANCE – Baltic Sea Management – Nature Conservation and Sustainable Development of the Ecosystem through Spatial Planning

IHO - International Hydrographic Organization

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1. Introduction

1.1 Background

Measurements of the Swedish seafloor and producing sea charts are important to ensure safe marine travels. The quality of sea charts can be described with category zones of confidence (CATZOC), as well as the age and scale of the surveys (John Riding et al., 2016). Bathymetric measurements in Sweden are categorized in CATZOC by the Swedish maritime administration (SMA) depending on the accuracy of the survey.

There is a risk of inaccuracy in old hydrographic measurements and sea charts since the bathymetry of the sea floor are everchanging. (John Riding et al., 2016). To this day there is still no universal approach for assessing old measurements and sea chart validity as they age (Bongiovanni et al., 2021).

A request by the SMA was made to adapt a classification system in Sweden with more categories than previously used. CATZOC has five zones and in Sweden we today only use two of them, A1 and C (appendix. 9). To initiate this project, an attempt to create a model which would predict changes in the bathymetry of the Baltic Sea was made. This model would be used to indicate which areas would have to change from classification A1 to a lower class.

Studies using GIS to ensure safer marine travels have been made previously (Chénier et al., 2018; John Riding et al., 2016). GIS can be used as a tool for hydrographic risk assessment and to improve sea surveying. A hydrographic risk assessment explains the risk for ships to travel in certain areas. The assessment depends on how old the measurements were, which instrument was used, and how exact it was (John Riding et al., 2016).

1.2 Bathymetric measurements of the Swedish seafloor and the Swedish Maritime Administration (SMA)

The SMA was founded in 1956 when several different authorities were combined into one organization but measuring the depth of the Swedish seafloor has been done for centuries. The oldest known measurement is mentioned in a book by King Valdemar which was written in the 13^{th} century and the oldest still preserved measurement is from the 17^{th} century. Due to the inaccuracy of maps and navigation at the time, old measurements are usually flawed (Ehrenswärd & Frithz, 1993). There are still measurements from the 19^{th} century used today in

Swedish sea charts, these are from more shallow waters such as Stockholm's archipelago where only four percent is today measured using modern methods (Sjöfartsverket, 2022).

About 70% of the Swedish seafloor was predicted to have been measured with modern tools such as multibeam sonar and bar sweeping by 2020 (Sjöfartsverket, 2016). The SMA today uses multibeam sonar and bar sweeping to investigate the depth of the sea. Multibeam sonar uses multiple sonar beams to measure the bathymetry of the seafloor and objects on the seafloor or in the water column (fig 1). Multibeam sonar is placed under the ships and measures in a fan-shaped pattern. It can measure both the depth of the seafloor and determine the type of seabeds such as mud or bedrock by using backscatter data. (National-Ocean-Service, n.d.) Bar sweeping uses a bar attached to the underside of the ship. It uses a mechanical sensor that registers when the bar touches the ground a can therefore register the most shallows depth in the measured area. Bar sweeping is common in shallow areas, harbors, and maritime transportation corridors (Holmstrand, 2011).

Depth Information System (DIS) is a database with all the measured sea depths in Swedish waters. It was created in 2007 with the purpose was to digitalizing SMAs 20 000 maps of sea depths. All new measurements made in Swedish territorial waters are stored in DIS. By 2017 there were 134 billion depths stored in DIS and 61% of the bathymetry of the Swedish territorial waters had been measured. (Wiberg & Wallhagen, 2018).

1.2.1 CATZOC

Category zone of confidence (CATZOC) is a classification system for bathymetric measurements of the sea floor. CATZOC values depend on position, seafloor coverage, and depth accuracy. The zones are a tool for assessing risks in navigation. There are five zones of confidence and U which stand for unassessed (appendix. 9) (UK-Hydrographic-Office, 2017).

The process of starting to use CATZOC in Sweden was made in 2019-2020 by the SMA. When a new measurement of the seafloor is made, a decision is made by SMA on what classification it should have. If the survey has gaps, it gets the classification C, if the survey is complete, it is assigned A1. The SMA has now made a work plan to be able to change CATZOC classifications for measured areas. The first step of this project is this master thesis along with one by Anna Olsson to make a method that would describe changes in the bathymetry over time for Swedish

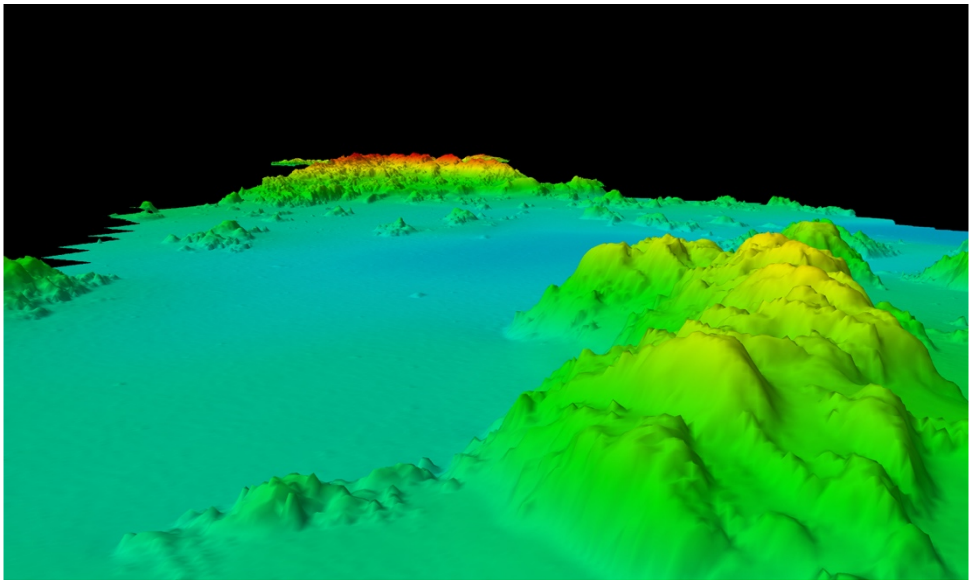

Figure 1: Bathymetry of the seafloor of a confidential area in Swedish territorial waters. The picture is derived from the SMA.

territorial waters shallower than 30 meters. This method needs to describe which factors that affect the bathymetry. This method is a basic condition for changing CATZOC classification to be made systematically. The SMA proposed the following factors as possibly crucial for down classing: currents, seabed type, maritime transportation corridors, other anthropogenic influence, climate, weather, and sedimentation from rivers. To implement this model, it is important for a technical solution where calculations of different areas could be made.

1.2.2 FSIS-44

FSIS-44 is a Swedish and Finnish implementation of the International Hydrographic Organization (IHO) standards for hydrographic surveys. It is a joint initiative by the SMA and the Finnish Transport Agency with the purpose of safe navigation. To follow the FSIS-44 standard, it is important to have accurate knowledge of sea depth. A better understanding of the sea depth is both economical and more environmental because it enables the maximum carrying capacity of cargo ships without the risk of grounding. FSIS-44 has a requirement of a full sea floor search without any larger gaps in the measurements (Finnish-transports-Agency & Swedish-Maritime-Administration, 2010). In Sweden, all geographical areas that have an approved FSIS-44 standard also have an A1 classification (Sjöfartsverket, 2021).

1.3 Previous studies

In Canada, the Canadian Hydrographic Service (CHS) is responsible for collecting, processing, and transforming nautical information. They are also responsible for ensuring navigational safety and distributing nautical products (Grenier & Hally, 1991). The CHS developed a priority planning tool called CPPT with the use of GIS to help with prioritizing hydrographic surveys and charting. Canada has the largest coastline in the world and therefore it was deemed helpful with a priority tool that would help them determine which areas to prioritize. The CPPT was made with a GIS model which used different geospatial layers. The geospatial layers include traffic patterns, water depth, and infrastructure. Other than that wind speed and ice was used as factors together with a model for the risk of grounding and collision. The CHS used existing surveys for their priority model. All areas with CATZOC classification A and classification B below 50 meters in depth were deemed accepted under international standards. With this, a priority could then be made for areas with classification C or lower (Chénier et al., 2018).

In GIS factors that were deemed the most important were given a higher weight in the final model. These included seven factors, water depth, traffic corridors, CHS existing surveys, seafloor complexity, survey requirements, risk of grounding and collision, and drift model analysis. Environmental factors such as wind speed and ice were given a lower weight. The model was made with a multicriteria decision analysis (MCDA). The CPPT was deemed successful and is currently being used by the CHS for short- and long-term planning (Chénier et al., 2018).

The Hydrographic Authority of New Zeeland made a report on hydrographic risk assessment of the sea in the New Zeeland's exclusive economic zone excluding the Sub-Antarctic Islands and the Kermadec island shelf. To make the risk assessment spatial analyses in GIS were used. For the analysis shipping traffic records covering twelve months were used. The study was made to improve charting and from the analysis, they created a survey priority plan to span over a few years. Three-component was used, risk, ship type and size, and economic growth, and the resulting combination was then used for prioritizing areas for hydrographic surveys (John Riding et al., 2016).

The National Oceanographic and Atmospheric Administration (NOAA) are responsible for hydrographic data for nautical charts in the United States of America. The NOAA created a hydrographic health model (HMM) which is a risk-based approach to evaluating charted data. It focuses on the quality of the survey and environmental factors such as storms, tides, and marine debris. To create the HMM they used ArcGIS. The charted data that was evaluated was from over 200 years and lots of different measurement tools had been used. This made it more difficult to evaluate areas and classify the uncertainty. To create the HMM the area of the Chesapeake Bay and the Delmarva Peninsula was used, because of the frequent re-measuring taking place in the area, significant sediment transport, and heavy ship traffic. The results from their study were promising and they suggested the inclusion of environmental models on a national scale (Bongiovanni et al., 2021)

1.4 Factors that affect the bathymetry of the seafloor

The ocean is a complex system. Several factors affect and continuously change the bathymetry of the seafloor. In an attempt to understand how the seafloor changes, different factors were chosen. Below are factors that play an important role in how bathymetry is described.

