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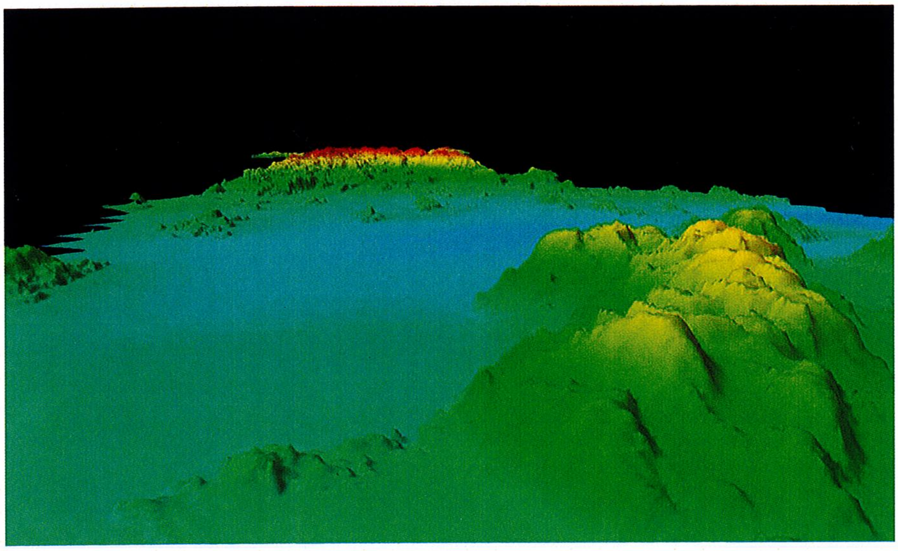
How fast does the bathymetry change on the Swedish west coast?

Modeling how fast the bathymetry change, to know where to prioritize new hydrographic surveys



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Cover image: Picture from a multibeam scanning, provided by the Swedish Maritime Administration

Abstract

The Swedish Maritime Administration is responsible for the passability and availability of vessels on the Swedish coast. They are doing hydrographical surveys to ensure the safety of the maritime transportation corridors on the coast. The surveys are classified after precision in the classification systems FSIS-44 and Category Zones of confidence (CATZOC). To know how long data can be classified with the highest standard, it is essential to know how fast the bathymetry change and how often you need to remeasure the seafloor. Two different GIS models were built, one to see how bathymetry has changed over the years and one that can predict risk for future changes. Different factors that can affect the bathymetry are the type of bottom (sediments or bedrock), currents, slope, maritime transportation corridors, sedimentation rates, sea level rise, and land uplift, to name a few. Previous studies that have been made on how safe nautical charts are have mainly focused on the risks according to how much traffic operates in the area. One study made in the US has focused on more different factors, this included many years of remeasuring the bathymetry in the Chesapeake Bay and the Delmarva Peninsula area. This study has been focused on the Swedish west coast (Skagerrak and Kattegat), and the factors used in this model were slope, maritime transportation corridors, seabed type, and currents. The model was at first tested on smaller areas where the result could be compared to actual changes. The result showed that slope has the most significant effect, seabed type comes second, and maritime transportation corridors have the least impact on the bathymetry (currents could not be included in the small-scale model). These conditions were then used for the large-scale model over the coast. The result gave a map that shows where it might be good to resurvey the bathymetry. Since much of the data is confidential (seabed type and slope), data in the large-scale model is very generalized. This must be considered when studying the results. The outcasts made in this report need to be improved with more precise data and more factors that have not yet been included. To ensure that the model is correct more areas need to be remeasured regularly during a period.

Sammanfattning

Sjöfartsverket är ansvariga för framkomligheten och tillgängligheten för sjötrafik längs den svenska kusten. För att säkerställa detta gör de sjömätningar över de svenska sjöfartslederna för att hålla sina sjökort uppdaterade. Mätningarna är klassificerade efter precision och korrekthet i klassificeringssystemen FSIS-44 och CATZOC (Category zones of confidence). För att veta hur länge datan kan vara klassificerad av högsta standard är det viktig att veta hur batymetrin i havet ändras för att veta när den bör mätas om. Två olika modeller gjordes i det databaserade systemet GIS (Geografiska Informations System), en modell baserad på sjömätningsdata som visar hur batymetrin ändras över tid samt en modell som förutsäger framtida ändringar. Olika faktorer som kan påverka batymetrin är typ av botten (sediment eller berggrund), strömmar, lutning, sjöfartsleder, sedimentationshastighet, landhöjning och havsnivåhöjning för att nämna några. Tidigare studier har främst fokuserat på risker i områden baserat på mängd båttrafik. En studie gjord i USA har fokuserat på fler faktorer genom att ha mätt om batymetrin flera gånger i studieområdet över tid. Studien i denna rapport har fokuserats på den svenska västkusten (Skagerrak och Kattegatt) och faktorer använda i denna modell är lutning, bottenbeskaffenhet, sjöfartsleder och strömmar. Modellen testades först på mindre områden där resultaten för förutsagda ändringar kunde jämföras med den ändrings som skett. Resultatet visade att lutning är det som har störst effekt på botten, bottenbeskaffenhet var näst viktigast och minst påverkan hade sjöfartsleder i de två områden modellen testades på (strömmar finns bara på stor skala och kunde ej testas). Dessa förutsättningar används sedan för att göra en modell över hela västkusten. Resultatet blev en karta som visar vart de kan vara bra att göra nya sjömätningar för att garantera säkerheten i området. Mycket av datan som behövs i ett projekt likt detta är konfidentiell (Bottenbeskaffenhet och lutning), därför har en mer översiktlig data använts i modellen över hela västkusten. Detta måste has i åtanke då resultaten studeras, eftersom de kan påverka hur korrekt resultatet är. Modellen i detta projekt är en början på hur Sjöfartsverket ska kunna klassa ner sin data men mycket behöver förbättras. Det är inte bara mer korrekt data som behövs utan också fler faktorer som inte inkluderats i denna modell. För att kunna säkerställa att modellen fungerar hade det också behövts fler områden, som mätts om under en viss tid för att se att de överensstämmer med resultaten.

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1. Introduction

1.1 Project Background

The Swedish Maritime Administration (SMA) is responsible for the passability and availability of vessels on the Swedish coast and for enabling safe seafaring. The organization constantly develops and entertains the blue infrastructure by conducting hydrographical surveys to update nautical charts and mark new seaways (Sjöfartsverket, 2020). Today, the charts are based on data of different quality, from hydrographic surveys made by using a rope with weight during the 19th century until today's high-resolution multi beams. Due to the high quality of bathymetric data collected today, it is unnecessary to remeasure the bathymetry due to quality. Since the seafloor is a constantly moving surface due to geological and anthropogenic processes, one must regularly redo the hydrographic surveys to keep the nautical charts accurate and of the highest standard. Hydrographical surveys are expensive and take a lot of time. To avoid redoing the surveys too often, SMA has requested a model that predicts how fast the bathymetry changes along the Swedish coast, to know how long a hydrographic survey can be classified with the highest standard and when it must be downgraded.

1.2 Aim of the project

This project aims to analyze the bathymetric changes on the Swedish west coast (Kattegat and Skagerrak) and to build a model that can predict future changes. The project is made to help the Swedish maritime administration in their work to always provide nautical charts of the highest quality for their customers. The primary focus of the report aims to:

1. Compare different data from different years to detect areas that have changed
2. Build a model that can predict future changes in the bathymetry
3. Help the Swedish Maritime Administration in their work to do a classification system on how long the data can be assumed to be accurate.

1.3 List of Acronyms

AIS	Automatic Identification System Data
BALANCE	(Baltic Sea Management – Nature Conservation and Sustainable Development of the Ecosystem through Spatial Planning)
CATZOC	Category Zones of Confidence
CHS	Canadian Hydrographic Service
CPPT	CHS Priority Planning Tool
DIS	Depth Information System
GIS	Geographic Information System
HELCOM	Helsinki Commission
HHM	Hydrographic Health Model
IHO	International Hydrographic Organization
IPCC	Intergovernmental Panel on Climate Change
MCDA	Multi Criteria Decision Analysis
NOAA	National Oceanographic and Atmospheric Administration
NERI	National environmental research institute
SMA	Swedish Maritime Agency
SMHI	Swedish Metrological and Hydrological Institute

Table 1: Summary of acronyms used in this report

2. Background

The shipping industry has changed dramatically in recent decades, vessels are getting faster and larger and are approaching fewer hub ports. The growth in the shipping industry is projected to continue. To keep the industry safe, up-to-date nautical chart information that is reliable is vital (Riding et al., 2016).

2.1 Previous studies

There is no universal standard methodology for how long data from a hydrographic survey can be seen as reliable. A few other studies have been made on the subject, for example, one in the Chesapeake Bay and the Delmarva Peninsula. In this study, different factors were compared through different methodologies of calculating changes in historical hydrographic data and modeling how the data has changed over time. Understanding how a particular area changes through time makes it easier to allocate resources to the right places. A better understanding of how climate change can affect already charted waters allows for updates to disaster response requirements. The National Oceanographic and Atmospheric Administration (NOAA) has developed a model to identify areas that need to be prioritized for new hydrographic measurements called the Hydrographic Health Model (HHM). This model approximates the current state of hydrographic data and its reliability, depending primarily on the quality of the surveys, and takes heuristically account for environmental changes like marine debris, tides, and storms. The Chesapeake Bay and the Delmarva Peninsula area were frequently hydrographically surveyed to monitor sediment transport in heavily trafficked regions. From these surveys, they could see how the bathymetry has changed and the sedimentation rates in meter/year for example. This indicated that the seafloor has probably changed during the last 50 years, but it was not possible to consider temporal variability (Bongiovanni et al., 2021).
Another study has been made over the Canadian coast by the Canadian Hydrographic Service (CHS). Their priority was to find a method that shows areas that need to be prioritized for new hydrographic surveys and charting. Canadian Hydrographic Service Priority Planning Tool (CPPT) was created and based on the risk of grounding, risk of collision, drift, and critical navigational information such as depth, seafloor complexity, and survey requirements. The methodology was made in two steps, including Geographic Information System (GIS) and a

dynamic matrix. First, a GIS model was created that gave an output of areas that need to be prioritized for hydrographic surveys. Second, a dynamic matrix was designed to generate a production plan for CHS charts in the matrix phase. These two components were later compared to each other to see that the areas from the matrix contained areas generated from the GIS model (Chénier et al., 2018). A similar risk assessment has also been made over New Zeeland's coast to locate sites that could need charting improvements and therefore needs hydrographic surveying. The risk assessment is based on data evidence, and GIS spatial analysis techniques were used. The primary data used in this assessment comes from AIS (Automatic Identification System Data), which is data over the shipping traffic in New Zeeland water. Recordings over twelve months have been used, and the data was broken down into different ship types. Other factors that have been used in the model are chart scale, chart extents, and chart quality (survey age, survey scale, and ZOC (position accuracy, depth accuracy, and seafloor coverage)). These different factors (layers) have been weighted in Weighted Overlay Analysis in GIS, and the risk criteria have been combined with marine traffic levels. This has given areas that could benefit from a charting update, but it is also clear that it is larger areas, and it's practically impossible to update them all simultaneously (Riding et al., 2016).

