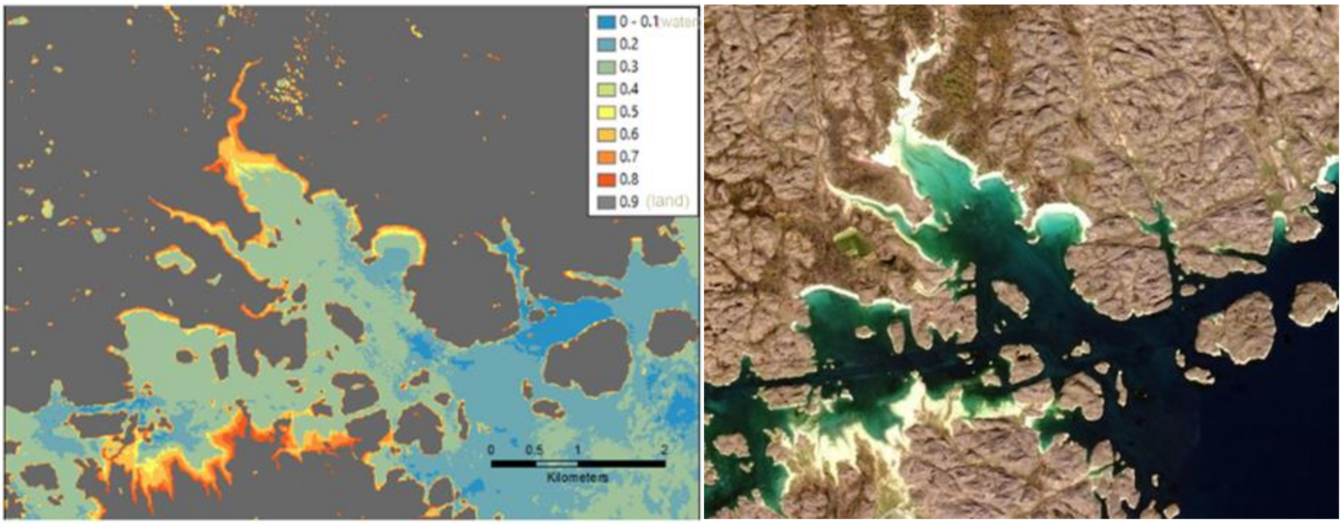
Mapping the Coastal Zone in North East Greenland

Detection of coastal morphology, tidal flats, and shallow water bathymetry using high-resolution satellite imagery covering sites in West and North East Greenland

Mikkel Høegh Bojesen, Rasmus Eskerod Borgstrøm, Kirsty Langley, Eva Mätzler, Alexandra Messerli, Mikkel Lydholm Rasmussen, and Karl Brix Zinglersen



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ASIAQ GREENLAND SURVEY

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English Summary

This report highlights the findings of the mapping of the coastal environment on two locations in Greenland based on analysis of satellite imagery. The study includes satellite derived bathymetry, mapping of the intertidal zones, and classification of the coastal areas, which we could map successfully. The analysis involved algorithms applied to high- and medium-resolution satellite imagery, validation with field measurements, and morphological analysis from coastline data. The study successfully demonstrated the feasibility of using satellite-based analysis for remote areas, but also highlighted the logistical complexities of field work conducted there. Nevertheless, the technologies hold high potential for efficient large-scale mapping in the Arctic.

Greenlandic summary – Kalaalissut Naalisarneqarnera

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Danish summary – sammenfatning på dansk

I denne rapport fremhæver vi resultaterne af kortlægningen af kystmiljøet to steder i Grønland baseret på analyse af satellitbilleder. Undersøgelsen indbefatter havdybder på lavt vand beregnet fra satellitdata, kortlægning af tidevandszonen og klassificering af kystområder, som kunne kortlægges med success. Analysen bestod i algoritmer anvendt på satellitbilleder af høj og medium opløsning, validering fra målinger i felten og morfologisk analyse fra kystlinjens forløb. Undersøgelsen fremviste mulighederne for at bruge satellitbaseret analyse i fjerntliggende områder, men fremhævede også de logistiske kompleksiteter af feltarbejdet på stedet. Ikke desto mindre har teknologierne et stort potentiale for effektiv kortlægning i stor skala i Arktis.

1. Introduction and Background

Motivation

The coastline of Greenland is long and complex, both in its form and in composition. Since the predominant part of the country consists of wild nature without roads, the coastal areas are the main transportation routes. There are a multitude of skerries, archipelagos, islands and islets, which are uncharted, and these present a significant hazard and risk for accidents. The lack of navigational charts and accurate topographic maps are a particular problem in the remote areas of Greenland, such as North East Greenland. With hydrocarbon exploration expanding ever further north it is essential to fill-in crucial missing information on the coastal environment.

The recent advances in satellite remote sensing and image analysis have increased the potential to obtain detailed insights, and updated information about vulnerable and remote coastal environments in the Arctic.
Freely available Sentinel satellite imagery from the European Space Agency (ESA) Copernicus programme, supplemented with advanced commercial satellite imagery represents an obvious data source for updating these maps.