Marine sediments consist of various content such as terrigenous muds, minerals, and shells accumulated in the sea. Lithogenous sediments which are fragments of rock of various sizes, dominate the ocean margins. (Seibold & Berger, 2017) Grain sizes of sediments can be divided into clay, silt, sand, and gravel, for the ocean floor, bedrock can also be taken into consideration. The grain size is essential to determining the source and transport processes. To do this and to determine how easily different sediment types move, the Hjulstroem diagram can be taken into consideration (appendix. 10) (Seibold & Berger, 2017).

Maritime transportation corridors (MTC) are routes on which large ships and vessels travel on. MTC has a high priority compared to other areas of Swedish territorial waters when it comes to hydrographic measurements and icebreaking. They exist to ensure safer marine navigation and reduce risks such as collision and grounding (Andrews et al., 2015). Few studies have been done on the effect large ships have on bathymetry. Increasing ship traffic at a higher speed and larger vessels can cause the bathymetry to change, evidence of this can be seen in the slopes carved on the edges of maritime transportation corridors (appendix. 11). Ships' movement generates both primary (drawdown) and secondary (transverse and divergent) waves. Secondary waves can erode adjacent shores which creates a loss of finer sediments (Almström et al., 2018). A study of Gothenburg harbor showed that erosion is dominant where heavy traffic occurs. The bathymetry in the harbor had been estimated to change about 2 cm a year. Results showed areas in the harbor that had eroded up to 1 meter and on average the harbor had eroded 0,5 meters (Stevens & Ekermo, 2003).

1.5 Study area - The Baltic Sea

The Baltic Sea including the Gulf of Bothnia is an old depression in the Fennoscandian bedrock. The sea itself is relatively young and was created as it is today during the end of the latest glaciation (Weichselian) 9000-13500 years ago. The glaciation created a deeper impression on the Fennoscandian bedrock and the sea underwent different stages due to eustacy and isostasy (Leppäranta, 2008).

The Baltic Sea has an area of about 387,000 km2 (Meier & SMHI, 2006). The sea is an intercontinental sea with a strait between Denmark and Sweden connecting the sea to Kattegat, Skagerrak, and the North Sea. In comparison to other seas, The Baltic Sea is relatively small and shallow. The sea is also brackish due to limited exchange with high saline water and river influence. The sea has a salinity of about 7‰ and the conditions have been about the same for 2000 years (Leppäranta, 2008).

1.6 Aim and research objectives

- Create a model in GIS for predicting how changes in the bathymetry in the Baltic Sea would occur at different locations.
- Create a model in GIS for a proposed survey priority in the Baltic Sea.

2. Method

For this thesis data processing, maps and models were made with ArcMap GIS. The first part of the thesis started in Norrkoping at the SMA where the first step was to identify available data to use in GIS that could affect the bathymetry. Available data that were found and possible to process in ArcMap were sediment types, the slope of the sea floor, maritime transportation corridors, and the age of the latest survey with approved FSIS-44 classification. A decision to focus on previous factors was made to limit the thesis. The seabed type of Swedish territorial waters is classified and owned by SGU and was not available at the SMA, except for some smaller areas which were ordered by the SMA. Other factors were suggested by the SMA at the beginning of this project: currents, seabed type, maritime transportation corridors, other anthropogenic influences, climate, weather, and sedimentation from rivers. All mentioned factor was investigated to whether data was available to use in the model. Slopes of the seabed were added as well after finding that CHS in Canada used slopes in their paper (Chénier et al., 2018). Other factors which affect the bathymetry such as sedimentation rates, river sediment discharge, sea ice, and bottom currents were not available for both the large- and small-scale model and maps which were created and were therefore chosen to be left out of the thesis. Some of the data we used is from DIS and the data is classified. Because of this, some detailed models cannot be presented. Maps showing the bathymetry with coordinates are classified. Seabed type with coordinates is classified.

Open access data was collected from The Baltic Marine Environment Protection Commission or Helsinki Commission (HELCOM). Helcom was established in 1974 and is an intergovernmental organization created to protect the marine environment of the Baltic sea (HELCOM, n.d.). From Baltic Sea Management – Nature Conservation and Sustainable Development of the Ecosystem through Spatial Planning (BALANCED) slope of the seafloor and seabed type was collected reworked and used (HELCOM, 2010). The data covered all of Sweden's territorial waters and most of the Baltic Sea. Since the details of seabed type and slope are classified in Swedish waters, the open-source data from HELCOM was used to make a map covering the entirety of Sweden. Since the maps would have to be well simplified to be able to show trends of changes in the bathymetry, public data was decided on as the best way to present the results.

2.1 Data

2.1.1 FSIS-44

The area of Swedish territorial waters in the Baltic Sea and Gulf of Bothnia with approved FSIS-44 classification was divided into four different classes. The division was as follows: surveys older than 20 years, 19 to 10 years, 9 to 5 years, and younger than 5 years. The data was then converted from vector into a raster and reclassified so that the oldest surveys were given the value 4, the second oldest value 3, the second youngest value 2, and the youngest value 1. This division and given values were made since the oldest still approved surveys would have a higher priority to be re-measured compared to younger ones.

2.1.2 Slopes

Deciding which division of slopes to use (0-90°) was tried out with different divisions. The final slope division was divided into 5 classes. <2°, 2-7°, 7-13°, 13-25°, and >25°. This division was chosen because the Swedish seafloor is quite steep compared to for example the Canadian territorial waters where they had chosen 0-0.25°, 0.25-4°, and 4-60° (Chénier et al., 2018).

2.1.3 Seabed type

The seabed type for the small-scale areas was provided by SGU and had 4 categories: bedrock; stones and boulders; sand gravel and stones; clay. The weight chosen in the reclassification was based on the Hjulstroem diagram (Seibold & Berger, 2017). Sand gravel and stones were given the value 6. Clay was given the value 5. Stones and boulders were given the value 2. Bedrock was given the value 1. The higher values given to clay and sand, gravel, and stones are motivated by these sediment layers are much more likely to change compared to the seafloor type dominated by bedrock or stones and boulders. The seabed type for the large-scale model was provided by BALANCE by Helcom. The categories differentiate somewhat from the data provided by SGU but there was still a possibility to transfer the reclassified values. The different categories from the Helcom data were bedrock; hard bottom complex; sand; hard clay and mud. With hard bottom, complex means patchy hard surfaces with grain sizes from coarse sand to boulders. Here sand was given the value 6, hard clay and mud the value 5, hard bottom complex the value 2, and bedrock the value 1.

2.1.4 Maritime Transportation Corridors

The data for maritime transportation corridors was provided by the SMA, both for the large- and small-scale maps. The data was provided in vector and was then transformed into a raster to work in the model. The data was reclassified so that all the maritime transportation corridors were given the value 2 and all the areas without maritime transportation corridors were given the value 1.

2.2 GIS

2.2.1 MCDA

To create large- and small-scale scale models in ArcMap a multicriteria decision analysis (MCDA) approach was chosen. MCDA is a method for combining different datasets and creating a combined output. This procedure allows for geographical decisions based on the criteria and preferences made by the decision-maker (Malczewski & Rinner, 2015). Other authorities have used a similar approach, for the hydrographical risk assessment made in New Zeeland weighted overlay in GIS was used (John Riding et al., 2016).

2.2.2 Data processing

For the data processing, the first step was to identify overlapping bathymetric surveys made with a multibeam sonar. This so that it was possible to compare changes in the bathymetry between different years. 11 areas of the Swedish territorial waters with sizes of about 50 000 m^2 to 90 000 m^2 were investigated.

To use the bathymetric data, it had to be processed in ArcMap. The data was provided in point files which then were converted into raster. The data needed to have the same cell size and a processing extent without decimals. This so that when calculating the difference in bathymetry between different years it would be without errors. In some areas the bathymetry would have changed up to 17 meters over just a few years, these extreme numbers could be explained by double points still in the point layers provided by the SMA, giving the appearance of large elevation changes when it could just be misplaced points. This problem makes it hard to know which values are correct and which are because of faulty data.

After a comparison of changes in bathymetry over different years, the next step was to build a model which would predict changes in the same area. The first step was to look at different datasets such as seabed type, maritime transportation corridors, and slope data of the seafloor to try to identify any clear visual connections between these layers and the change in bathymetry. After confirming a connection between changes in the bathymetry and the three environmental datasets the maritime transportation corridors layer was converted to raster. The three layers were then reclassified and added together in the spatial analyst tool weighted sum. Weighted sum combines multiple rasters into one combined output raster. Each cell has a value from the reclassification and in the tool, different inputs manually are chosen a weight. The weighted sum does not rescale the reclassified values back to an evaluation scale which is useful for identifying areas where the bathymetry of the seafloor is most likely to change (pro.arcgis.com, n.d.). Trying out the weighted sum tool with different weights and given different values in reclassifying the environmental layers was made to find a solution that mimics the actual changes of the bathymetry the most at different locations. The final weights for the slope data were 2, seabed type 1.5, and maritime transportation corridors 1.

2.2.3 Models

Models were made in ArcMap GIS model builder to easily save and replicate the processes made at different locations. Two different models were used (appendix. 7, 8). In the model, raster data was reclassified and added to a weighted sum. Different weights were tried out and the final weight given to the factors was: 2 for slope, 1.5 for seabed type, and 1 for maritime transportation corridors. The weight 3 was given for therefore the age of the latest survey in the weighted priority model.

3. Results

The results are divided into two parts. The small-scale and the large scale-models and maps. The small-scale models and maps have an area of about 90 000 m^2 and were made to verify the accuracy of the model with changes in the bathymetry. The weights from these models were then used for the large-scale models. The results from the large-scale model are divided into two areas, The Baltic Sea and the Gulf of Bothnia. The division is because it is easier to interpret the results with a smaller area. The model shows predicted changes and is not specified whether the elevation of the seafloor has increased or decreased.

3.1 Small-scale models

Figure 2 shows three different maps. The dominating seabed type is a combination between sand, gravel, and stones with some areas dominating with clay along the edges. Through the area is a maritime transportation corridor, covering almost the entirety of the area. The slope of the area varies between below 2° and over 25° where a trend of steeper edges and a flatter area in the middle can be made.