2.2 History of Swedish nautical charts

The mapping of the Swedish seafloor can be traced back to 1643, when the senior master of admiralty, Johan Månsson, was assigned a project to improve the conditions for navigation in Swedish water. Månsson was appointed as the first hydrographer in Sweden, and the first nautical manual was published in 1644. The project "the Improvement of nautical charts" was created in 1756, and the work with hydrographic surveys was intensified. It was during this time that they started to use the geodetic basis. The geodetic determinations used were not precise and were behind many errors in the charts. This could, for example, be seen on the Swedish west coast, where the longitude was dislocated, which led to an earlier arrival to the coast than predicted by the seafarer in lousy weather, this has probably been the reason for many shipwrecks (Ehrenswärd & Frithz, 1993). Due to a fire in the hydrographic chart archive in 1790, there is not much information to find from this time, but the surveys made before that year were probably small and local. The mapping started to improve a lot after the French decision to measure the dimension of the earth ellipsoid during the 1800-century, and in 1841 the longitude began to be given in the Greenwich meridian. The geodetical network has improved a lot since, both on land and along the coast, and since the end of the 1970s, satellites have been used to determine the geodetic locations. The methods for the hydrographic measurements have varied through time. Before the 1700-century, hand leads and sounding roads were used, and the positions were found with the help of significant places on land, compass, and calculated distances. Since then, the first echo sounders were introduced on HMS Falken in 1930. In 1993 laser bathymetry and airborne equipment is introduced for hydrographic surveying (Ehrenswärd & Frithz, 1993).

2.3 The Swedish Maritime Administration today

In its present form, the Swedish Maritime Administration was established on the 1st of July 1969. The agency is governmental, responsible for making safe seafaring on Swedish waters possible, prioritizing merchant shipping and leisure boat traffic, fishing, and military interests. The primary tasks are hydrography, nautical information, maritime and traffic information, fairway services, ice breaking, seamen's service, and pilotage (Sjöfartsverket, 2021). Most SMAs' hydrographical surveys are made from five vessels Peter Gedda, the smallest one, Anders Bure, Gustaf Af Klint, Jacob Hägg, and the largest one, Baltica (Sjöfartsverket, 2021). Not only the measurements are made on the vessels but also survey planning, measurements for position and water level, and geodetical measurements, to name a few. Since the launch of the multibeam echosounder in the middle of the 1990s, measures with full ocean floor coverage have been possible. In 2013 a decision under the HELCOM (Helsinki Commission) collaboration was taken under the name of the Copenhagen declaration, including a plan to conduct hydrographical surveys over the most critical maritime transportation corridors in the Baltic sea. To accomplish this, the goal for SMA was to do hydrographical surveys that meet international standards over 72% (118 000km$^{2)}$ of Sweden's coast until 2020 (Kartografiska sällskapet, 2018). Most surveys on Sweden's coast are made on deep water, and only 4% of shallow water is measured with modern methods (Sjöfartsverket, 2022). Multibeam sonar and bar sweeping are the two most common methods for hydrographic surveying in Sweden today. Multibeam sonar is a type of an echosounder placed under the ship that sends out multiple, simultaneous sound waves in a fan-shaped pattern. This method makes it possible to measure the space directly underneath the ship and out on the side. The instrument collects data over seafloor depth and backscatter data, making it possible to get information on what material the seafloor is made of (NOAA, 2022). Bar sweeping is used on depths too shallow to use echo sounding. This method is based on a bar underneath the ship that hits the ground to determine the shallowest depth. This method can also secure the shallowest depth in transport corridors and harbors (Sjöfartsverket, 2011).

2.4 Depth Information System

The need for knowledge about our coast has increased, and a project to digitize all high-quality maps were started in 2007 by SMA. This data was collected in a database named DIS – Depth Information System, and today all new data from hydrographic surveys are collected in this database. Data collected in the database varies in quality since much of the data is very old. Old data appears especially in shallower areas in 0–10 meter depth intervals. These data are often collected with handload, and there can be considerable distances between the measurement spots (Kartografiska sällskapet, 2018). In 2019 DIS consisted of over 178 billion depth points (Sjöfartsverket, 2019).

2.5 HELCOM

The Baltic Marine Environment Protection Commission, or Helsinki Commission (HELCOM), is a governmental organization among the countries around the Baltic Sea. The organization was established to protect the Baltic Sea from pollution in 1974. The Baltic Sea and its entrance are of interest, and lots of data have been collected to ensure the sea's ecological status (HELCOM, 2022). Some of the data in the HELCOM project origins from BALANCE (Baltic Sea Management – Nature Conservation and Sustainable Development of the Ecosystem through Spatial Planning), that was a project financed by the European Union to collect relevant data from Skagerrak, Kattegat, and the Baltic Sea to help with planning and implementing an efficient way to protect the unique environment (Balance, 2005).

2.6 FSIS-44

The Swedish Maritime Administrations classification system for hydrographic surveys is FSIS-44, a joint implementation of Sweden and Finland's IHO (International Hydrographic Organization) standards. An area can only reach the FSIS-44 standard if the measurements cover

100% of the seafloor. In this context, a 100% cover means dense measurements made systematic so that all depths are well presented, and all features of impact on the seafloor should be detected. Extra measures need to be examined in greater detail for features like a wreck and other anomalous things to determine their positions and most minor depth accurately. The preciseness of the data depends on the maximal horizontal uncertainty, the minimum feature detection capability, and the accuracy of the position of the depths and features. These features are weighted together with a statistical model and must be in a 95% confidence interval to reach the FSIS-44 standard (Finish Transport Agency, 2010). The surveys made in Kattegat and Skagerrak are of different quality, with a clear pattern those areas closest to the coast (inside the archipelago) are older and don't fulfill the FSIS-44 standard except for a few areas. In contrast, areas outside the archipelago tend to fulfill the criteria for FSIS-44 (Fig. 1). The oldest hydrographic survey on the west coast that meets the FSIS-44 standard was made in 1983.

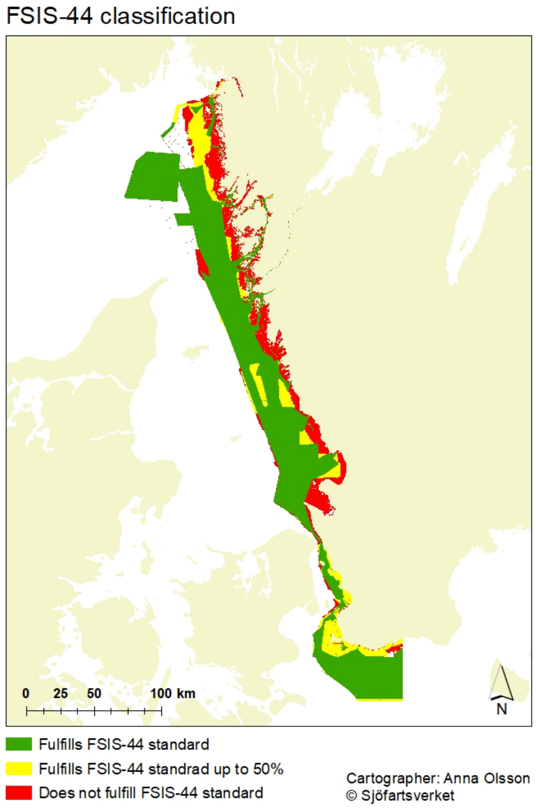

Figure 1. *FSIS-44 Classification on the Swedish west coast in three categories. Areas that fulfill the standard, areas that fulfill 50%, and areas that don't fulfill the standard.*

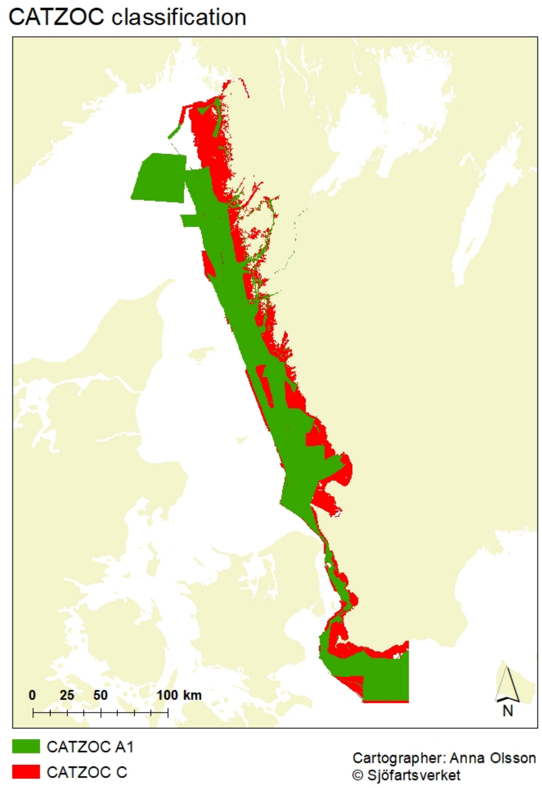

Figure 2. *Category Zones of confidence (CATZOC) classification on the Swedish west coast with the two categories A1 and C.*

2.7 Category Zones of Confidence

Category Zones of confidence (CATZOC) is a classification system that categorizes the accuracy of different measurements of the ocean floor. The system consists of six categories from A1, the most accurate one that includes complete coverage of the bottom with depth and significant seafloor features, to U, which are unassessed parts of the ocean floor. The position and depth accuracy limitations help the mariners with safe seafaring by managing the different risk levels (Appendix 1) (UK Hydrographic Office, 2017). The Swedish maritime administration is currently only using two categories, A1 with an accuracy of ± 5m + 5% depth and C with an accuracy of ± 500m. Areas that fulfill the FSIS-44 standard are interchangeable with CATZOC A1 areas, areas that don't fulfill FSIS-44 will be classified as C. The significant parts of the seafloor that are measured until today are classified as CATZOC A1, mainly where larger ship routes are located. Most of the CATZOC C areas are located close to the coast (Fig. 2).

2.8 Types of seabeds

The ocean floor consists of different materials that are more or less likely to change due to different impacts. The main sediment groups are clay, silt, sand, gravels, and boulders, the last two are uncommon except around reefs and on high latitudes. Sand covers the largest areas of the ocean floor and consists of solid particles from 0.0064 to 2 mm in diameter. Silt consists of particles 0.0063 and 0.004 mm, and clay consists of particles smaller than 0.004 mm. These size categories are only based on grain size and not material. What material the particle is made of does not matter for the classification, it can be shell fragments, small pieces of rocks, or mineral grains, for example. (Seibold & Berger, 2017).

The sediments are mainly categorized into two larger groups depending on what they consist of, lithogenous and biogenous sediment. Lithogenous sediment consists of dead material, often eroded particles from preexisting rocks and volcanic materials. Due to the thick layers of fine-grained lithogenous sediments on the continental margins, the sediment takes up about two-thirds of the total volume of marine sediments. Biogenous sediment consists of pre-living materials, the most common material is skeletal parts consisting of calcium carbonate from foraminifers, calcareous algae, and corals, for example. The materials can be dispersed with waves and currents or settled in situ. Biogenous sediments cover about 50% of the sea shelf and around 55% of the deep ocean floor (Seibold & Berger, 2017).