In this report we highlight the findings of the coastal mapping projects based on satellite imagery. It includes satellite derived bathymetry, mapping of the intertidal zones, and classification of the coastal areas, which we could map successfully in two regions of Greenland.

1.1 Satellite based analysis

In this study, we have demonstrated how satellite imagery can be used for mapping the coastal zones in the remote area of North East Greenland. Additionally, we developed and applied methods for deriving shallow water bathymetry, intertidal zones, and classifying different coastal types. The analysis was carried out using 1) high resolution, commercial satellite imagery of selected areas, and 2) freely available medium resolution satellite data, which has a larger spatial coverage and therefore allowed for an upscaling of the area of interest. Field measurements were carried out in order to validate the satellite-derived products.

This project served as a feasibility study that successfully demonstrated the use of satellite-based methods for mapping the coastal characteristics of the study area.
The challenges encountered during the project (such as sea ice coverage, turbidity, and small tidal level variability) have helped us to define the limits of the methods, thereby reducing the risks for future applications.
These positive results open up the possibility for applying the newly developed methods to other coastal areas in Greenland, and thus holds an enormous potential for a cost-efficient large-scale mapping of the coastal zone in Arctic.

1.2 Field Sites

Two areas of interest (AOI) - one in West Greenland and another in North East Greenland (Figure 1.2.1) were chosen for this pilot study.

Figure 1.2.1. *Map of Greenland indicating the two AOIs used in this study, Nipisat in West Greenland and Vega Sund in North-East Greenland.*

West Greenland AOI – Nipisat:
Nipisat is a shallow-water inlet located close to the capital of Nuuk (Figure, 1.2.2). The area is an inlet of Nuup Kangerlua (Nuuk Fjord), which has a depth range from 0.5m to 20m and a tidal range of 3-4m. This AOI was used to establish the methodological framework, data management and analysis procedures for the study. Additionally, the depth measurements acquired in Nupisat were used to calibrate and validate the satellite-derived bathymetry. The proximity of the AOI to Nuuk allowed for effective and safe collection of ground-based validation data used during the development phase of the project. Nipisat Sund was visited using a boat provided by the Greenland Institute of Natural Resources.

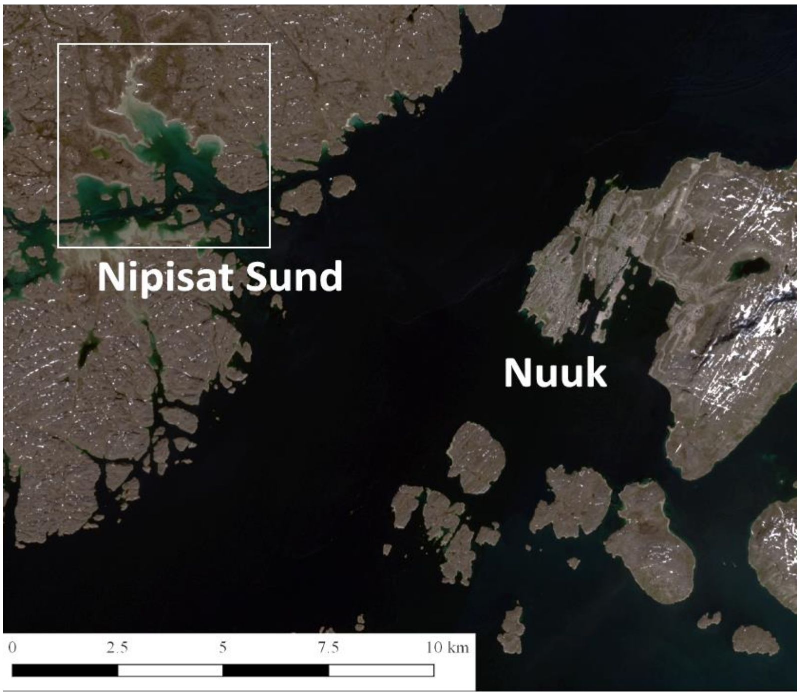


Figure 1.2.2. *Field site Nipisat Sund, a shallow-water inlet close to Nuuk*

North East Greenland AOI – Vega Sund:
Within North East Greenland, we have focused on especially vulnerable coastal areas, for example breeding grounds of bird colonies, areas with interesting seaweed deposits or archaeological sites that are threatened due to coastal erosion. These AOI's were selected with input from biologists and archaeologists (Fig. 1.2.3). High-resolution satellite imagery of the AOI's were examined in conjunction with near-shore bathymetry datasets. The Vega Sund area was highlighted as the most appropriate location due to its vulnerable and valuable seaweed deposits, which would be at risk in case of an oil spill incident. Vega Sund is a shallow area between Foster Bugt bay and the inner fjords, located north of the town of Ittoqqortoormiit (Scoresbysund). Archive satellite images show that the area has been free or partially free of sea ice cover during the last years from beginning of august, deeming it a suitable AOI for satellite-derived bathymetry analysis.