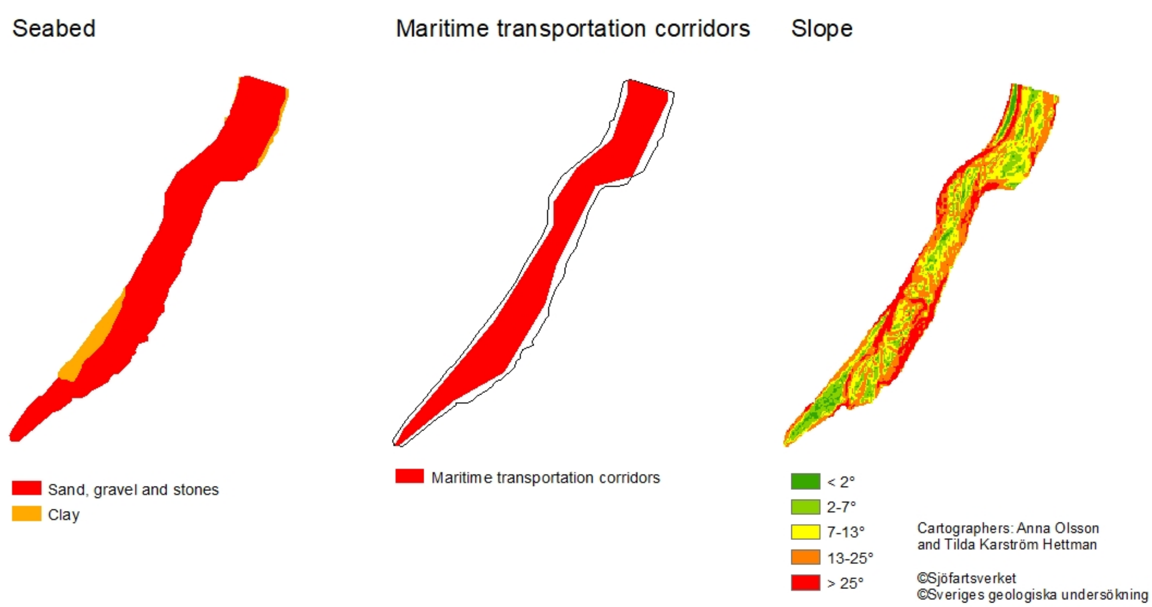

Figure 2*: Shows three maps of a confidential area in the Swedish territorial waters. Map one shows the seabed type of the area made from SGU data. Map two shows the maritime transportation corridor made from SMA data. Map three shows the slope of the area created from bathymetry data provided by the SMA.*

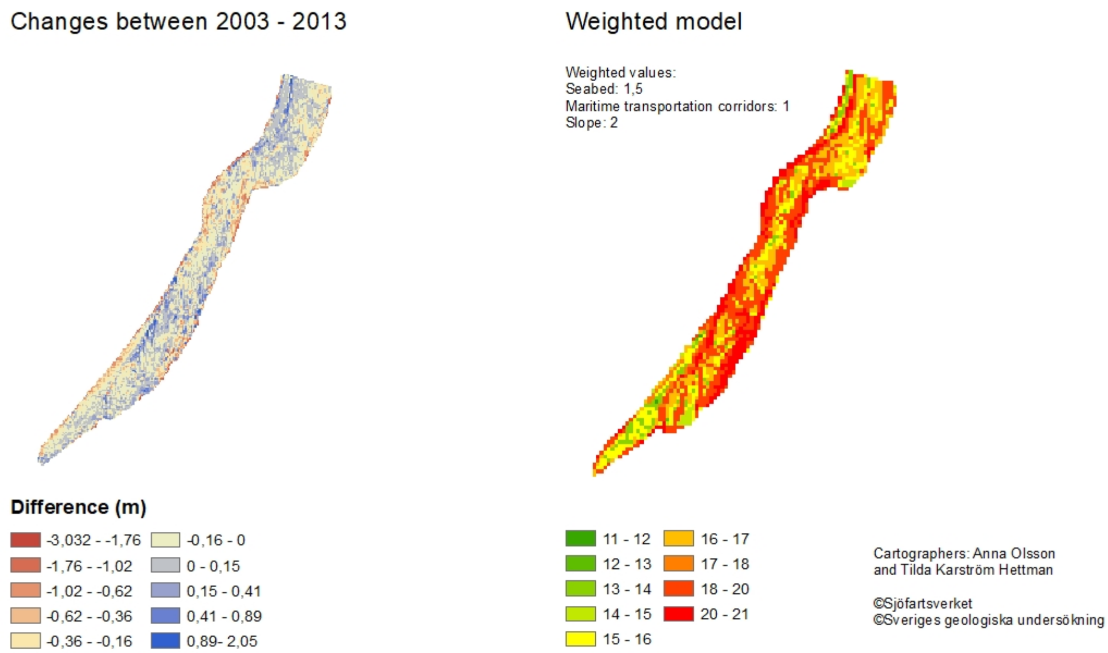

Figure 3: Shows two maps of a confidential area of the Swedish territorial waters. Map one shows the height difference between the years 2003 and 2013, both shallowing and deepening of the seafloor. Map two shows the weighted model with calculated differences created in ArcMap. For the weighted model slope, seabed and maritime transportation corridors were used.

Comparing the changes in the bathymetry between 2003 and 2013 a general trend of deepening of the bathymetry, visualized in blue can be observed. Shallowing is visualized in red and can be seen mostly along the edges of the area. When comparing to the predicted changes from the model, the highest changes are predicted along the edges of the area and the least changes in the middle and the bottom left corner (fig. 3). Figure 4 shows three different maps. The dominating seabed type in the area is clay and it has a maritime transportation corridor running through it. The area is mostly flat with less than 2° with some steeper areas over 25°. The weighted model compared to actual changes of the bathymetry (fig. 5) shows some correlations. Changes in the bathymetry between 2003 and 2016 are visualized in red where the area has gotten shallower, and blue where the area has gotten deeper. Predicted changes with the highest values are visualized in red. The predicted model cannot differentiate between where the bathymetry has gotten more deep or shallow, only where changes are most likely to happen.

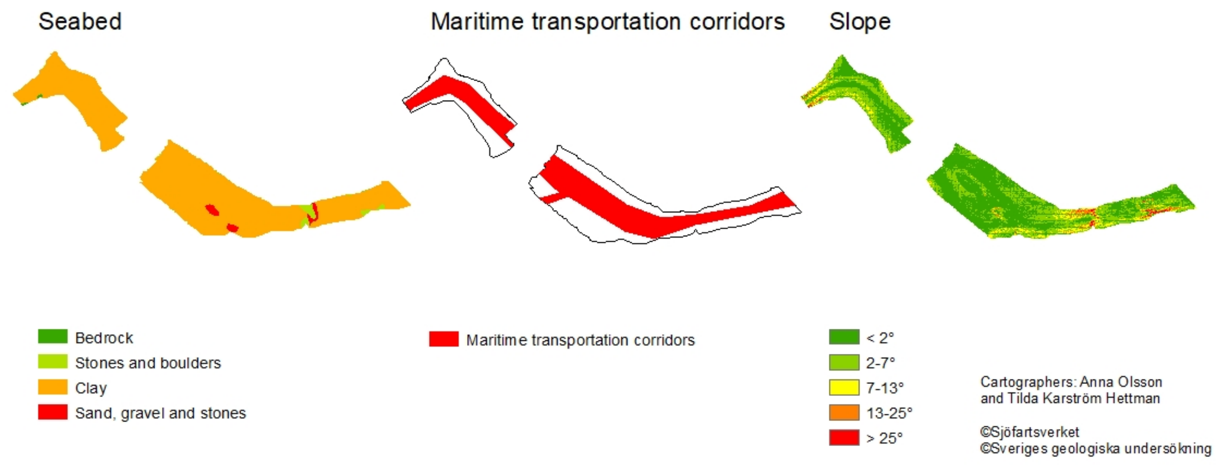

Figure 4*: Shows three maps of an confidential area in the Swedish territorial waters. Map one shows the seabed type of the area made from SGU data. Map two shows the maritime transportation corridor made from SMA data. Map three shows the slope of the area created from bathymetry data provided by the SMA.*

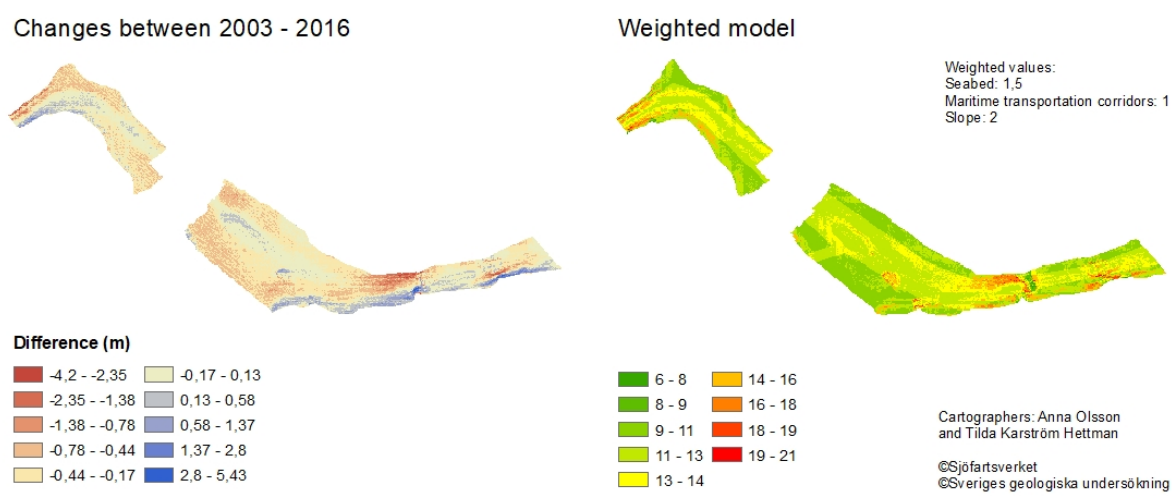

Figure 5*: Shows three maps of a confidential area in the Swedish territorial waters. Map one shows the seabed type of the area made from SGU data. Map two shows the maritime transportation corridor made from SMA data. Map three shows the slope of the area created from bathymetry data provided by the SMA.*

3.2 The Baltic Sea and the Gulf of Bothnia

Figure 6 shows a model of environmental factors which includes seabed type, maritime transportation corridors, and slope with different weights in the Baltic Sea. The green areas indicate regions of the seafloor which are the least likely to change and the red areas indicate which areas are most likely to change. The areas predicted most likely to change are located southeast of Öland, mostly in maritime transportation corridors (appendix. 5). Other areas with a higher value of predicted changes are located in the Stockholm archipelago.