2.9 Sediment Transportation

From source to the place of deposition, there is usually graduation of the grain size. A larger particle will (most often) settle closer to the source than a small particle. Larger sediment sizes like gravel (2-256 mm) and boulders (> 256 mm) do usually not travel that far (except when carried by ice) (Seibold & Berger, 2017). On the ocean floor, sediment deposition and erosion are driven mainly by waves (in general, not deeper depths than 10-20 m) and currents. The efficiency of these two mechanisms depends on their strength and sediment grain size. It is difficult to predict what will happen in a given situation since the porosity, grain size distribution, and cohesiveness is rarely the same in two situations and earlier studies are hard to use as a comparison. A general relation between grain size and velocity of the currents is shown in the Hjulströms diagram. A current of around 0,4 m/s can carry a small sand grain of 1 mm in diameter, but it takes a current of several meters per second to move a boulder. This simple relationship between grain size and velocity is only working down to grain size of 0,1-0,2 mm, for grain size smaller than that, it might require a higher velocity to initiate erosion (Appendix 2). This behavior of clay and silt origins in that these very fine particles tend to create a smooth surface when they settle, reducing turbulence that can move particles. Large smooth areas also tend to have a higher cohesion between particles and bacterial mats on them, reducing the impact of the water (Seibold & Berger, 2017).

The slope of the bed will affect the net sediment transport (Fredsøe & Deigaard, 1992). Sediment on slopes tends to move, and erosion can, for example, be an effect of sediment instability or the strong currents that flows horizontally along the slope (Seibold & Berger, 2017). Marine traffic has a known impact on the seafloor. It disturbs the sedimentation process, resuspends already settled sediment particles, and is a cause of erosion. Large ships are the human-based factor that leaves most traces in the ocean. The effect is mainly caused by ship-generated waves that can cause erosion of channel slope and shoal, the jet flow generated by ship propellers, and frequent traffic that can cause an increase of different sediment layers. The amount of suspended sediment can increase up to 30 times more than the background concentration in heavily trafficked areas, significantly impacting marine geomorphology (Xue et al., 2021). Since large vessels mainly use Maritime transportation corridors for transportation, it generates primary (drawdown) and secondary (transverse and divergent) waves that not only affect the bottom underneath but also cause an impact on adjacent shores (Almström et al., 2018).

2.10 Sea level rise and land uplift

Hundreds of tons of ice melt in the earth's cryosphere every year, leading to a rise in the water volume in the sea. From 1994 to 2017, the earth lost an ice volume of 28 trillion tones that has caused an approximately global sea level rise of 35 mm (2,7 mm/year) (Slater et al., 2021). The ocean loses water volume by evaporation. Around 430 000 cubic kilometers of water is evaporated from the ocean every year. Of that volume, about 90% is precipitated back into the sea again, and 10% is precipitated on land (Gimeno et al., 2013). The postglacial land uplift on the Swedish west coast varies from under 1 mm/year in the south to 4 mm/year in the north (Timmen et al., 2011). The total sea level rise in Sweden since 1886 is around 25 cm or 2 mm/year. Measurements made by SMHI and IPCC shows that the sea level rise has accelerated in recent year. In Sweden, there is both land uplift and sea level rise, leading to no change in sea level in most of the country. In the southern part of Sweden, like Skåne, where the land uplift is small, the sea level has risen (SMHI, 2022).

2.11 Study Area

Skagerrak is a part of the North Sea located in the northeastern region, it has a sill depth of 270 m, a mean depth of 210 m, and a surface area of 32 300 km^2 (Binczewska et al., 2018; Fonselius, 1990). The area has complex hydrography with anticlockwise circulation. Currents above 30 m depth in the area are mainly dominated by outflowing low saline water from the Baltic Sea, The Baltic current, that follows the Swedish west coast, and the inflowing high saline water from the southern North Sea and the North Atlantic (Binczewska et al. 2018; SMHI 2014). The Jutland coastal current is northward moving and amplifies when approaching the Swedish coast via Skagen. Since the Baltic current is less saline than the Jutland current, the Jutland current flows underneath (SMHI, 2014). Currents under 30 m depth consist of Atlantic deep water, the water enters the central part of Skagerrak via the Norwegian Trench (Binczewska et al. 2018). The tidal currents in Sweden are also strongest here (SMHI, 2014). A few studies have been made on sedimentation accumulation in the Skagerrak basin. This shows that at least 28.4 million tons of sediment settle every year in Skagerrak. The eastern parts of Skagerrak have the highest sedimentation rates with 0.4 cm/yr. A research by Van Weering (1987) showed that the sedimentation rate in the cores closest to the Swedish west coast was between 0.30 – 0.34 cm/yr (Van Weering et al., 1987). Skagerrak is connected to the Baltic Sea through the Kattegat (Binczewska et al., 2018). Kattegat has an area of around 22 000 km^2 with a mean depth of 23 m. No sill separates Skagerrak from Kattegat, but the border is decided to be a line between Marstrand and Skagen. High saline Atlantic water enters Kattegat's bottom layer from the north side and flows towards the Baltic Sea. In the surface layer, the Baltic current flows from the Baltic Sea towards Skagerrak, where it turns to the west as the Norwegian Coastal Current (Leppäranta & Myrberg, 2009).

3. Method

The method in this project has been made in collaboration together with Tilda Karström Hettman. Data has been shared with each other and the model has been discussed together.

3.1 Data

Data in this project originate from three sources, the HELCOM project, the Geological Survey of Sweden (SGU), and data collected by the Swedish Maritime Administration.

3.1.1 Seabed Sediments

The seabed cover origins from the BALANCE project and it is generalized due to confidential data. The data set is divided into five categories, Bedrock, Hard bottom complex (that includes hard objects like coarse sand and boulders but also patches of clay), Sand (Fine to coarse sand with patches of gravel), Hard clay (Often covered by a thin layer of sand or gravel), and mud (including gyttja-clay to gyttja-silt) (HELCOM, 2021). Another data source for the seabed comes from the Geological Survey of Sweden which has mapped the seabed cover. The data set named Marine geology 1:100 000 is categorized into six different groups, soft clay; fine sand; sand, gravel, and stone; stone and boulders; bedrock and artificial substrate. This data is accurate, but the area is confidential (Geological Survey of Sweden, 2017).

3.1.2 Seabed Slope

The BALANCE project has provided the HELCOM organization with generalized data over the seabed slopes, with a resolution of 500m (HELCOM, 2021). A slope map based on data from the Swedish Maritime agency has also been produced in GIS over smaller areas on the coast.

3.1.3 Bottom currents

The data over bottom currents are based on the average velocity (m/s) of currents from January 2003 and one year ahead. Since currents can be generated from many sources like wind stress, tidal motion, and density difference, these elements must be combined to calculate the predicted currents. The currents will also change in speed due to friction, and it will be turbulent closer to the bottom. This turbulent layer varies in thickness from a few meters to several tens of meters.

The speed will be lowest closer to the bottom and larger further up in the water layer. The data sources are BALANCE and NERI (National environmental research institute)/Denmark (HELCOM, 2021) (Bendtsen et al., 2007).

3.2 Geographic Information System

Data in this project has mainly been processed in different tools in the ArcGIS based program ArcMap.

3.2.1 Multi Criteria Decision Analysis

Multi Criteria Decision Analysis (MCDA) is a concept that supports decision-making. The method explores the pros and cons of different alternatives. This procedure involves geographical data, the decision-makers preferences, and merging the data and priorities according to a specified decision (combination) rule. In GIS, at the most fundamental level, GIS-based MCDA transforms and combines geographic data and then takes the “decision-makers” preferences into account to produce a decision map (Malczewski & Rinner, 2015).

3.2.2 Weighted sum

The weighted sum is an MCDA tool in GIS that makes it possible to weigh and combine multiple factors and create an integrated analysis. Each factor can be given different weights relative to its importance. The tool works by multiplying the designated values for the different raster layers. It sums the values for all the input rasters and creates an output raster. The weighted sum tool keeps the rescaled values without reclassifying them back to an evaluation scale as the tool Weighted Overlay does. This makes it possible to maintain the resolution of the analysis. Maintaining the resolution is good in cases where the user wants to identify a specified number of sites or just the top favorable locations (Arcgis PRO, 2022).

3.3 Data processing

Shapefiles with points over depths from the multibeam and bar sweeping measurements were taken from the DIS database. These point files were converted to raster layers. The difference between two rasters from different years is compared to detect actual changes between different years in the bathymetry. The oldest data was extracted from the newer data, which gives the result that negative values indicate that the seabed has become shallower. Positive values indicate that it has become deeper. This process was made in 11 different areas.

3.3.1 Prediction of changes in smaller areas

Different factors that can impact the bathymetry were compared to predict where changes are most likely to appear. For this, a model has been created, and the type of sea bottom, maritime transportation corridors, and slope have been set to input features. All the layers have been transformed into rasters. They have been reclassified to different values to test how much they eventually can affect the bottom (ex, sand is more easily eroded than clay). The seabed is divided into four categories: bedrock, stones and boulders, clay, and sand, gravel and stones. The slope was organized into five different categories, < 2°, 2 -7°, 7 – 13°, 13 - 25°, and > 25°. Then, the factors were weighed against each other in the tool weighted sum. A layer has been created that tells us which areas are most likely to change. Several reclassifications and weightings have been compared to the actual changes to see which weights are closest to the actual changes (Appendix 3, Table 2).

	Slope	Maritime transportation corridors	Seabed
Test 1	1	1	1
Test 2	1	1	2
Test 3	2	1	1
Test 4	2	1	1,5

Table 2. *The different weightings that have been used in the weighted sum tool for the small-scale models. This has been combined with different reclassifications*

3.3.2 Prediction of changes in Kattegat and Skagerrak

A model was created with data covering Skagerrak and Kattegat, presented in figure 3. The input data that has been reclassified to predict changes, comes from four categories: Maritime transportation corridors, seabed, currents, and slope. The slope is classified into five categories < 2° = 1, 2 -7° = 2, 7 – 13° = 3, 13 - 25° = 4, and > 25° = 5. Maritime transportation corridors are reclassified so that the transport corridors weigh 2. Currents are classified in three groups, under 0.02 m/s=1, 0.02-0.05 m/s = 2 and values over 0.05m/s = 3. The seabed is divided into bedrock=1, hard bottom complex = 2, hard clay and mud = 5, and sand = 6. Previously mentioned factors have been weighed against each other in the Weighted sum tool that gives a clue where it could be good to prioritize a hydrographic survey.

A priority map for surveying in Skagerrak and Kattegat has also been made, based on Seabed, slope, maritime transportation corridors, currents, and age of surveys that reaches FSIS-44 (CATZOC A1). The FSIS-44 areas have been reclassified after age, 1979 - 2001 = 4, 2002 – 2011 = 3, 2012 – 2017 = 2, 2018 – 2021 = 1. The rest of the factors were reclassified in the same way as for the prediction model over Kattegat and Skagerrak.