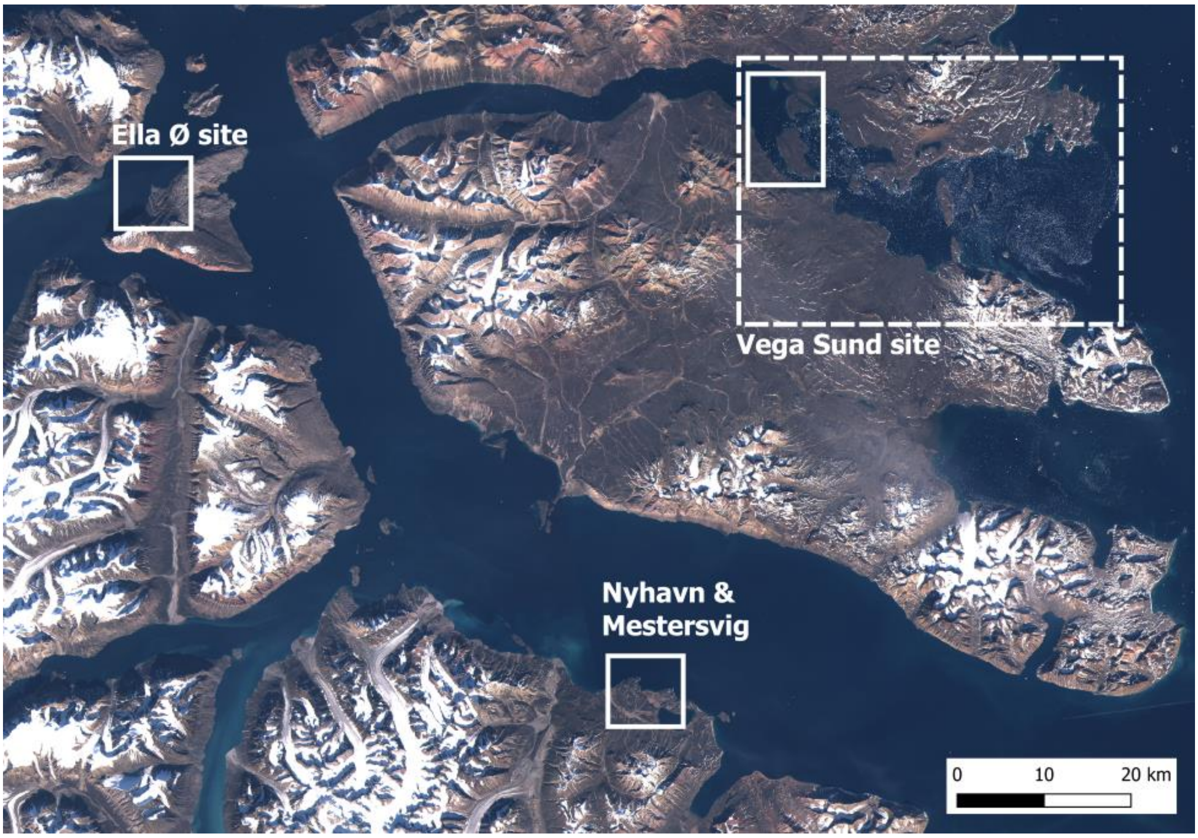


Figure 1.2.3. *The three field sites of North East Greenland*

Travelling and logistics for field surveys in North East Greenland are challenging, requiring expensive charters for transport and collaboration with other operators to minimize costs and enhance safety. The survey team collaborated intensely with NANOK, The North-East Greenland Company, a non-profit organization restoring cultural heritage cabins in the National Park. Together we shared logistical platforms: charter of airplanes, shared cabin accommodations, and as passengers on their boat travelling towards the study area. The locally based military units of the Mestersvig Station and the Ella Ø Station (Sirius Dog Sled Patrol) of the Joint Arctic Command, the Danish Defence, provided logistical support of driving, accommodation and boat transport. Such collaboration and kind assistance with existing logistical resources in the area highly minimized the costs and supported the operations but cannot be taken for granted in future cases.

1.3 Fieldwork activities

A workshop with all project participants was held in Nuuk during Spring 2018. The goal of the workshop was to prepare field activities, and to test the preliminary near-shore bathymetry analysis. The workshop included collection of ground truthing data in a shallow tidal zone close to Nuuk.

Fieldwork was conducted in North East Greenland for four weeks in July-August 2018, planned to coincide with minimal snow cover and low sea ice extent. However, abnormally high snow cover and a short melt season created unfavourable conditions for both aerial and boat logistics. Thus, as a result of the abundant sea ice cover in Vega Sund, access to Vega Sund was limited and the majority of the fieldwork was instead carried out at Ella Ø and Mestersvig.