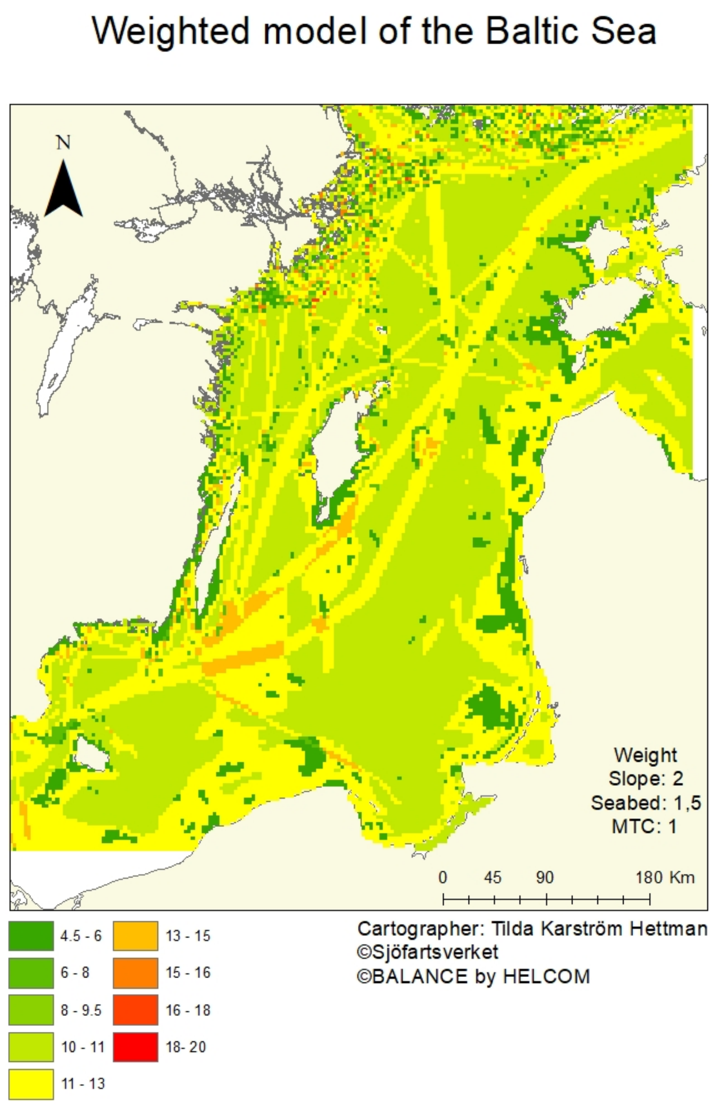

Figure 6*: shows a weighted model of the Baltic Sea. The model was created in ArcMap using three inputs. Slope data provided by BALANCE by HELCOM. Seabed type was provided by BALANCE by HELCOM. Maritime transportation corridors were provided by the SMA. The weight used for the different inputs of the model is the same as for the small-scale maps.*

Figure 7 shows a weighted priority model which includes seabed type, maritime transportation corridors, slope, and age of survey. Only approved FSIS-44 surveys are included because the not approved areas already have a higher priority to be re-measured. Some identified priority areas are located in the Kalmar strait and southeast of Öland and Stockholm's archipelago.

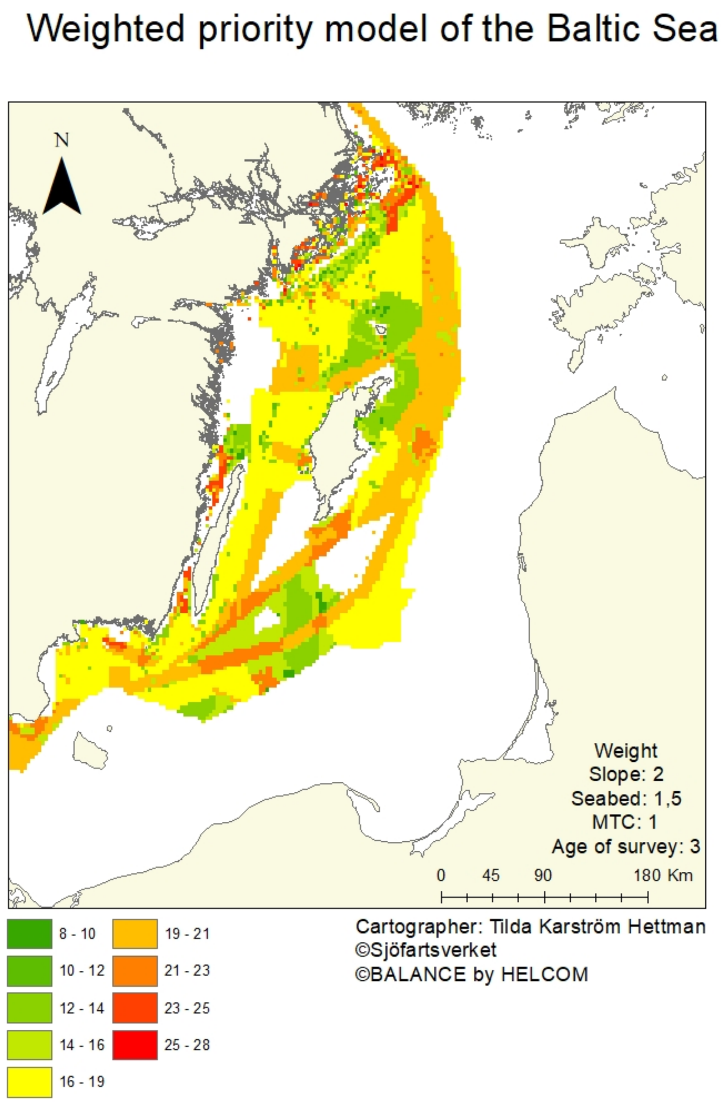

***Figure** 7: Shows a weighted priority model of the Baltic Sea. The model was created in ArcMap using four inputs. Slope data provided by BALANCE by HELCOM. Seabed type was provided by BALANCE by HELCOM. Maritime transportation corridors were provided by the SMA. The age of survey data was provided by the SMA.*

Figure 8 shows a weighted model of the Gulf of Bothnia. The model includes slopes, seabed type, and maritime transportation corridors. Areas identified most likely to change are the northern part of the Gulf of Bothnia along with the coastline and along the maritime transportation corridor (appendix. 5). Figure 9 shows a weighted priority model of the Gulf of Bothnia. The model includes slopes, seabed type, maritime transportation corridors, and age of the latest survey made with approved FSIS-44 classification. Identified priority areas include the northern part of the gulf and the middle of the gulf.

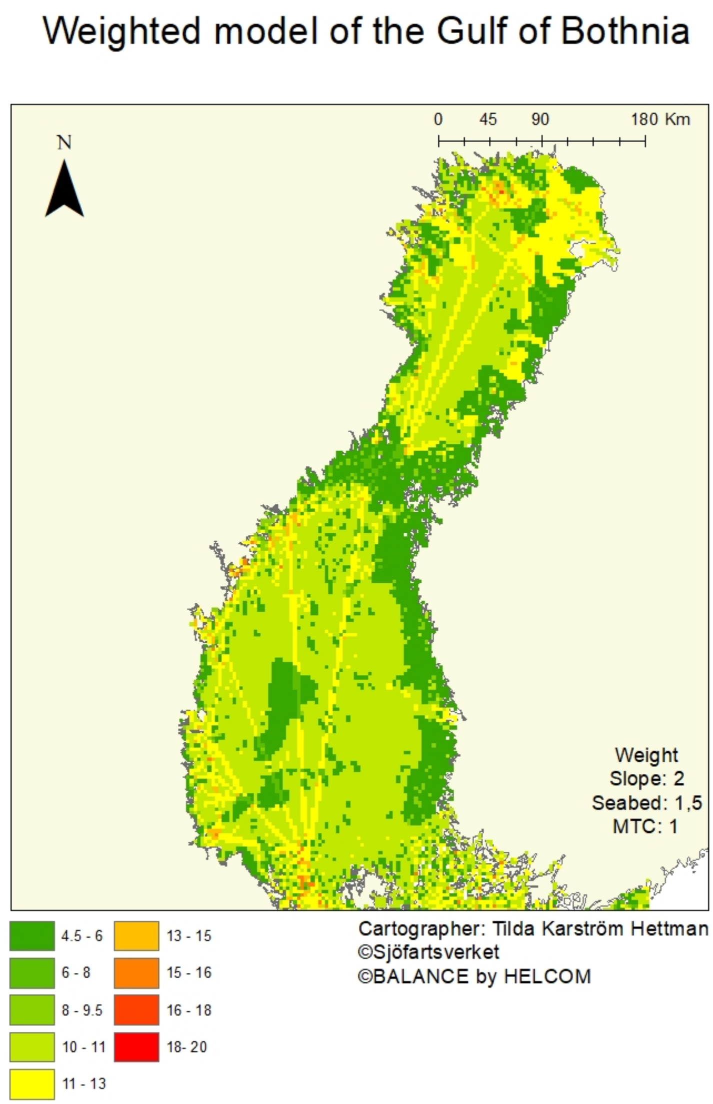

Figure 8*: shows a weighted model of the Gulf of Bothnia. The model was created in ArcMap using three inputs. Slope data provided by BALANCE by HELCOM. Seabed type was provided by BALANCE by HELCOM. Martime transportation corridors was provided by the SMA. The weight used for the different inputs of the model is the same as for the small-scale maps.*