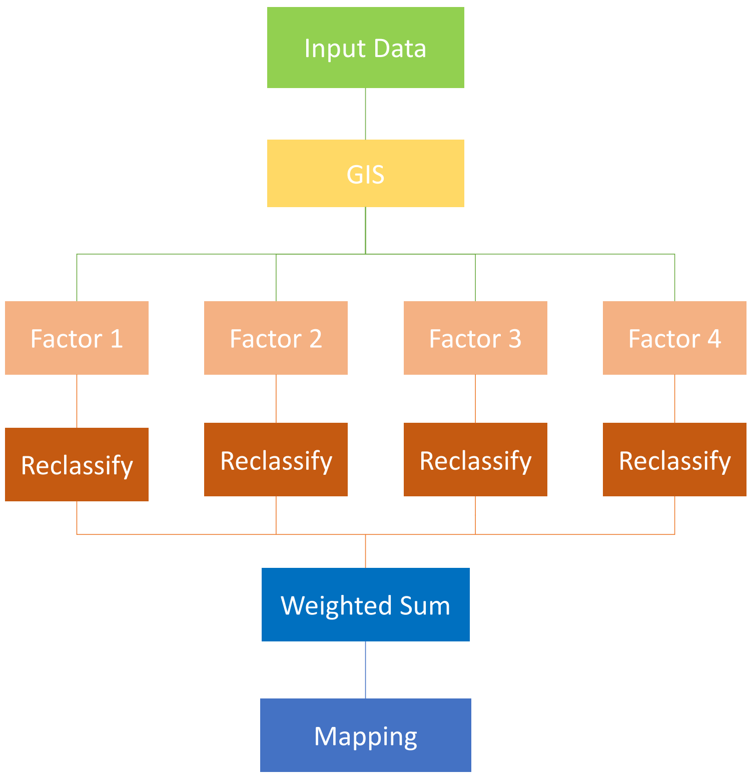

Figure 3. *The workflow of producing a map that shows prediction over changes in the bathymetry.*

4. Results

4.1 Seabed

According to the generalized map from BALANCE (HELCOM), there are larger bedrock areas close to the coast in the northern parts of the Skagerrak. There are also many areas with hard clay along the west coast. In between bedrock and hard clay areas, there is mud and sand and small areas of the hard bottom complex. Further out from the coast in the north, the seabed is mainly covered in mud, and in the southern parts, there are larger patches of mud or sand with hard bottom complex (Fig. 4A). Data from SGU shows that in area A, most of the bottom is covered in clay with some smaller patches of another substrate (Fig. 5). Area B consists mainly of sand, gravel, and stones, with two smaller areas consisting of clay (Fig. 7).

4.2 Seabed slope

The seabed slope over Kattegat and Skagerrak from BALANCE is a generalized map since the detailed data are confidential information. The slope is steeper closer to the coast, where the coast seems to change a lot. The slopes are greater north, while the sea bottom is flatter further south on the coast (Fig. 4B). Area A is flat in the middle, it has some patches of more sloping regions primarily to the left corner and three patches on the left side (Fig. 5). For area B, the sea bottom varies a lot, the side seems to have a steep slope while it tends to be flatter in the middle (Fig. 7).

4.3 Modeled bottom current

The modeled bottom current comes from BALANCE (HELCOM). There is a clear pattern of stronger currents closer to the coast. Between Sweden and Skagen (Denmark), there is also a clear pattern of stronger currents. The currents seem to be more substantial further north and weaker in the south (Fig 4D).

4.4 Maritime transportation corridors

The maritime transportation corridors are areas used by marine traffic where a lot of heavy ship traffic goes. They are usually located outside the archipelago with smaller passages that take the ships into the archipelago where the harbors are located. Two larger ones follow the Swedish west coast (Fig. 4C).

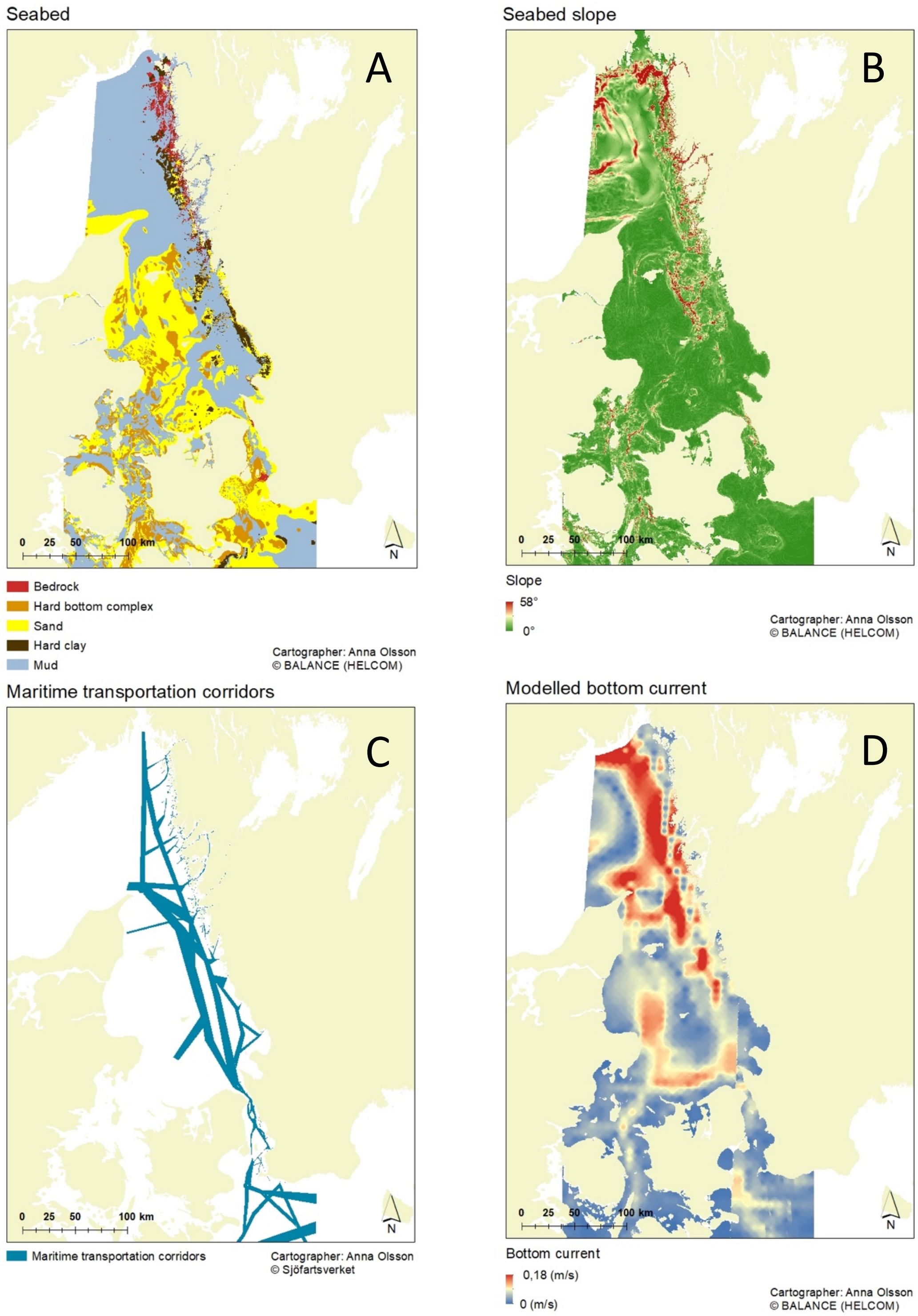

Figure 4. *Factors that can affect the bathymetry in Skagerrak and Kattegat; (A) An overview map over seabed from BALANCE (HELCOM). (B) An overview map over slope from BALANCE (HELCOM). (C) Maritime transportation corridors from SMA, (D) Modelled bottom current from BALANCE (HELCOM).*

4.5 Model result

4.5.1 Prediction of changes in smaller areas

Two of the eleven analyzed areas were chosen to build the model around. The decision was made on how realistic the values for actual change were (Appendix 5), the size of the area, and if it was possible to use marine geology data from SGU. Several different weightings and reclassifications have been made and compared to the actual changes in the sea bottom (Table 2, Appendix 3). The different factors that can impact changes in the bathymetry are reclassified in this order: Seabed: Bedrock = 1, stones and boulders = 2, clay =5, and sand, gravel and stones = 6. Maritime transportation corridors = 2, and slope: < 2°=1, 2 - 7°=2, 7 - 13°=3, 13 - 25°=4 and > 25°=5.

4.5.2 Area A

Since the model includes actual slope and seabed data, the area's location is confidential, but it is located somewhere along the Swedish coast. Figure 5 shows the three different factors that can affect the changes in the bathymetry. Figure 6 shows how the bottom has changed based on multibeam data from 2003 to 2016 compared to the weighted model of predicted changes.
The factors are weighted like this; seabed as one and a half, Maritime transportation corridors as one, and slope as two. This weighing was the one that tended to match the most with the actual changes based on visual comparison. The red and blue areas match the red and orange regions better. On the left side, there has become deeper on the lower part and shallower on the upper part. On the more minor part on the right side of the site, the lower part has become deeper and there is a larger patch that has become shallower in the upper part, these changes can be traced on the map for predicted changes. The area that tends to match less good is the areas outside of the maritime transportation corridors. On the map for actual changes, there are lots of light red stripes on the side, but on the predicted map, this area is only light green.

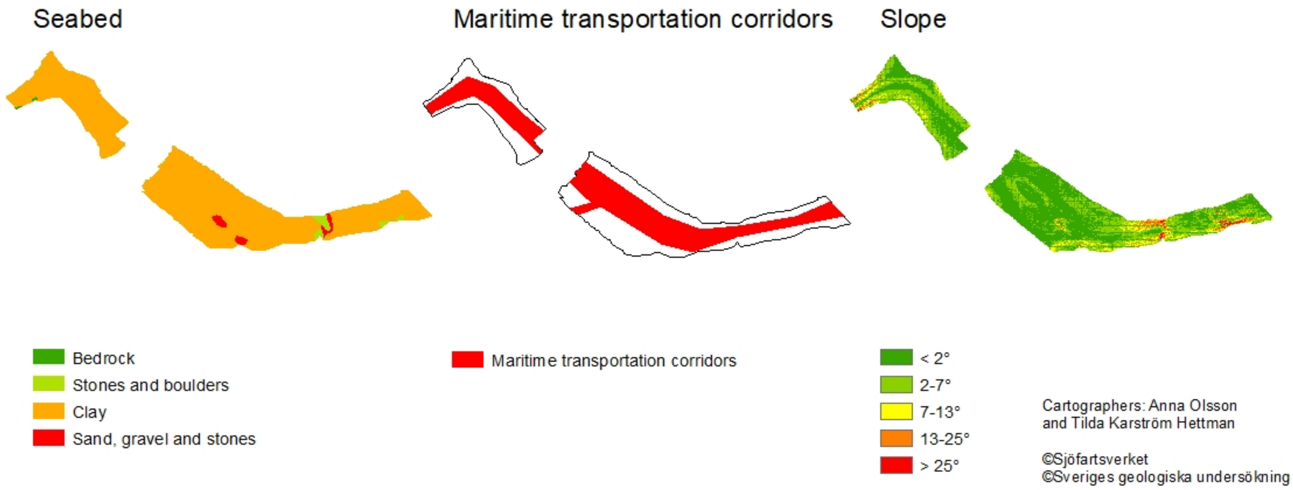

Figure 5. *The three factors that are weighted in the model to predict future changes in the bathymetry in area A.*