The Ella Ø Station harbour was accessed via a nearby landing strip on Trail Ø at Holms Bugt with support from the civilian and military operators. From here, Ella Ø was accessed by boat with assistance from the Sirius Dog Sled Patrol. A fieldwork activity programme was subsequently established, which included setting up a GNSS base station for continuous positioning and installing two tidal gauge stations for continual tidal baseline measurements. The team covered the near shore water with an inflatable boat for depth mapping with a Garmin echo sounder, positioned using the GNSS base station. Exposed rocks and skerries were mapped, and physical depth measurements were conducted using a lead weight. On land, the team documented the coastal morphology, geological properties and vegetation cover with geolocated photos. The ground-truthing data collected here was used to validate the shallow bathymetry and coastal zones. The coastal waters around Ella Ø are deeper than those in the original AOI at Vega Sund. This resulted in a more limited near-shore bathymetry survey and tidal zone classification than intended. Despite the challenging logistical conditions, this did not have a negative impact on the overall outcome of the project.

A short trip to Vega Sund was possible at the end of the field campaign thanks to logistical support from the Sirius Dog Sled Patrol. The AOI could be visited for 3-4 hours, within which echo sounds measurements and photography of the coastline were completed.

2. Data and Methods

2.1 Satellite derived bathymetry

Advances in image analysis, mean it is now possible to estimate the depths of clear, shallow waters using optical satellite imagery.

The advantage of satellite-derived bathymetry (SDB) are that it is cost effective, has a large spatial coverage of remote and dangerous regions, at a high temporal resolution. The main disadvantage of the method is that it relies on the use of optical satellite data, which has a limited water depth penetration (around one secchi depth). The SDB method is most effective in clear waters, as the penetration depth decreases in relation to increased water turbidity, low light, and the presence of ice.

The SDB's in this study were produced using Sentinel-2A & WorldView-2 satellite imagery. The high spatial resolution of Sentinel-2 and WorldView-2 imagery at 10m and 2m respectively, allows for detailed bathymetric mapping. This is of a higher spatial resolution than existing bathymetric datasets.

Theoretical framework for SDB analysis

There are a number of approaches that can be used to derive SDB. The background of some key methods are briefly outlined below.

For this project, a DHI GRAS proprietary physical radiative transfer model (extended version of Guzinski et al. 2016; Klonowski et al, 2007; Lee et al. 1998, 1999, 2001) was applied. Other methods of note used for deriving SDB are empirical models, based on the early work of Lyzenga, 1978, refined by Stumpf, 2003. Additionally, radiative transfer-based models, such as the SAMBUCA model developed by CSIRO (Brando & Dekker, 2003; Wettle & Brando, 2006) can also be applied. The fundamental difference between the empirical models, and the radiative transfer models, is that the empirical models calculate an index that correlates with depths, but has to be transformed into water depths, while the radiative transfer methods model the water column as primarily a function of the water depth and the seabed reflectance.

The model used in this study minimizes the differences between an observed satellite image and a modelled satellite image, which is created as a function of six parameters – depth, bottom type, backscattering, chlorophyll-A, gelbstoff, and the slope of the backscattering function. Through minimizing the difference between the observed and the modelled satellite images, accurate water depths can be retrieved in optically shallow waters, meaning light reflecting from the seabed is observed.
Essentially, the SDB can be reduced to the following series of pseudo equations:

$$rrs_{modelled} = f(chlorophyll, gelbstoff, b_b, b_x, \rho, H)$$

Where $rrs_{modelled}$ is the modelled satellite image, b_b is the backscattering, b_x is the slope of the backscattering function, ρ is the summed up bottom reflectance, and H is the depth.

The next step is to minimize the difference between the modelled and observed satellite images:

$$\chi^2 = \frac{1}{N}\left[\sum \quad (rrs_{observed} - rrs_{modelled})\right]$$

With N being the number of spectral bands, where the satellite image provides information, and $rrs_{observed}$ is the observed satellite image.

Through the two pseudo equations above, and the equations that define the relationship between the parameters in equation one, the depths can be retrieved in a timely and reliable manner.

The above methods have been used in this study and the results are presented in section 5.

2.2 Intertidal zones

The intertidal zone is the region of the shoreline that is periodically exposed and submerged between low tide and high tide, respectively. Many flora and fauna take advantage of the light and abundant food supply available in the intertidal zone, thus increasing the potential environmental impact of contaminants in these zones.

The aim of this work package was to classify water and land from optical satellite imagery (Roth *et al.*, 2015), and thereby delineate the intertidal zone at a variety of tidal stages/water levels. Intertidal zones were identified as those occasionally covered by water in the satellite image time series.

Only summer satellite scenes were selected to limit the amount of sea ice in the fjord and due to daylight limitations in the winter months. Clouds, topographic shadows, snow and ice, are all variables that introduce noise in the classification. These are identified and masked on a scene-by-scene basis and thus do not affect the statistics of the final binary raster. Clouds are identified using the cloud mask provided by ESA. The ArcticDEM (Porter *et al.*, 2018) together with the position of the sun at the time of each satellite scene acquisition are used to simulate shadows. The Automated Water Extraction Index (Feysia *et al.*, 2014) is derived for each scene. Sentinel-2 bands 11 and 8, are used along with the empirically derived thresholds to classify each scene. Pixels classified as snow and ice are masked and remaining pixels assigned to the category of land or water. The result is a scene-by-scene binary raster, where a pixel value of 1 is water and a pixel value of 0 is land.