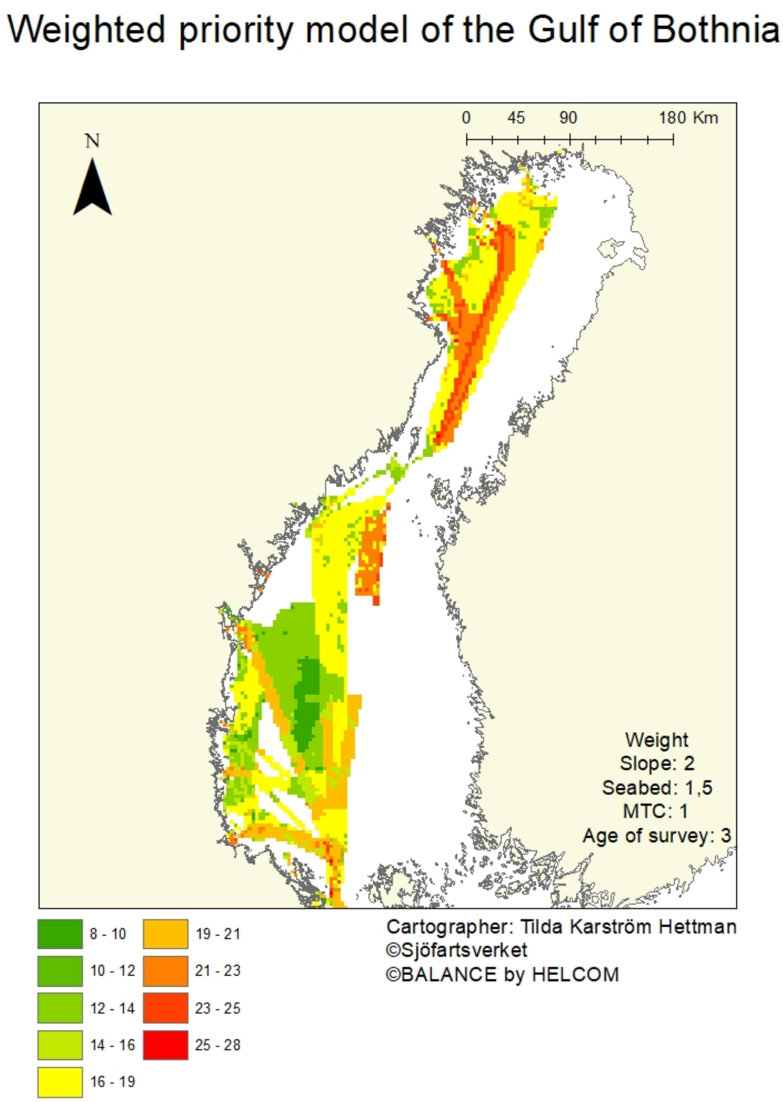

Figure 9: *Shows a weighted priority model of the Gulf of Bothnia. The model was created in ArcMap using four inputs. Slope data provided by BALANCE by HELCOM. Seabed type was provided by BALANCE by HELCOM. Maritime transportation corridors were provided by the SMA. The age of survey data was provided by the SMA.*

4. Discussion

The SMA requested this master thesis to create a model that could predict changes in the bathymetry and, if possible, how much over time. The results show a promising start on how this might be possible. A priority map was also made for the SMA to use which seemed promising since other authorities have used this approach (Bongiovanni et al., 2021; Chénier et al., 2018; John Riding et al., 2016).

The SMA proposed the following factors to use in the thesis: currents, seabed type, maritime transportation corridors, other anthropogenic influences, climate, weather, and sedimentation from rivers. All factors were investigated if possible to use in the model. As previously mentioned, only the factors with available data to work with in ArcMap GIS were used. Slopes of the seafloor were not proposed to use by the SMA, but since the CHS used it in their model it was tried out. Slopes of the seafloor had an impact on the bathymetry and were therefore decided to use in the model.

It is important to note that a lot of the work made in this thesis has not been tried out before, the environmental factors seabed type has not been previously used and the slope of the seafloor has only been used by the CHS in Canada. Because of this, the reclassification and weight given to the models are solely based on trials and visual similarities.

Of the eleven smaller areas with an area of about 90 000m^2, only two maps were chosen to be a part of the thesis. This is because of large differences in the bathymetry between years, some up to 15 meters. The large differences could be explained by small errors in the data provided. For some areas investigated it was not possible to order seabed type data from SGU and was therefore chosen not to be used in the thesis either. The model for the small-scale maps showed similarities with actual changes in the bathymetry. The clearest correlations can be made in figure 5 where slope seems to be the most important factor in determining where the bathymetry will change.

Focusing on the small scale maps the clearest correlation between actual changes and the model's predicted ones seems to rely on the slope. This data was also the most accurate and had the highest spatial resolution which showed more details than compared for example seabed type.

With the data available today, it was not possible to create a robustly reliable map on a larger scale. Correlations between changes in the bathymetry and the model could be made at the small-scale maps but with the larger scale maps, there was no way to validate the model.

The weighted priority maps were made for the SMA to either decide which areas would need to be reclassified from A1 to a lower classification or show areas that need to be re-measured to keep an A1 standard. The request from the SMA to start up the project to extend CATZOC classifications can therefore be used with these models. The decision to use FSIS-44 approved areas instead of CATZOC A1 was because these classifications are interchangeable, but the data provided from the SMA was more recent and complete for the FSIS-44 areas compared to the CATZOC classifications, and the decision to use FSIS-44 data was therefore made. The results from the weighted priority maps show that areas that have A1 classification from measurement that is older than 20 years (appendix. 2) have the highest need to be reclassified or be re-measured.

Limited time and data inhibited further possibilities to validate the model in other ways, but it would be desirable to test the model at different locations and with more factors. I was not able to obtain data on river discharge or river sediment discharge and therefore could not apply it in the model. The slope data used to make the large-scale model seems to be much more detailed in some places such as the Stockholm archipelago compared to the southern part of the Swedish coast (appendix.4). More detailed data is possible to obtain from the SMA but cannot be shown in the thesis due to the secrecy of the data. To make the model more accurate on a larger scale, slope data from SMA is advised compared to the HELCOM data used.

4.1 Further research

The seabed sediments data that was used for the large-scale model is simplified. This is because the detailed data is classified and owned by SGU, and there is a possibility to obtain it for the entire Swedish territorial water, but with communications with the SMA, the process to get access to the data could take months up to one year to obtain. If the model is chosen to be used by the SMA a more comprehensive collaboration with SGU would be desirable.

Other factors which affect the bathymetry such as sedimentation rates, river sediment discharge, sea ice, and bottom currents were not available for both the large- and small-scale model and were therefore chosen to be left out of the thesis. These factors may still have a significant impact on the bathymetry of the seafloor and could be further investigated.

More tests and validations of the model are recommended. With limited time to access the data from DIS only smaller areas could be tested. Apart from that, only areas with seabed type which are not restricted by the SGU was used, these areas are from river and lakes. It is therefore recommended that the model is tested in more saline water.

To further develop the model made in this thesis a more comprehensive collaboration between Swedish authorities would benefit different parties involved and enable safer nautical navigations.

To develop a model in Sweden that could estimate where we would have changes in the bathymetry there could be useful to employ a control program where measurements of the bathymetry would occur maybe once a year at the same location. This could be at a few different locations so that comparison with different influential factors could be possible. The areas could have different conditions such as different seabed types, strong and weak currents, and influence from riverine waters. Continuously studying different areas might help us understand more about how and why the bathymetry changes.

5. Conclusions

This project was written for the SMA's extended CATZOC classifications project. The results show a promising start and suggestions on how SMA might develop a model for predicting the Swedish bathymetry. Priority maps made suggest were reclassification or re-measuring might be necessary but further validation on a larger scale and the inclusion of other factors would benefit the model.

6. Acknowledgments

I would like to thank my dear friend and future colleague Anna Olsson for a great partnership in producing and working with the data for our thesis.

I would also like to thank Jakob Heyman for his great supervision during this thesis and thank the University of Gothenburg.

I would also like to thank the SMA for giving me this opportunity to write this thesis. And thank you Anna Wall with colleagues in Norrköping for great supervision and good ideas during my stay there.