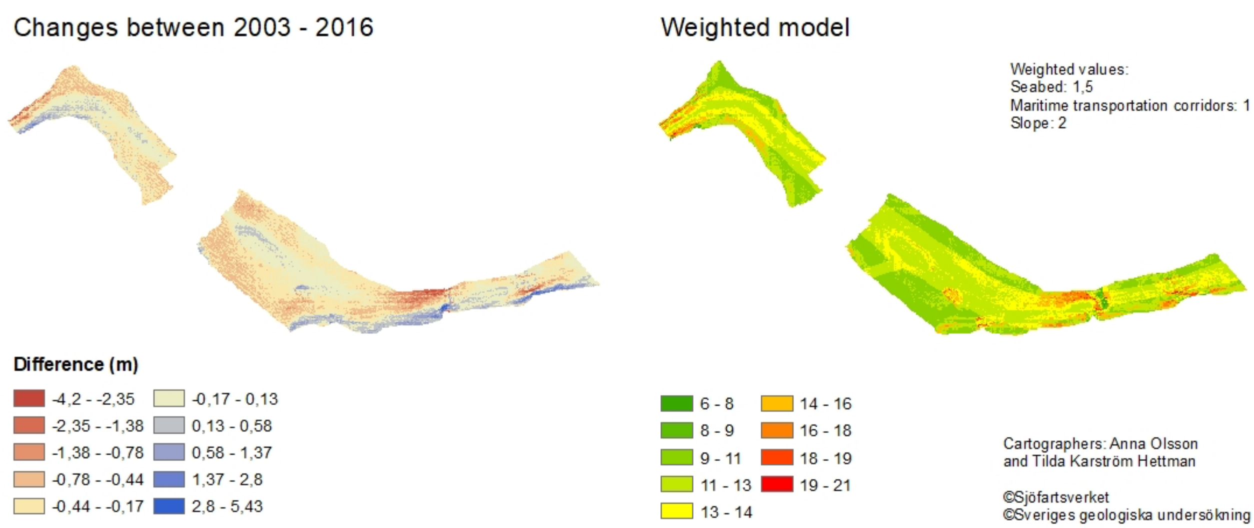

Figure 6. *Shows the actual changes in area A from 2003 to 2016, and the weighted model over the area. The weighing presented is the one that was most accurate to the actual change.*

4.5.3 Area B

This area consists of sand, gravel and stones, and clay. A large part of the area is covered by a maritime transportation corridor and has a steep slope on the sides (Fig. 7). In area B, some places on both sides of the survey area have become shallower from 2003 to 2013. A large part has a change of only a few decimeters, areas that have changed tend to be deeper. There has generally been a larger sediment movement on the side where the slope is more significant. The red part has become even larger for the weighted model where seabed weight 1,5 maritime transportation corridors =1 and the slope =2. A large area is covered in red and orange in the weighted model. It can be seen that most factors in the area are of high risk. Sediment that tends to move, a transportation corridor, and steep slopes on the sides. Spots that are dark blue or dark red on the map with actual changes tend to match with red areas in the weighted map (Fig. 8).

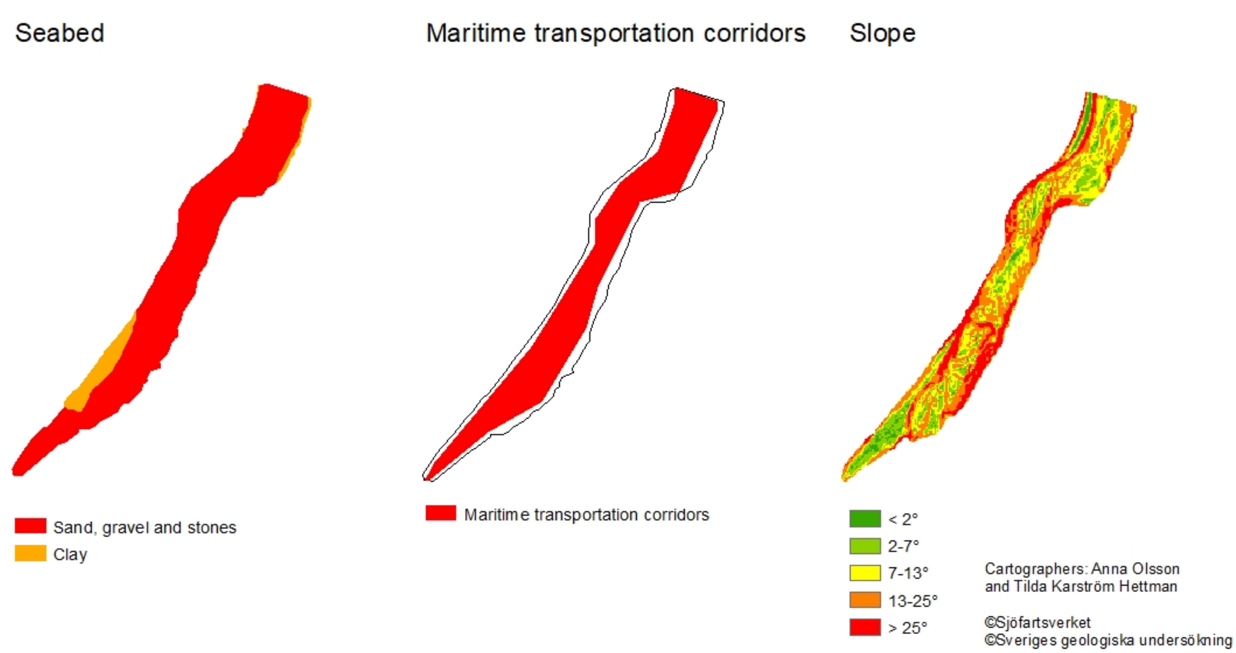

Figure 7. *Shows the three factors weighted in the model to predict where the bathymetry is most likely to change in area two.*

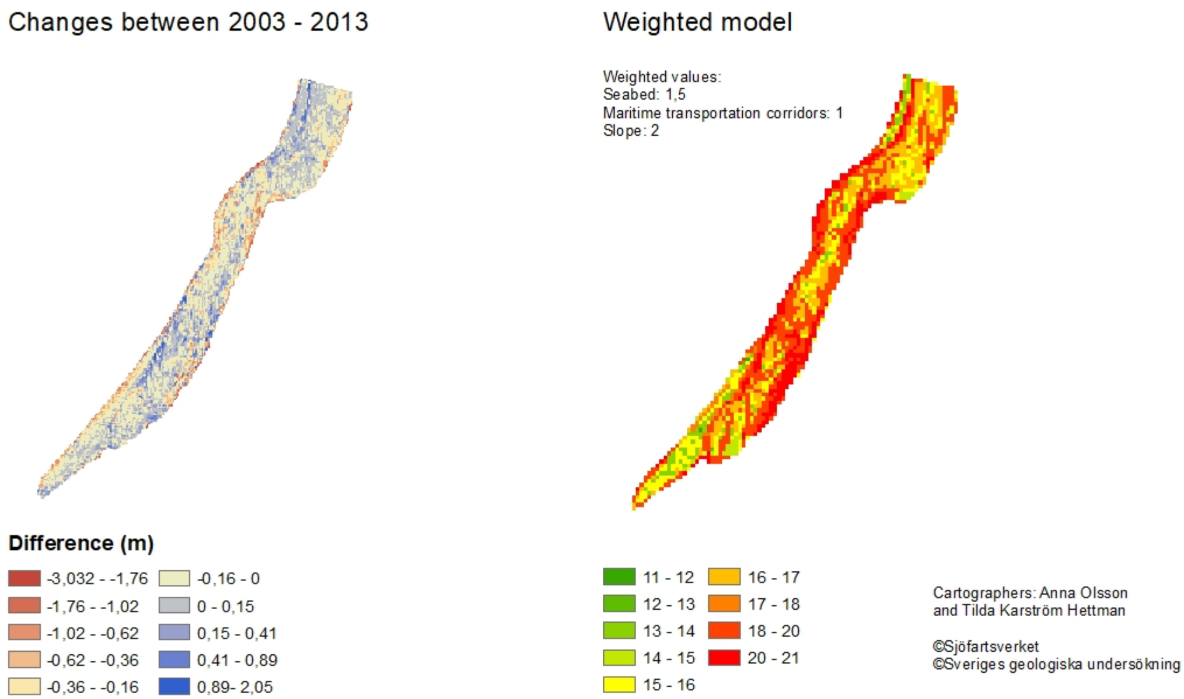

Figure 8. *Shows the actual changes in area A from 2003 to 2016, and the weighted model over the area. The weighing presented is the one that was most accurate to the actual change.*

4.5.4 Prediction of changes in Kattegat and Skagerrak

The large-scale model is based on slope, seabed, maritime transportation corridors, and currents. All factors are reclassified as mentioned in the method and with the same value as for the smaller areas. Since HELCOM has a map of currents available, this data has been added to the large-scale map, divided into three categories: < 0.02=1, 0.02- 0.05 =2, > 0.05=3. There is a large variation in the weighted model over predicted changes. Areas that stand out with a higher risk for changes are outside Strömstad and around Öresund. There are also smaller areas further out from the coast that can be classified with a higher risk. According to this model, areas closer to land seem to have a smaller risk (Fig. 9).

A second large-scale model was made with the exact weighing's and factors as above but with the age of surveys with areas that reaches FSIS-44 included (Appendix 6). This map shows areas with the highest standard, but that might need to be redone to ensure preciseness because of older surveys. This is a priority map that shows areas that today reach the requirements for CATZOC A1 but might need to be remeasured. The area that has no data are areas classified with CATZOC C and it´s already known that these aren't of the highest standard (Fig. 10).