All binary scenes are mosaicked, and the mean of each pixel are calculated. The resulting raster has a range between 0 (always land), and 1 (always water), where the intermediate pixel values indicate regions of temporary water inundation, i.e. the intertidal zones (Figure 2.2.1). Thresholds are applied to the final mosaiced raster to define the water,

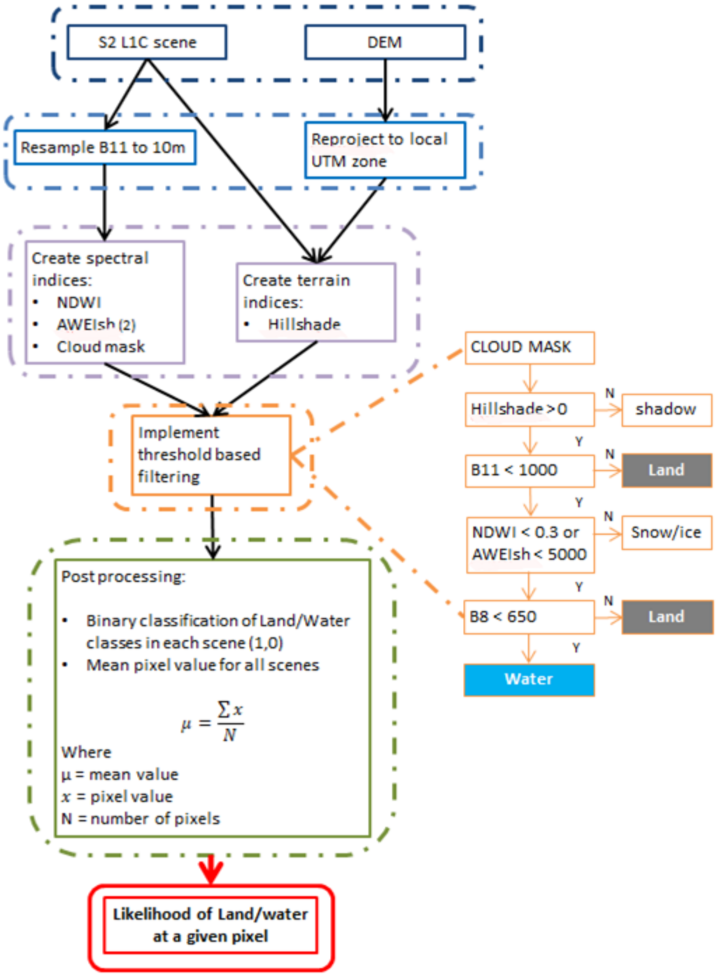


Figure 2.2.1. *Workflow used for determining intertidal zones*

land and intertidal areas. We use scenes acquired at high and low tides to set these thresholds. The results are shown in section 3.2.

2.3 Coastal classification

The main goal of this project is to provide a workflow for the classification of coastal types, with specific focus on its application to oil spill response. Because of this, coastal landforms (i.e. the shape of the coastline) have been a particularly large focus of this work – for instance, boulder size is an important factor in oil spill response (Larsen, 2018).

Coastline complexity index

The coastline was classified according to the coastline complexity index, as described by Bartley *et al.* (2001) which is based on the Angle Measure Technique (Andrle, 1994). 6000 observation points were randomly selected along the coastline from Vega Sund to Danmarkshavn in NE Greenland in order to obtain the coastline complexity measurement. The coastline data set used in this study is a combination of the G100 vector dataset developed by GEUS, and Sentinel-2 and Landsat 8 satellite imagery. Fig. 3.3.1 shows the procedure for computing scale-dependent complexity for each of the randomly selected observation points. For each selected observation point on the coastline (A), the points of intersection between the coastline and a circle with radius (R, centred at A) are identified. The two points of intersection separated from point A by the shortest continuous lengths of coastline are identified, and radii are drawn to them (AC and AB in Fig. 3.3.1). Angle BAD is the supplementary angle (measured in degrees) of angle BAC. This was calculated for R equal to 0.1, 1.0 and 10km. The angle BAD increases with increasing complexity of the coastline, at a given scale. The complexity index was applied to landmasses with a perimeter of at least 6000 m (corresponding to a radius of approx. 1km of a perfect circular island). This restriction was defined in order to avoid overlap in C and B (i.e. R > 180°) along the periphery of an island, or group of islands (see the Archipelago section below for more details).