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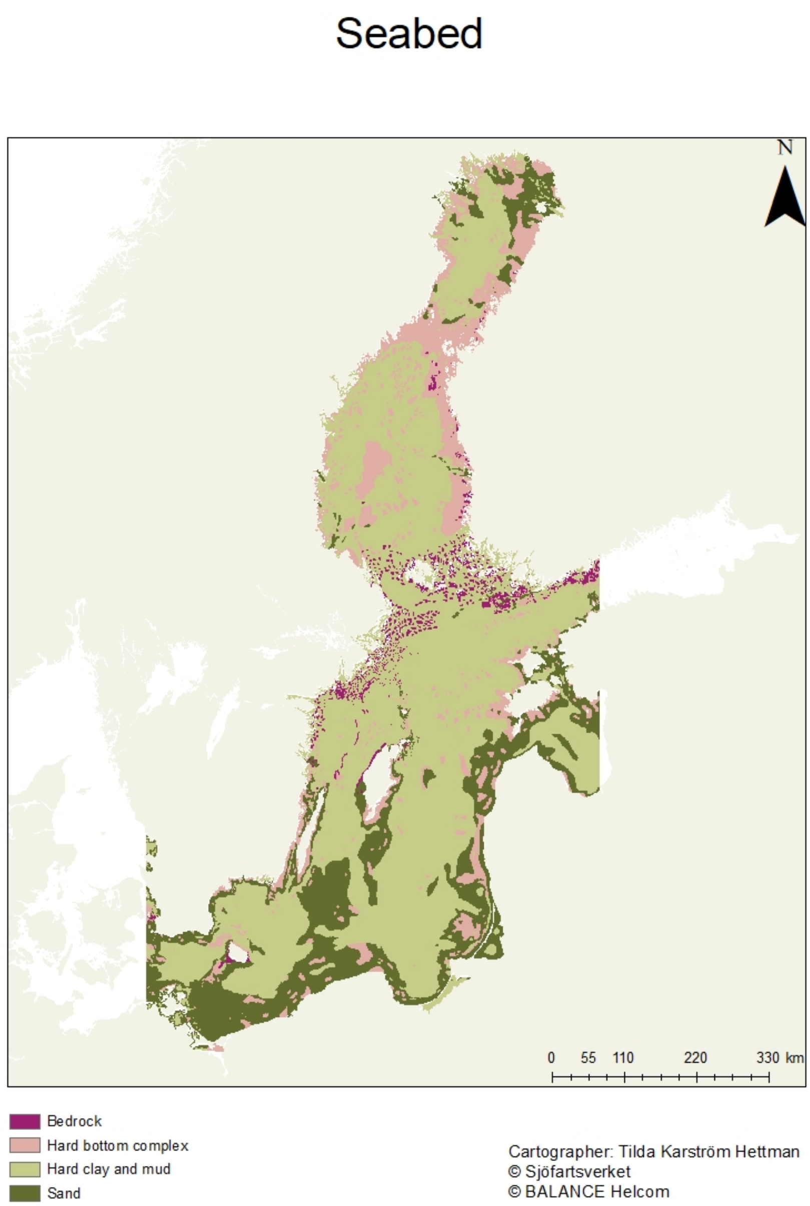
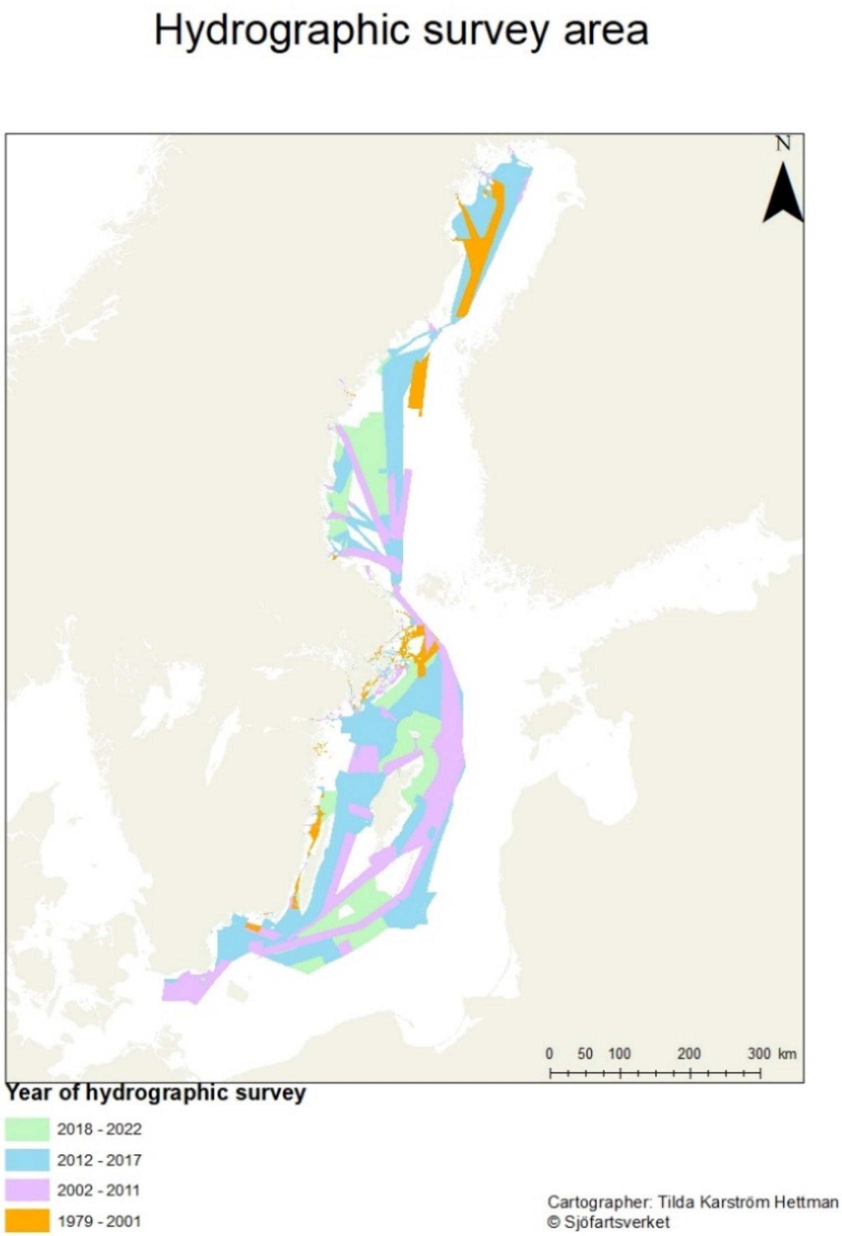
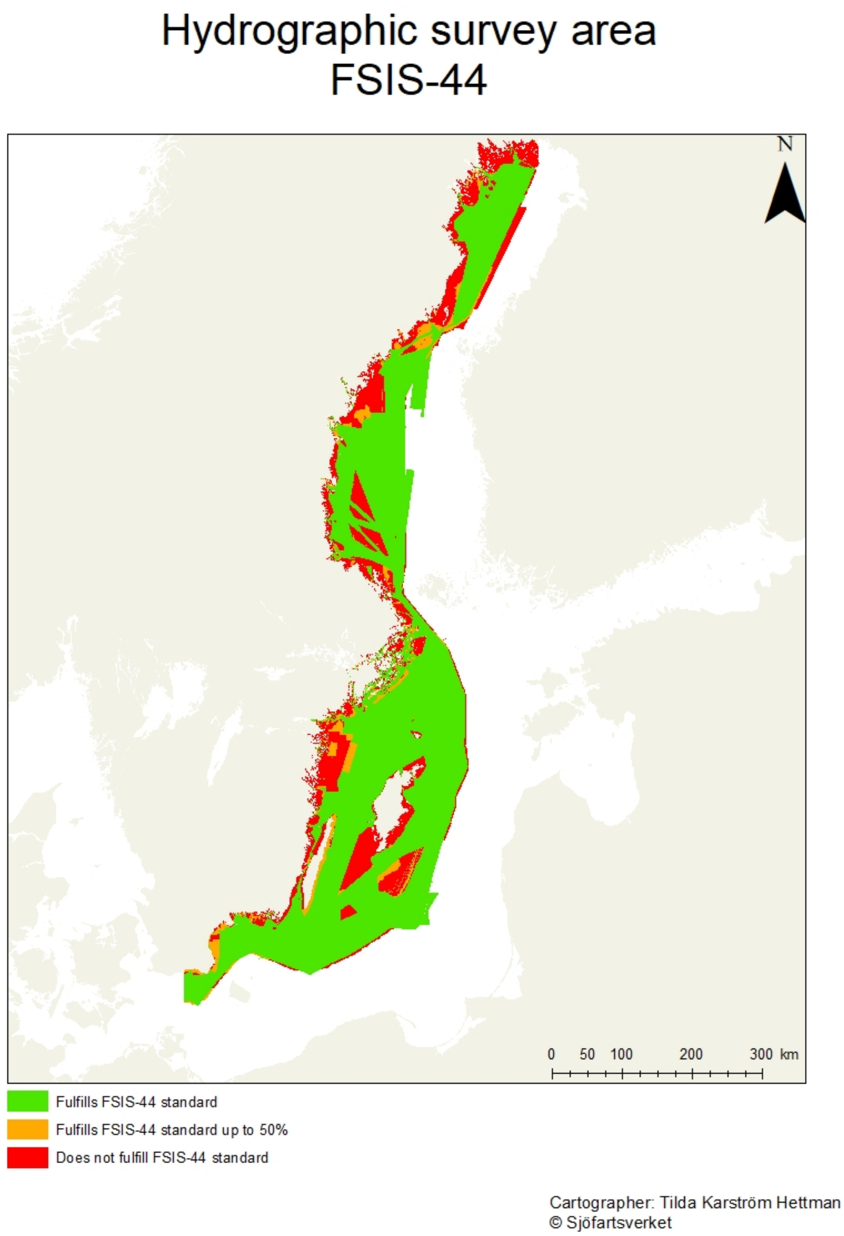
8. Appendix



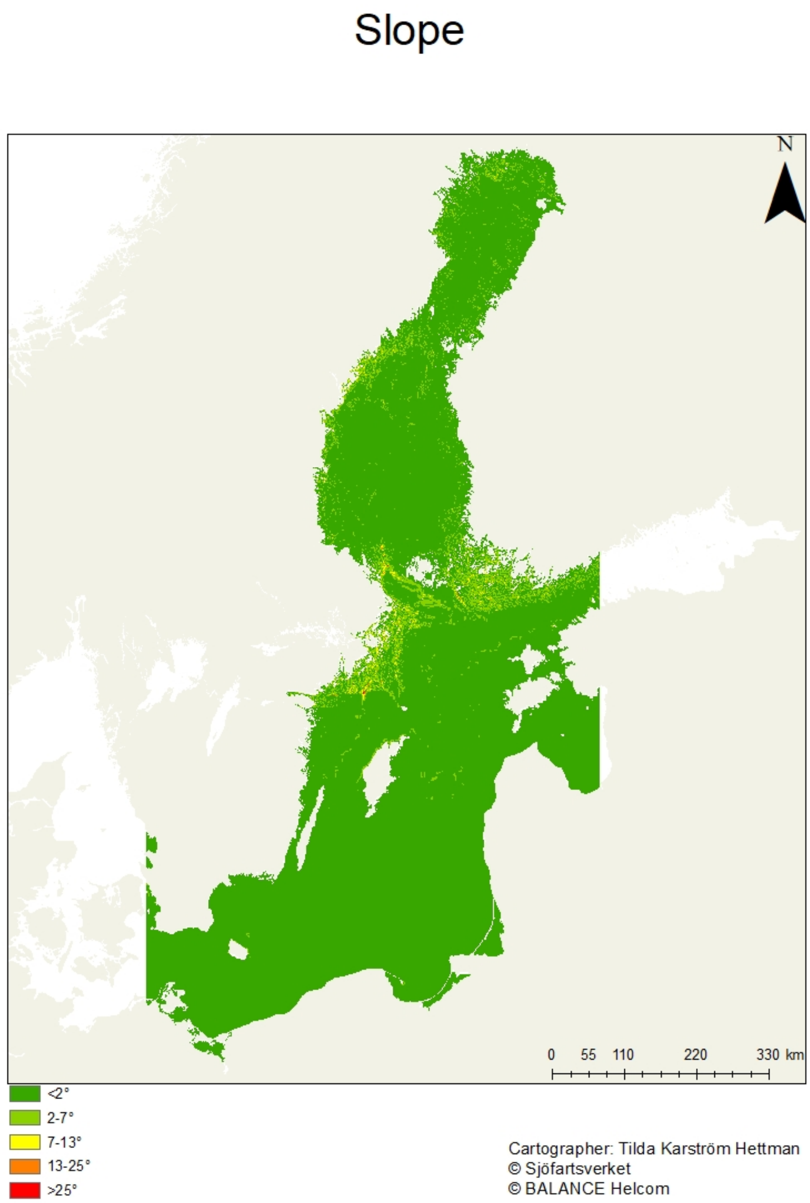
***Appendix 1**: Seabed type of the Baltic Sea and Gulf of Bothnia. The data of seabed type is derived from BALANCE by Helcom.*