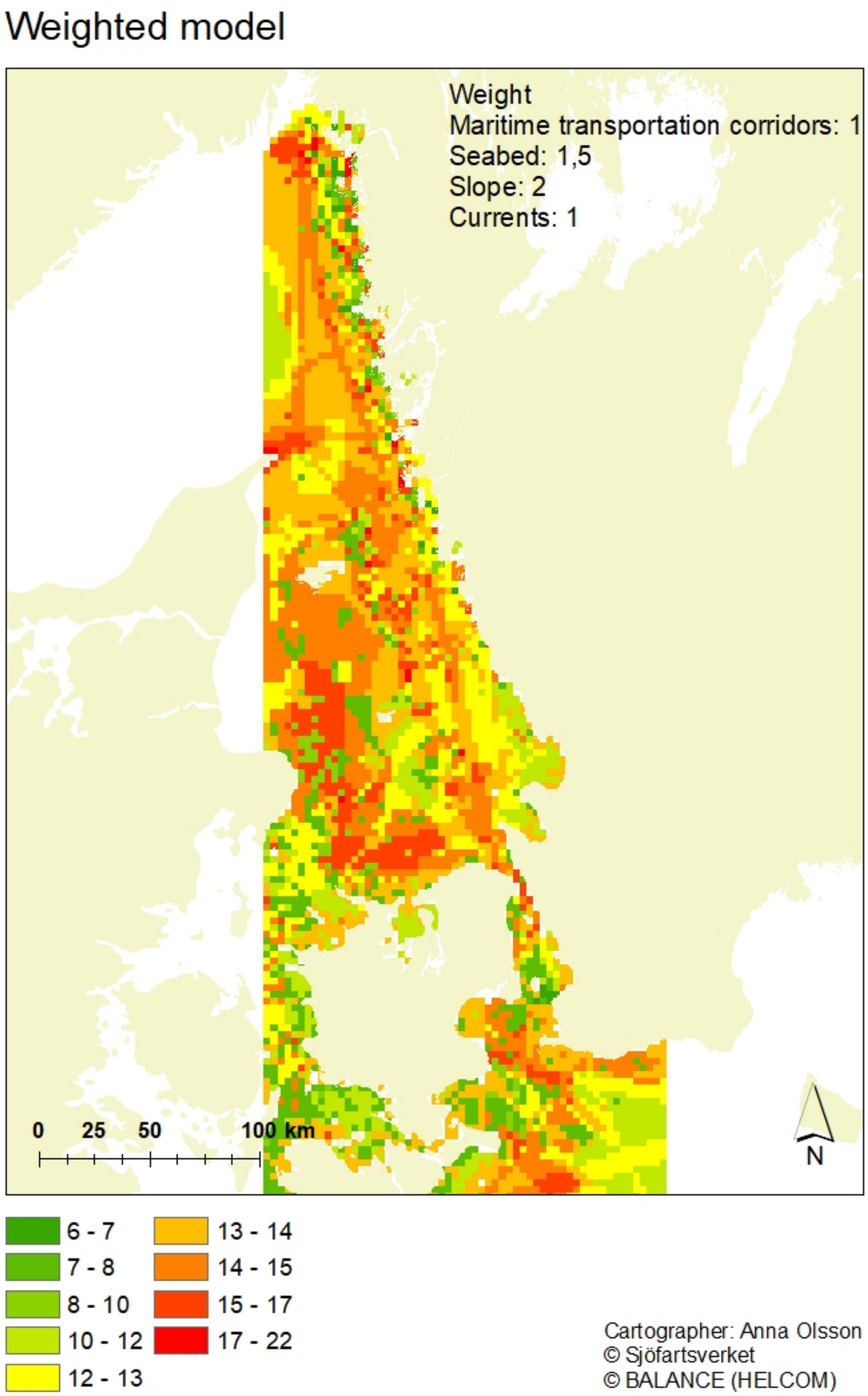

Figure 9. *Result from the weighted model over Kattegat and Skagerrak where red is the area where most change is predicted, and green is the area with less predicted change.*

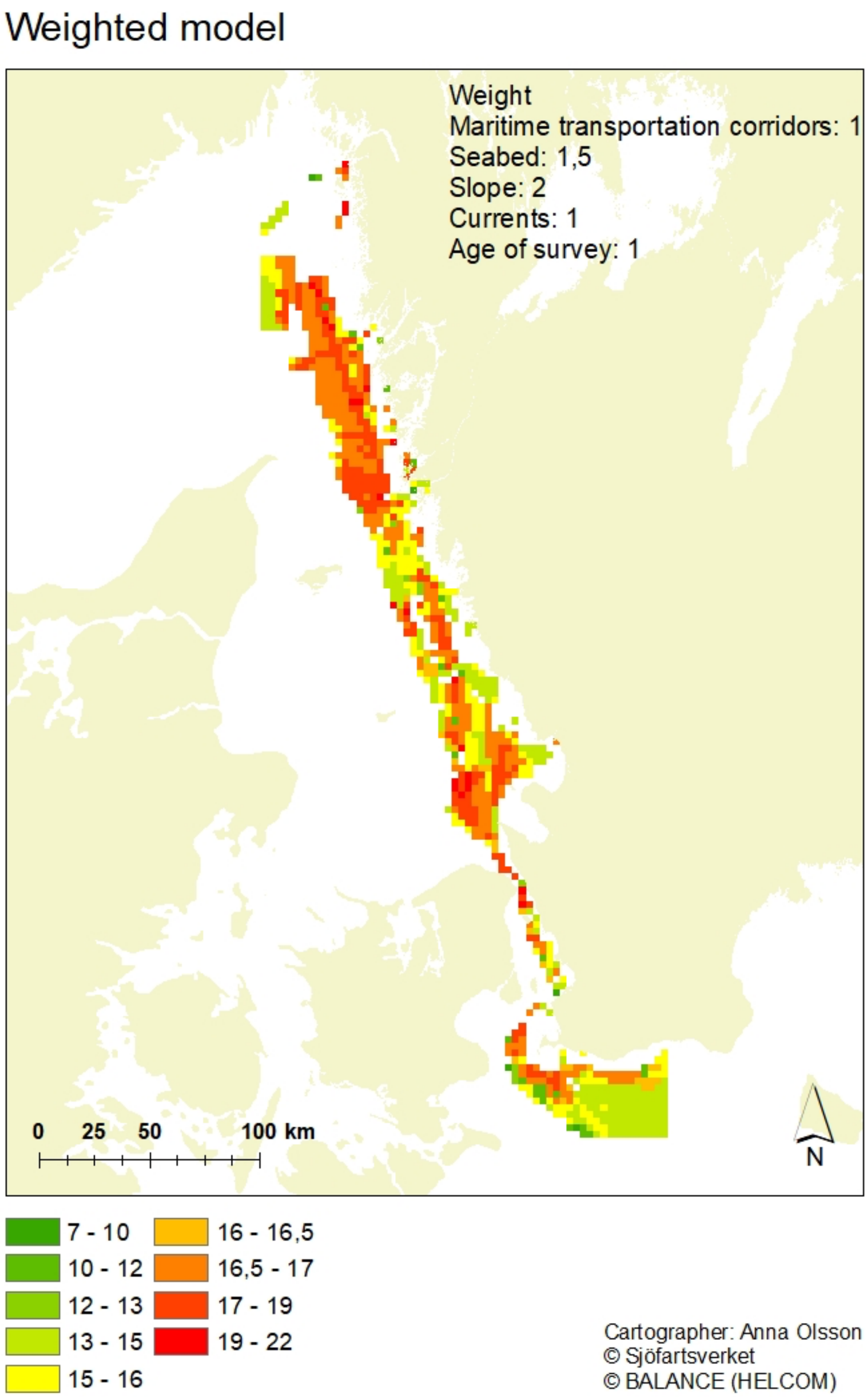

Figure 10. *Result from the weighted model over Kattegat and Skagerrak with the age of survey included. This map shows where it should be prioritized to redo the hydrographic survey.*

5. Discussion

The Swedish Maritime Administration asked for a model that could help them determine how long you can keep an area classified as CATZOC A1 after the survey has been done. The original plan was to create a model that could estimate how fast the seafloor would change on the Swedish west coast. With the data available for this project, that has not been possible. The plan was to determine how fast the seafloor has changed in the past to predict future changes. It was soon discovered that it was not that much space along the coast that had been surveyed multiple times with multibeam or other high-resolution instruments. Therefore, the model created from this project instead focused on where the seafloor might change the most according to the type of seabed, slope, maritime transportation corridors, and currents (only available for the large-scale model).

5.1 Actual changes in the bathymetry and prediction of changes in smaller areas

Eleven different locations were analyzed for the small-scale areas. Many of the areas seem to have unreal values for actual change, some places had a change of over 10 m in depth just over a few years (Appendix. 5). It might be possible that the bathymetry has changed a lot, it could be old wrecks that have been removed, or dredging may have occurred in the area, but there were no reasonable grounds for a significant change in most places. Instead, these values can be explained by some of the data coming from old hydrographic surveys, it is not so sure that they are reliable, it can be false depth points left that should have been cleaned, and the accuracy of the position might not be 100% correct. The model over where there is a risk for change can be used to find areas that need to be prioritized for new hydrographic surveying. An example of how this model works is shown in this report. When comparing different weighing with the actual changes, it could be seen that slope is the factor that probably has the most significant effect on the bathymetry. The type of seabed comes second, and Maritime transportation corridors as third. How the currents affect the bathymetry was not possible to test since that data was not available in the small-scale areas and was therefore only given a higher value with a higher speed. For area A there are low values for change on the side of the maritime transportation corridor in the area. There are however many red lines that show that there has become shallower in the area (Fig. 6). Since the vessels disturb the bathymetry, this can be sediment resuspended from the transportation corridor area that has settled outside. One issue to consider for the future is how far from the transportation corridor the bathymetry is affected. Only a visual comparison between actual changes and predicted changes were made in this report. Math needs to be involved to compare the real changes more accurately with the expected changes. In this project, it was tested to reclassify the predicted changes to the same values as the actual changes. The problem is that the actual changes go from minus to plus since the bathymetry becomes shallower and deeper, while the predicted changes just go from zero and up – it shows the change but not if it is deeper or shallower. This could be solved by using a model that simulates erosion and accumulation.

5.2 Prediction of change in Skagerrak and Kattegat

For the large-scale model over Skagerrak and Kattegat, the dataset for slope and seabed type are rough estimates, especially seabed, since the actual data is confidential. With the model created in this project, it is possible to test and see where there is a higher risk of finding areas that have a higher risk for change. Still, it needs to be considered that some of the data is a rough estimation and it is not sure that it is reliable. The more exact seabed type by SGU, used for the small-scale areas and data over the actual slope would be recommended to ensure a good result. The prediction over changes showed that areas closer to the coast generally had a more negligible risk of change. According to that, it probably is a lot of local currents, traffic from smaller vessels, anthropogenic influence, and influence from river outflow, this might not be the accurate values. Areas closer to land are also shallower in general, giving a more significant impact from vessels and wind etc. It is well known that currents impact sediment and its transportation. The currents on the Swedish west coast are a combination of local currents generated by weather and geomorphology and larger currents like the Atlantic current, Baltic current, and Jutlantic current. The data source for currents in this project originated from the HELCOM project. The values in this data are very low and seem to miss currents closer to the coast and in Öresund. Inside the archipelago, there are lots of local currents that can't be traced on this map. The values in the current data are also very low, the highest value is around 0.18 m/s, and that's not even strong enough to erode silt according to the Hjulströms diagram. Since the data over currents are average data between the bottom and a few meters up, it is hard to know the highest velocity that occurs in the area. That velocity is essential since that will move larger sediment particles. Data that includes currents on a smaller scale and data for the other mentioned factors that affect the bathymetry close to the coast needs to be included to give a more realistic estimation of the changes in the bathymetry.

5.3 Priority for new hydrographic surveying

What SMA requested of this report was a method that could help them know how long an area could be classified with CATZOC A1 before it needs to be downgraded. Since it was not possible to build a model that showed absolute predicted changes it is not possible to say how long an area can be classified with CATZOC A1. The priority map made shows which areas classified with A1 that might need an update to maintain the A1 status based on age and where there is a higher risk for change.