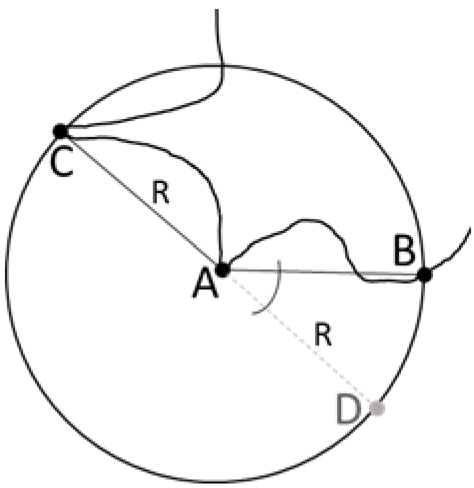


Figure 2.3.1. *Illustration of Coastline Complexity Index*

Supervised classification and post classification

Supervised classification of material in the coastal zone were carried in ArcGIS Pro. Multiband, Very High Resolution (VHR) World View 2 images (approx. 2m resolution) were used to develop the indices NDVI, WV soil index and WV water index for the Vega Sund region, along with an ArcticDEM mosaic of slope and elevation information (8m resolution, Porter *et al.* 2018). In addition, photographs were taken during the field campaign at Ella Ø and in Vega Sund. The VHR, DEM and photographs provided effective training data for the supervised classification, which was applied to two Sentinel 2 colour-matched scenes covering both Ella Ø and Vega Sund.

The supervised classification consisted of eight classes:

1. Fjord
2. Rock
3. Unconsolidated rock
4. Sand
5. Fluvial flood plain
6. Snow
7. Streams
8. Shadows

The result of the supervised classification were subsequently evaluated and re-classified based on the following nine classes:

1. Rock
2. Unconsolidated rock
3. Sand
4. Fluvial flood plain
5. Snow
6. Other geology/vegetation
7. Streams
8. Shadows
9. Unclassified

A majority filter was applied to reduce speckle noise in the final classification, in order to improve the overall visual output and aesthetics.

Archipelago

The archipelago classification is based on a definition of archipelagos from the United Nations Law of the Sea (Preamble, Article 46):

"Archipelago means a group of islands, including parts of islands, interconnecting waters and other natural features which are so closely interrelated that such islands, waters and other natural features form an intrinsic geographical, economic and political entity - the ratio of the area of the water to the area of the land, including atolls, is between 1:1 and 9:1".

Therefore, all islands within this given land-water ratio are regarded as archipelagos (Figure 3.3.2.)

2.4 Field survey methods

To validate the methods and results of the SDB analysis of the sites, we have developed a simple field survey method. This includes echo sounding measurements, tide recordings and photography of surface and coastal geology.

Echo sounding measurements

To validate the output of the SDB models, we measured seabed depths using a consumer-grade, portable Garmin 42dv echo sounder with GPS, mounted on an inflatable boat.

The positioning precision of the echosounder built-in GPS is approximately 3-5m. To increase the horizontal accuracy of the positioning, a survey-grade Trimble GNSS (Global Navigation Satellite System including the US GPS system) receiver ran parallel to the Garmin instrument. Additionally, a fixed Trimble GNSS base station was utilised, thereby increasing the accuracy of the positioning from approximately 1-1.5m down to 2-10cm.

For the Nipisat field site in West Greenland we used the fixed GNSS base station at Asiaq in Nuuk. However, at the remote field sites in East Greenland a temporary GNSS base station was mounted in the local survey area. This data was later reprocessed against the continuous base station at Mestersvig Airport, which is part of the wider geodetic GNET GNSS base station network.

The vertical measurements from the echo sounder were recorded at 1-2 second intervals. It is appreciated that tidal change will cause variation in the vertical measurements, hence this was corrected for at the West Greenland site using a modelled 10-minute tide table from DMI (Danish Meteorological Institute. A temporary tidal monitoring station was established in order to correct for tidal variation at the East Greenland sites, which was active during the echo sounder survey. This tidal monitoring station consisted of a series of tide water measurements probes, calibrated with a spot location on the shoreline measured with a GNSS base station. Mean seal level was derived from this data, which was subsequently used to calibrate the depth measurements from the echo sounder, thereby increasing its accuracy. The refined horizontal GPS positions, along with the refined vertical echo sounder measurements, were used to validate the satellite-derived bathymetry.

Field photography for classification

Photographs were acquired at the East Greenland sites in order to identify sensitive ground surfaces for oil spills and validate the output of the surface classification index. Additionally, photographs of the terrain were collected to assist with the classification of soil and surface types, such as rock, sand, assorted pebble size, and soft/wet areas. Photographs were also taken of the coastline (from the sea) in order to illustrate the ruggedness and smoothness of the coast, which is difficult to discern from satellite imagery alone. Each photograph was geotagged with the camera’s in-built GPS. The location of each photograph is stored in the image file’s EXIF information.

3. Results

In this section, we briefly describe the mapping results produced in the project.

3.1 Satellite derived bathymetry

The derived bathymetry was applied to the entire WorldView-2 satellite image, resulting in the bathymetric map in Figure 3.1.1 for the Nipisat Sund field site in West Greenland. SDB has the advantage of large spatial coverage in shallow waters, which allows detailed bathymetry to be obtained rapidly and reliably. This reduces the reliance on ground-based observations and the health, safety and environmental (HSE).