Appendix 2*: Age of surveys with approved FSIS-44 classification in the Baltic Sea and the Gulf of Bothnia. The data is derived from the SMA.*

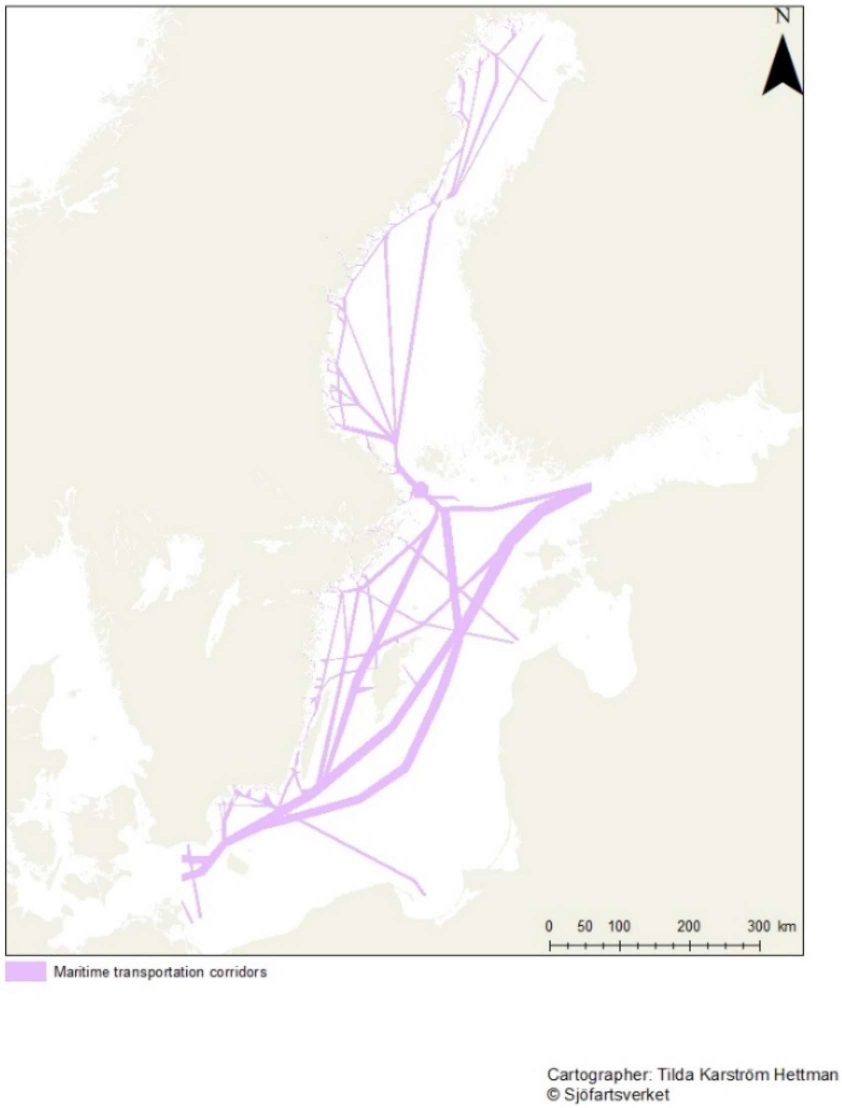


Appendix 3: *FSIS-44 classifications in the Baltic Sea and Gulf of Bothnia. The data is derived from the SMA.*

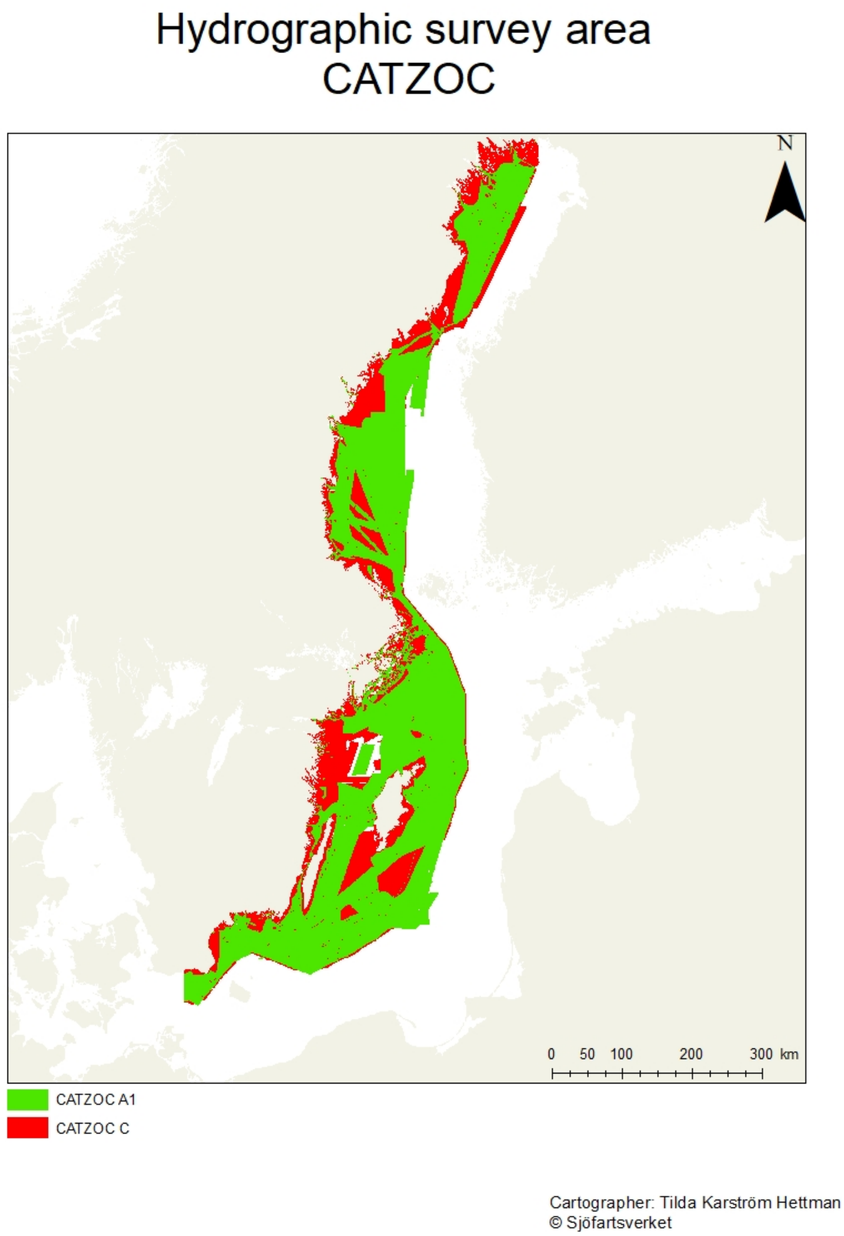


***Appendix 4**: Slope of the seafloor in the Baltic Sea and the Gulf of Bothnia. The slope data is derived from BALANCE by Helcom.*

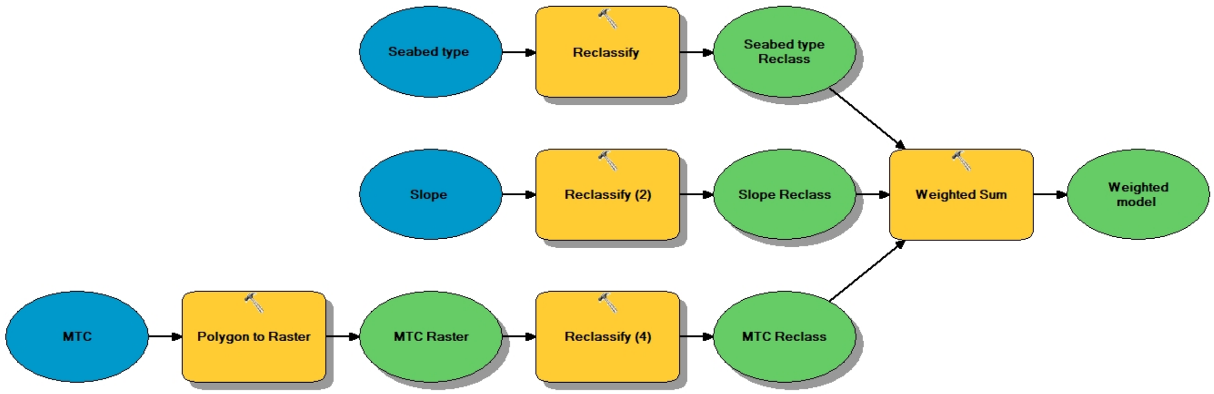
Maritime transportation corridors



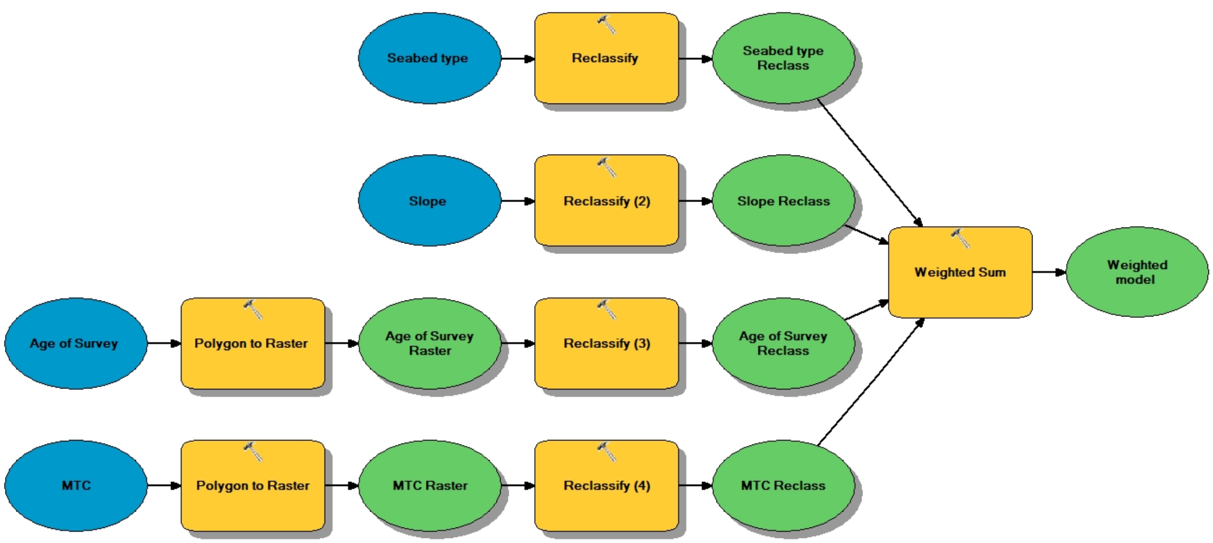
***Appendix 5**: Maritime transportation corridors of the Baltic Sea and the Gulf of Bothnia. The data is derived from the SMA.*