5.4 Future improvements

Future improvements that need to be done to predict changes in the bathymetry are first to do more surveys on non-disturbed areas. This needs to be done to see how much sediment moves without marine traffic. Today very few places are measured with high accuracy twice, that needs to be done to build statistical evidence. The sedimentation rate in Skagerrak is around 0.30 – 0.34 cm/yr (Van Weering et al., 1987) but the sediment core that these values are based on is taken far from the coast. The sedimentation rate in different locations would be a great knowledge for a future model. This model has not considered some factors that can affect the bathymetry like sedimentation rate, waves, river discharge, sea level rise, land uplift, and general anthropogenic influences. Factors like sea level rise and land uplift take each other out or are very minor in most parts of Sweden's coast. The anthropogenic influences are a problem since they often have no regularity. It has been challenging to find previous studies that explain how the seabed slope affects bathymetry. It is clear from the results that sediment tends to move more in areas with larger slopes, so this needs to be better investigated. That maritime transportation corridors have a large impact on the bathymetry can be seen in appendix 4. Vessels that travel at a shallower depth will impact the bathymetry even more. Factors like waves also have a larger impact on shallower waters, and that some factors have a larger impact on shallower water need to be considered in a future model. It is also important to consider that the model only predicts change, but not which kind of changes (deeper or shallower). As Bongiovanni et al. mention in their report from 2021, it was not possible to take temporal variability into account which is a problem even in this model. For example, a large storm with lots of waves and reinforced currents can affect the bathymetry and change the seabed a lot in just a couple of hours. A plan for dealing with these kinds of unpredicted changes will be needed.

5.5 Conclusion

The conclusion of this project is that it is not possible to predict how much bathymetry changes on the Swedish west coast through time with the data available today. More areas with duplicate high-resolution surveys are needed to base the model on. Research on how different factors affect the bathymetry, how much and in which ways (deeper or shallower) is required. Even though it was not possible to create a model that predicts how much the bathymetry changes it is possible to make a good model on where there is a risk for the bathymetry to change.

6. Acknowledgment

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References

Almström. B., Larson, M., Granath, L., Hanson, H. (2018). Ship Generated Waves Over a Complex Bathymetry. Abstract from 36th International Conference on Coastal Engineering (ICCE), Baltimotre, United States. https://journals.tdl.org/icce/index.php/icce/article/view/8861/7659

ArcGIS Pro (2022, May 18). *How weighted Sum works* (version 2.9). Retrieved from https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-weighted-sum-works.htm

BALANCE. (2005, September 14). *About the project*. Retrieved from https://balance-eu.org/about_us/index.html

Bendtsen, J., Söderkvist, J., Dahl, K., Hansen, J.L.S. & Reker, J. (2007*). Model simulations of blue corridors in the Baltic Sea*. BALANCE Interim Report no. 9. Available at http://balance-eu.org/xpdf/balance-interim-report-no-9.pdf.

Binczewska, A., Risebrobakken, B., Polovodova Asteman, I., Moros, M., Tisserand, A., Jansen, E., Witkowski, A., (2018). *Coastal primary productivity changes over the last millennium: a case study from the Skagerrak (North Sea)*. Biogeosciences, 15, 5909–5928. Doi: 10.5194/bg-15-5909-2018

Bongiovanni, C., Lippmann, T. C., Calder, B., Amstrong, A. (2021). *Identifying future hydrographic survey priorities: A quantitative uncertainty based approach*. International Hydrographic review (25).

Chénier, R., Abado, L., Martin, H. (2018). CHS Priority Planning Tool (CPPT) – A GIS Model for Defining Hydrographic Survey and Charting Priorities. *International Journal of Geo-Information*. 7(7), https://doi.org/10.3390/ijgi7070240

Ehrenswärd, U. & Frithz, H. (1993). *Sveriges Sjöfartsväsende 1643–1993*. Sjöfartsverket. ISBN: 91-86502-10-7

Fonselius, H.S.(1990). *SKAGERRAK – the gateway to the North Sea*. SMHI Oceanography (Nr 38).

Fredsøe, J., Deigaard. R. (1992). *Mechanics of coastal sediment transport* (2), World Scientific Publishing. ISBN 9810208405

Finnish transports Agency, S. M. A. (2010). FSIS-44 Finnish and Swedish joint implementation of the IHO Standards for Hydrographic Surveys Special Publication no 44 5th Edition (S-44).

Gimeno, L., Nieto, R., Drumond, A., Durán-Quesada, A.M. (2013). *Ocean Evaporation and Precipitation*. In: Orcutt, J. (eds) Earth System Monitoring. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-5684-1_13

Geological Survey of Sweden (2017). *Maringeologi 1:100 00*, version 1.1

HELCOM. (2022 February 17). *About us*. Retrieved from https://helcom.fi/about-us/

HELCOM. (2021 November). *Seabed sediments (BALANCE)*. Retrieved from https://metadata.helcom.fi/geonetwork/srv/eng/catalog.search#/metadata/41f4f5ca-4d07-4b76-b8ed-8ac2739d57a6

HELCOM. (2021 November). *Seabed slope (BALANCE)*. Retrieved from https://metadata.helcom.fi/geonetwork/srv/eng/catalog.search#/metadata/4b0038f4-fe69-401a-8d79-c754655f8942

HELCOM. (2021 November). *Modeled bottom current (BALANCE)*. Retrieved from https://metadata.helcom.fi/geonetwork/srv/eng/catalog.search#/metadata/10982458-8479-4f63-841d-1e11cb8dde3f

Kartografiska sällskapet (Wiberg, P. & Wallhagen, M.). (2018), *Sveriges Kartläggning Tillägg 2008–2017* (Chapter: Sjökartläggning 2008–2017). Gävle Offset, ISBN 978-91-629-5946-2

Leppäranta, M., & Myrberg, K. (2009). *Physical Oceanography of the Baltic Sea*. Springer. ISBN 978-3-540-79702-9

Malczewski, J., Rinner, C. (2015). *Multicriteria Decision Analysis in Geographic Information Science*. Springer Science, New York. DOI: 10.1007/978-3-540-74757-4

NOAA Ocean Exploration. (2022, April 13) *Multibeam Sonar*, Retrieved from https://oceanexplorer.noaa.gov/technology/sonar/multibeam.html

Riding, J., Roberts, J., Priovolos, G. (2016). *New Zealand Hydrographic Risk Assessment – national overview*.

Seibold, E., & Berger, W. (2017). *The Sea Floor – An Introduction to Marine Geology* (4th). Springer. DOI: 10.1007/978-3-319-51412-3

Sjöfartsverket. (2011, april 20). *Anvisning sjömätning* (https://www.sjofartsverket.se/globalassets/tjanster/sjomatning/anvisningsjomatning.pdf)

Sjöfartsverket. (2019). *Sjökortskatalog 2019*

Sjöfartsverket. (2020, september 06). *På uppdrag av regeringen*. Retrieved from https://www.sjofartsverket.se/sv/om-oss/vad-gor-sjofartsverket/pa-uppdrag-av-regeringen/

Sjöfartsverket. (2021). *Sjökortskatalog 2021*

Sjöfartsverket. (2021, June 18). *Det här är Sjöfartsverket*. Retrieved from https://www.sjofartsverket.se/sv/om-oss/vad-gor-sjofartsverket/

Sjöfartsverket. (2022, February 16). *Gamla och nya djup i sjökorten*. Retrieved from https://www.sjofartsverket.se/sv/tjanster/sjokortsprodukter/kopa-sjokort2/Gamla-och-nya-djup-i-sjokorten/

Slater, T., Lawrence, R.I., Otosaka, N.I., Shepherd, A., Gourmelen, N., Jakob, L., Tepes, P., Gilbert, L., Nienow, P. (2021). *Earth's ice imbalance*. The Cryosphere (15), 233-246, DOI: https://doi.org/10.5194/tc-15-233-2021

SMHI. (2022, January 19). *Framtida vattenstånd längs kusten*. Retrieved from https://www.smhi.se/kunskapsbanken/oceanografi/vattenstand-och-klimat/framtida-vattenstand-langs-sveriges-kust-1.133483

SMHI. (2014, April 23). *Surface currents*, Retrieved from https://www.smhi.se/en/theme/surface-currents- 1.12286#:~:text=The%20Baltic%20current%20consisting%20of%20outflowing%20Baltic%20water,saltier%20and%20therefore%20flows%20under%20the%20Baltic%20current.

Timmen, L., Gitlein, O., Klemann, V., Wolf, D. (2011). *Observing Gravity Change in the Fennoscandian Uplift Area with the Hanover Absolute Gravimeter*, Pure appl. Geophys. (169), 1331-1342. DOI: 10.1007/s00024-011-0397-9

UK Hydrographic office. (2017, May 17). *Category Zones of Confident (CATZOC) – Dispelling the myths*. Retrieved from https://www.admiralty.co.uk/news/blogs/category-zones-of-confidence

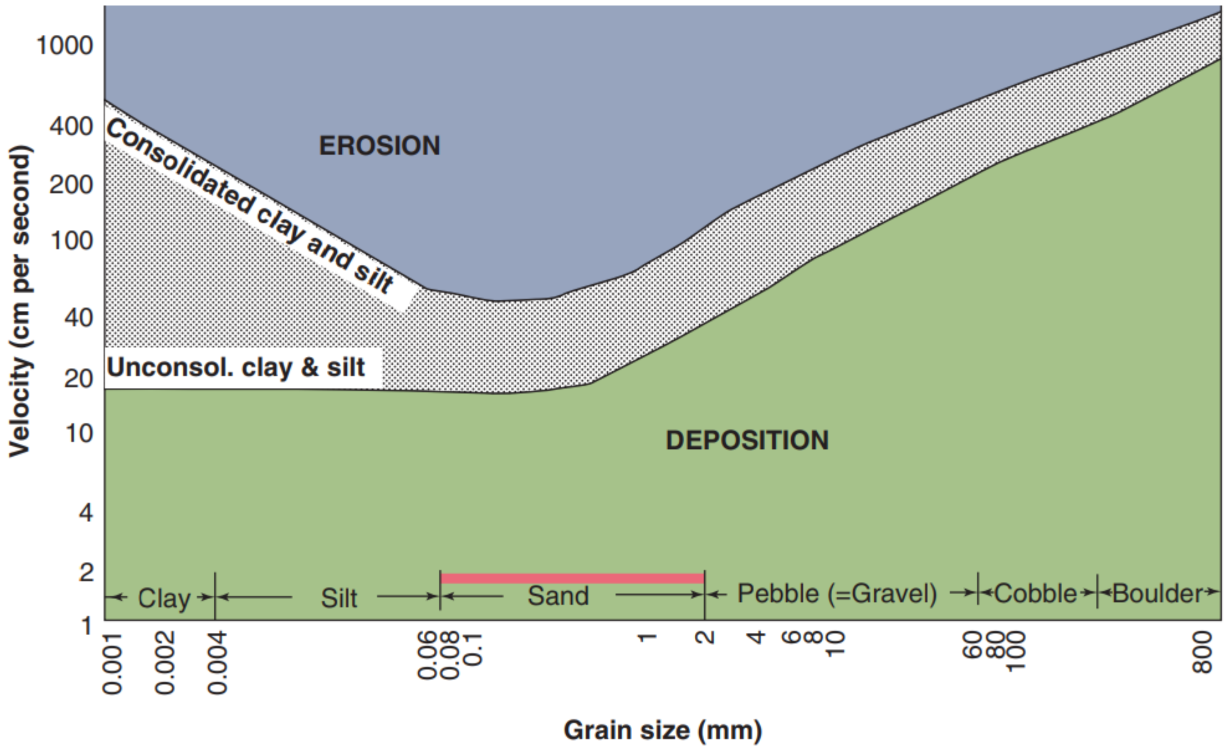
Van Weering, T.C.E., Berger, G.W., Kalf, J. *Recent sediment accumulation in the Skagerrak, Northeastern North Sea.* (1987). Netherlands Journal of Sea Research 21(3):177-189. DOI: https://doi.org/10.1016/0077-7579(87)90011-1