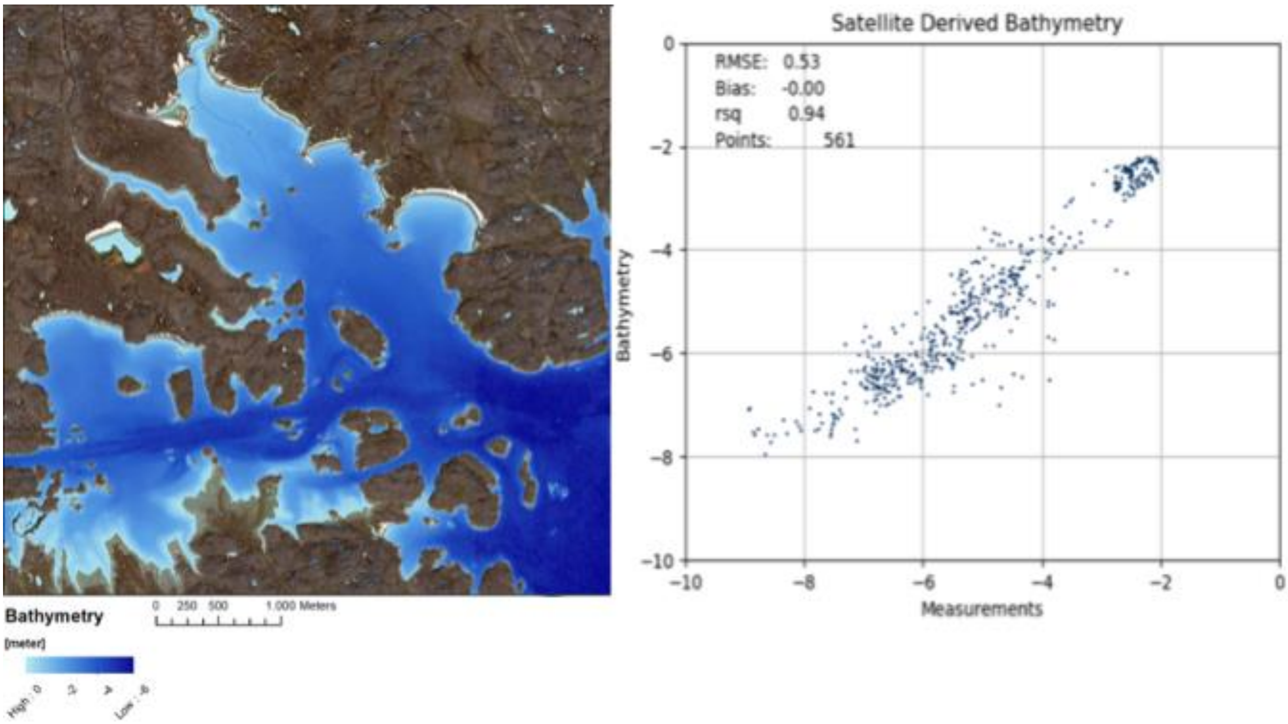
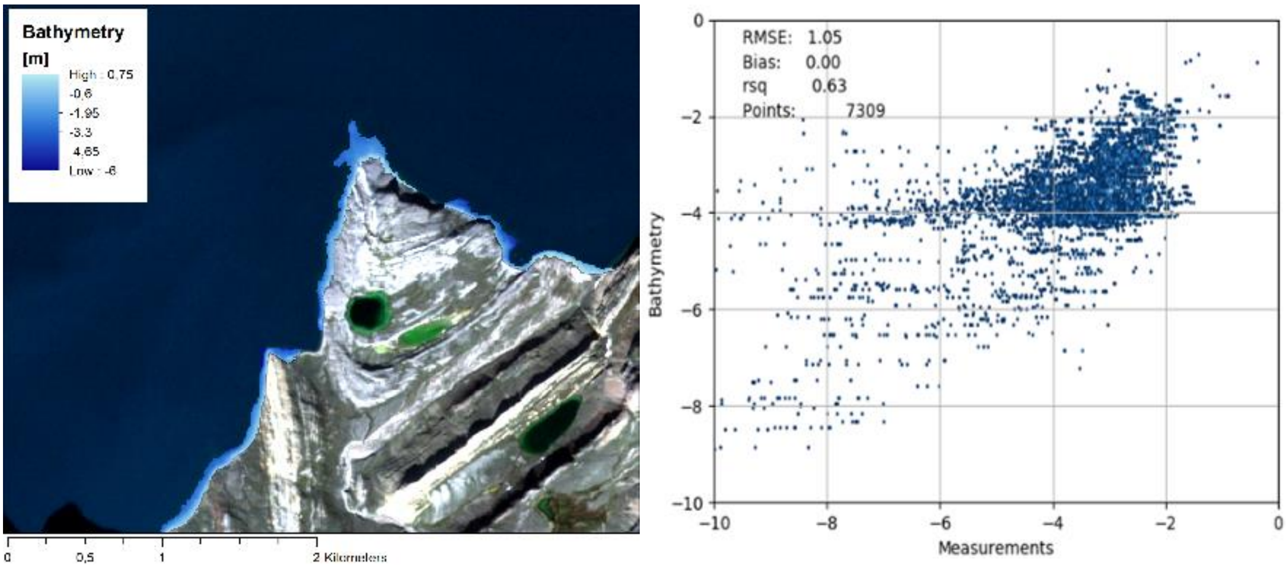


Figure 3.1.1 *- The satellite derived bathymetry overlaid on a true-colour composite satellite image showing the derived coverage in the Nipisat Sund study area.*
Scatterplot of the in-situ bathymetry survey data on the X-axis, and the SDB on the Y-axis for the Nipisat Sund site. The graph shows a strong correlation between the two datasets, with an R-squared value of 0.94. This indicates that SDB performs well when compared to in-situ data.
Source: DHI GRAS

The high correlation between the SDB and the measured bathymetry indicates the SDB performs well within clear water depths of approximately 8m.