***Appendix 6**: CATZOC classifications of Swedish territorial waters in the Baltic Sea and the Gulf of Bothnia. The data is derived from the SMA.*



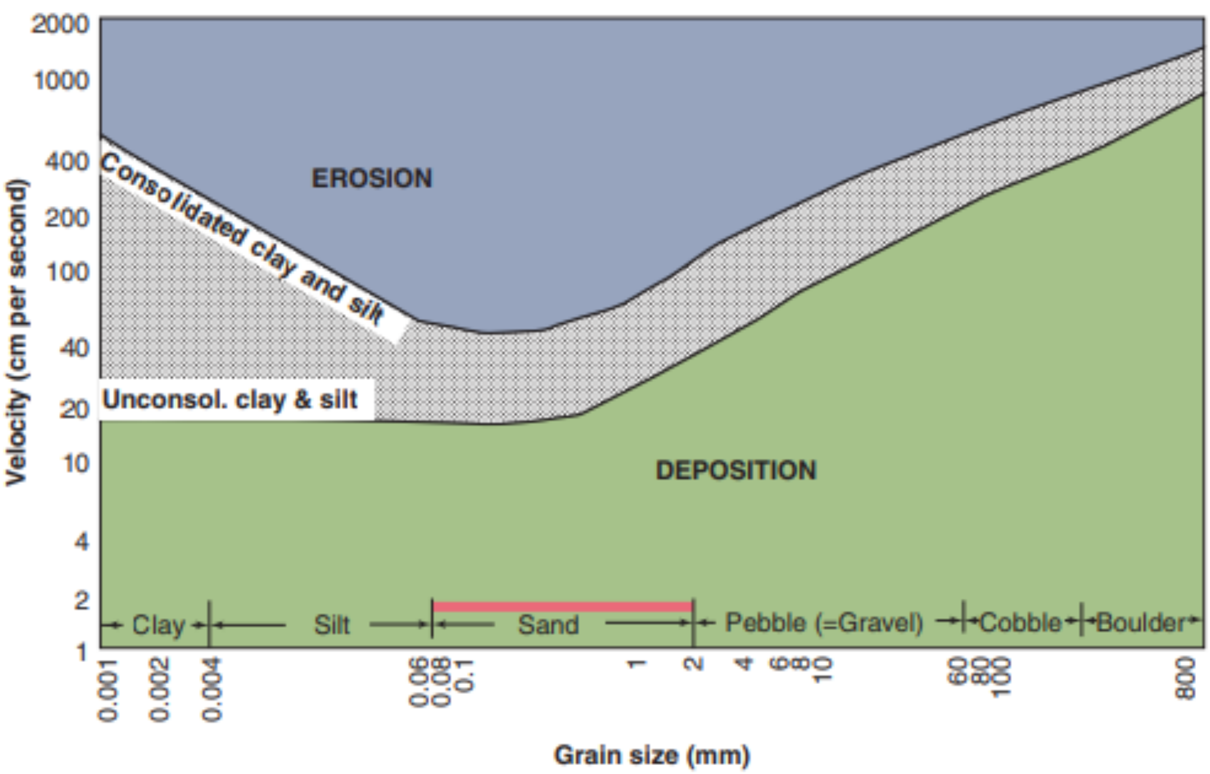
***Appendix** 7: Model created in ArcMap GIS used for large- and small-scale maps used for the Baltic Sea and Gulf of Bothnia.*



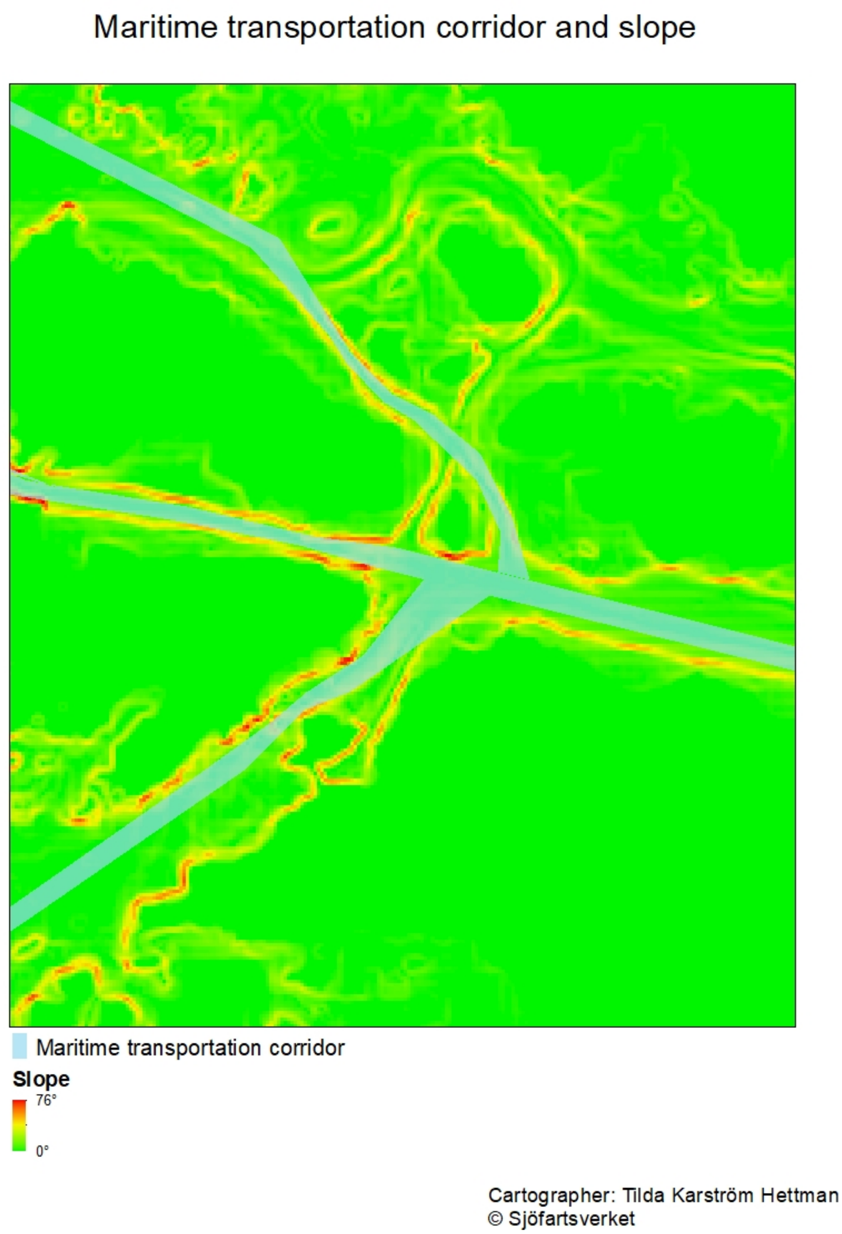
***Appendix 8**: Model created in ArcMap GIS used for weighted priority maps used for the Baltic Sea and Gulf of Bothnia.*

1	2	3		4	5
ZOC[1]	**Position Accurancy**[2]	**Depth Accuracy**[3]		**Seafloor Coverage**	**Typical Survey Characteristics**[5]
A1	± 5 m + 5% depth	= 0.50 + 1%d		Full area search undertaken. Significant seafloor features detected[4] and depths measured.	Controlled, systematic survey[6] high position and depth accuracy achieved using DGPS or a minimum three high quality lines of position (LOP) and a multibeam, channel or mechanical sweep system.
		Depth (m)	Accuracy (m)		
		10 30 100 1000	± 0.6 ± 0.8 ± 1.5 ± 10.5		
A2	± 20 m	= 1.00 + 2%d		Full area search undertaken. Significant seafloor features detected[4] and depths measured.	Controlled, systematic survey[6] achieving position and depth accuracy less than ZOC A1 and using a modern survey echosounder[7] and a sonar or mechanical sweep system
		Depth (m)	Accuracy (m)		
		10 30 100 1000	± 1.2 ± 1.6 ± 3.0 ± 21.0		
B	± 50 m	= 1.00 + 2%d		Full seafloor coverage not achieved; uncharted features, hazardous to surface navigation are not expected but may exist.	Controlled, systematic survey achieving similar depth. But lesser position accuracies than ZOCA2, using a modern survey echosounder[5], but no sonar or mechanical sweep system.
		Depth (m)	Accuracy (m)		
		10 30 100 1000	± 1.2 ± 1.6 ± 3.0 ± 21.0		
C	± 500 m	= 2.00 + 5%d		Full seafloor coverage not achieved, depth anomalies may be expected.	Low accuracy survey or data collected on an opportunity basis such as soundings on passage.
		Depth (m)	Accuracy (m)		
		10 30 100 1000	± 2.5 ± 3.5 ± 7.0 ± 52.0		
D	worse than ZOC C	worse than ZOC C		Full seafloor coverage not achieved, large depth anomalies may be expected.	Poor quality data or data that cannot be quality assessed due to lack of information.
U	Unassessed – The quality of the bathymetric data has yet to be assessed				

Appendix 9: *Category zone of confidence (CATZOC) with all the classifications and explanation for each of them. The table is derived from (John Riding et al., 2016).*



***Appendix 10**: Hjulstroem diagram. Describing the relationship between grain size (mm) and current velocity (cm/s) above the seafloor. Graph is derived from (Seibold & Berger, 2017)*



***Appendix 11**: Slopes in the seabed created by ships traveling on Maritime Transportation Corridors.*