Xue, C., Yang, Y., Zhao, P., Wei, D., Gao, J., Sun, P., Huang, Z., Jia, J. (2021) *Impact of Ship Traffic on the Characteristics of Shelf Sediments: An Anthropocene Prospective*, Frontiers in Marine Science, 8, Article 678845. https://doi.org/10.3389/fmars.2021.678845

Appendix

ZOC [1]	Position Accuracy [2]	Depth Accuracy [3]	Seafloor Coverage	Typical Survey Characteristics [5]
A1	± 5 m + 5% depth	=0.50 + 1%d Depth (m) / Accuracy (m) 10 / ± 0.6 30 / ± 0.8 100 / ± 1.5 1000 / ± 10.5	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.
A2	± 20 m	= 1.00 + 2%d Depth (m) / Accuracy (m) 10 / ± 1.2 30 / ± 1.6 100 / ± 3.0 1000 / ± 21.0	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.
B	± 50 m	= 1.00 + 2%d Depth (m) / Accuracy (m) 10 / ± 1.2 30 / ± 1.6 100 / ± 3.0 1000 / ± 21.0	Full area search 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 ZOC A2, using a modern survey echosounder [5], but no sonar or mechanical sweep system.
C	± 500 m	= 2.00 + 5%d Depth (m) / Accuracy (m) 10 / ± 2.5 30 / ± 3.5 100 / ± 7.0 1000 / ± 52.0	Full area search not achieved, depth anomalies may be expected.	Low accuracy survey or data collected on an opportunity basis such as soundings on passage.
D	*Worse than ZOC C*	Worse than ZOC C	Full search not achieved, large depth anomalies 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 1. *The six different CATZOC categories and explanation of each group (UK Hydrographic Office, 2017).*

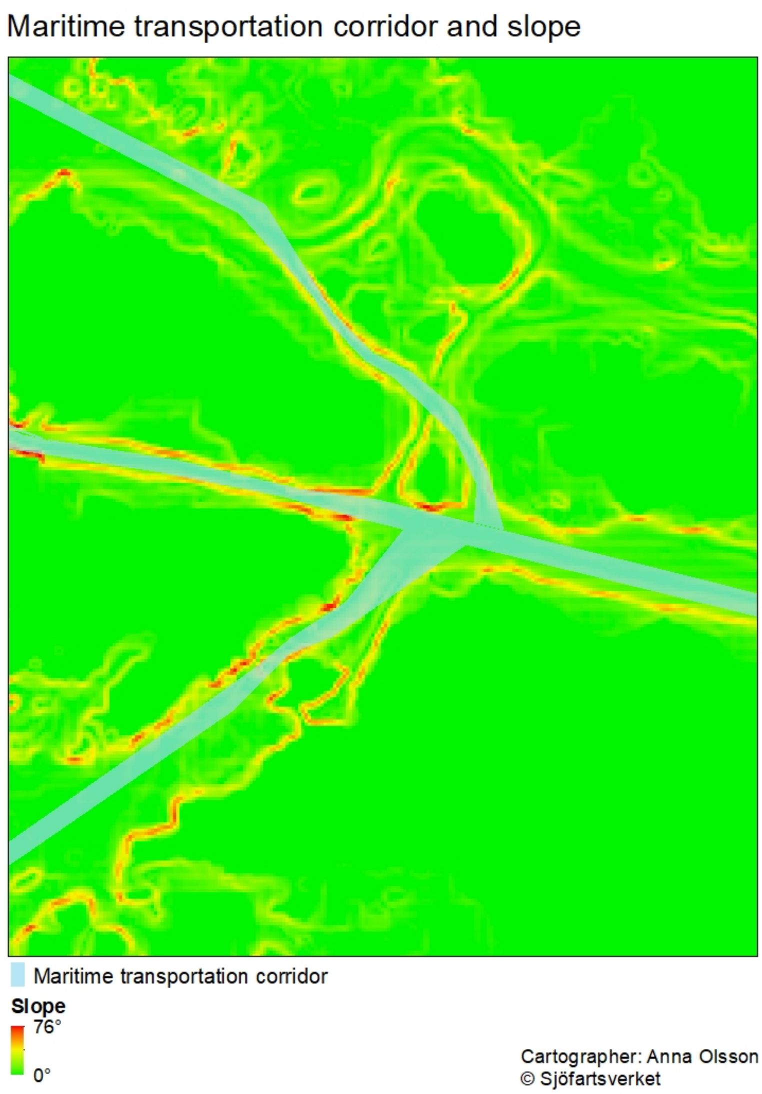


Appendix 2. *Hjulströms diagram that shows how sediment particle moves in water depending on grain size and velocity (Seibold & Berger, 2017).*

Factors	Categorization and reclassification				
Slope					
Categorization	< 1°	1 - 2°	2 - 5°	5 – 10°	> 10°
Reclassified value	1	2	3	4	5
Categorization	< 5°	5 – 10°	10 – 15°	15 - 20°	>20°
Reclassified value	1	2	3	4	5
Categorization	< 0.25°	0.25 – 4°	>4°		
Reclassified value	1	2	3		
Categorization	< 2°	2 – 7°	7 - 13°	13 - 25°	>25°
Reclassified value	1	2	3	4	5
Seabed type					
Categorization	Bedrock	Hard bottom complex	Hard clay and mud	Sand	
Reclassified value	1	2	3	4	
Categorization	Bedrock	Hard bottom complex	Hard clay and mud	Sand	

Reclassified value	1	2	5	6	
Maritime Transportation Corridors					
Categorization	No transportation corridor	Transportation corridor			
Reclassified value	1	2			

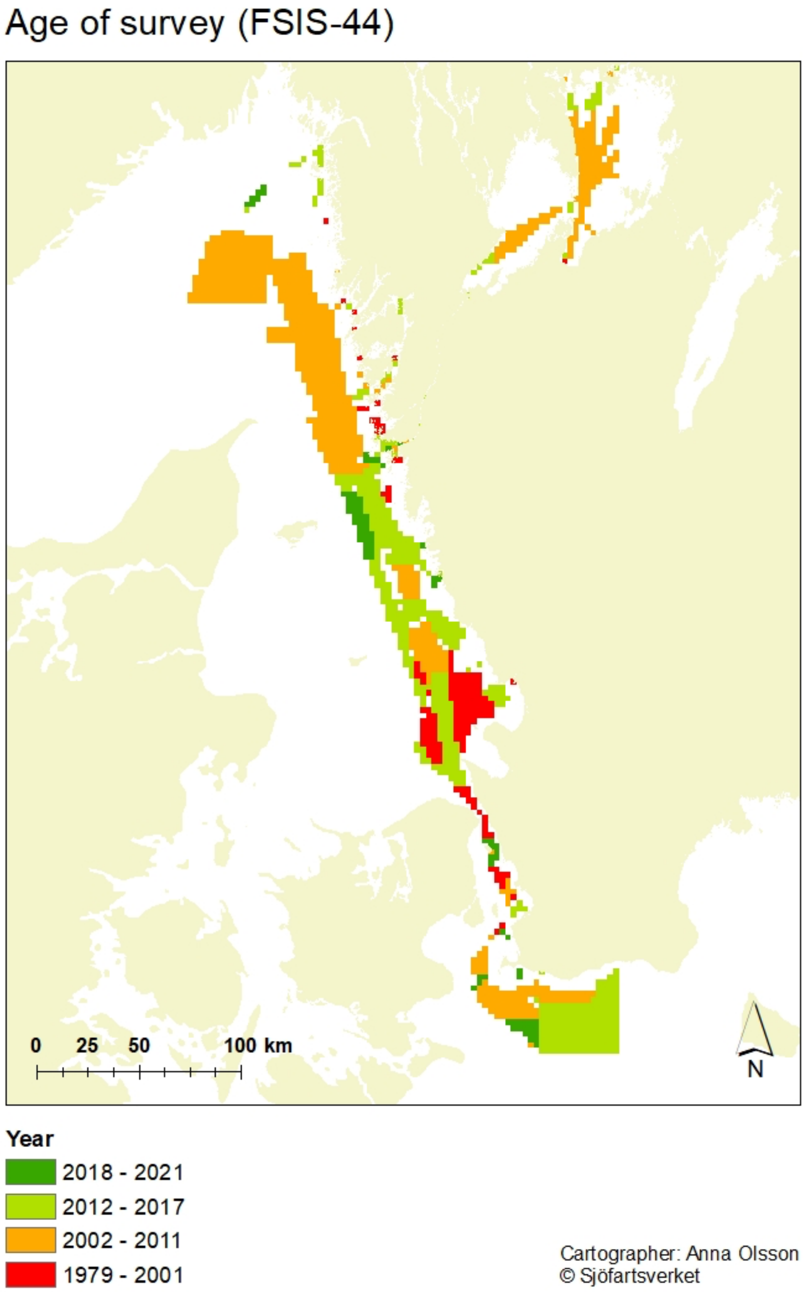
Appendix 3. *The different factors used in the small-scale model and their different reclassification values. These values have been used and tested differently together in Weighted sum to find out which reclassification that aligns best with the actual changes of the bathymetry.*



Appendix 4. *Slope and maritime transportation corridors. The slope is greater along the edges of the transportation corridors.*

Area	Year	Difference (m) (Shallower to deeper)
Area A	2003 – 2009	-3.3 – 3.4
	2009 – 2016	-4 – 5,1
	2003 – 2016	-4.2 – 5,43
Area B	2003 – 2013	-3.03 – 2.05
	2017 – 2018	-1.1 – 2.1
Area C	1998 – 2001	-3.4 – 9.9
	2003 – 2008	-3.7 – 2.4
	2008 – 2016	-2.8 – 3.4
	1998 – 2016	-5.4 – 5.7
Area D	1995 – 2003	-11.5 - 2
	2003 – 2007	-3.1 – 7.6
	2014 – 2019	-1.3 – 2.4
Area E	2004 – 2005	-8.1 – 11.2
	2005 – 2018	-15.9 – 3.3
Area F	2005 – 2010	-0.5 – 0.7
	2010 – 2012	-0.5 – 0.9
	2005 – 2012	-1.1 – 0.9
Area G	2004 – 2009	-3.1 – 1.4
	2009 – 2014	-4.2 – 1-2
	2004 – 2014	-5,9 – 1.9
Area H	1998 – 2005	-5.5 – 6.7
	2005 – 2007	-2.5 – 3.9
Area I	1997 – 1998	-1.1 – 1.1
	2008 – 2012	-3.5 – 2.4
	1997 – 2012	-3 – 3.3
Area J	2005 – 2016	-0.6 – 0.8
	2016 – 2020	-0.4 – 0.5
	2005 – 2020	-0.8 – 0.7
Area K	2003 - 2009	-3.3 – 3.4
	2009 – 2016	-4 – 5.1
	2005 - 2016	-4,16 – 5.5

Appendix 5. *This shows the 11 different locations that have been analyzed for changes in the bathymetry. It shows the difference in meters where negative values indicate that it has become shallower and positive has become deeper.*



***Appendix 6**. The age of surveys that reaches FSIS-44 and CATZOC A1 standards on the Swedish west coast.*