SDB's were also produced for Ella Ø and Vega Sund, both the SDB map and associated scatter plot can be seen in Figure 3.1.2. The SDB was applied to the medium resolution Sentinel-2 for the Ella Ø area as no suitable high resolution imagery was available.

Figure 3.1.2 *On the left, an overview of the Ella Ø site and the derived bathymetry. On the right, a scatterplot between the in situ survey data on the X-axis and the SDB on the Y-axis. The correlation*



between the two datasets contains a large amount of scatter. The large scatter is most likely due to the difference in the spatial resolution between the two datasets and the steep slope of the coastline. Source: DHI GRAS

The low coverage and the low correlation seen in Figure 3.1.2 for the Ella Ø site is related to the small number of depths retrieved in the area from the Sentinel-2 data, compared to the high number of in-situ data points.

In many parts of the Ella Ø field site, the 10m spatial resolution of the satellite image does not reflect the variability in the depths measured in-situ. Thus, there is low spatial coverage at the Ella Ø site when relying on the SDB, and two neighbouring points can vary by several metres.

Only the western most area of the Vega Sund was mapped, as this was the only region with overlapping in-situ and SDB, as is seen in Figure 3.1.3.

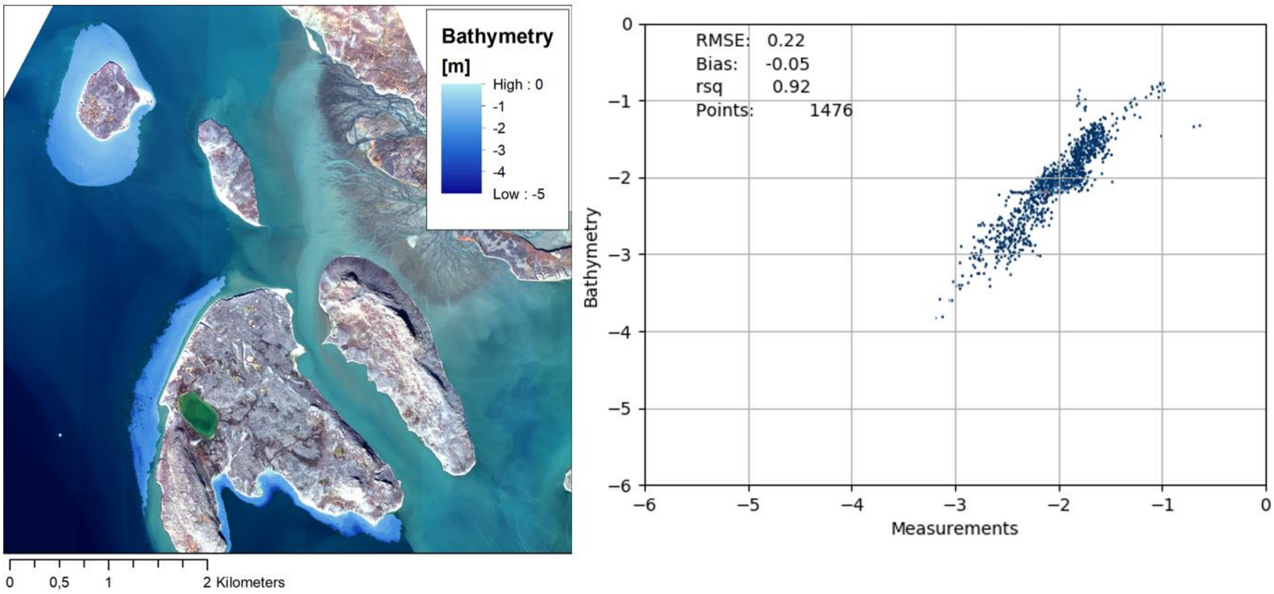


Figure 3.1.3 *On the left, an overview of the Vega Sund site and the derived bathymetry. On the right, a validation scatterplot between the in-situ survey data on the X-axis and the satellite derived bathymetry on the Y-axis. The correlation between the two datasets is shown to be high with an R-Squared value of 0.92, with only minimal scatter. Source: DHI GRAS*

The correlation between the survey and the satellite data in Figure 3.1.3 is high in areas where the water is clear. However, a large part of the water in the satellite image has very high sediment loads, which obscures the seabed and makes SDB impossible. As a result, the areas affected by these sediments have been removed from the dataset. The sediment cover obscured the overlap between the westernmost satellite image and the in-situ data, and therefore the SDB was not extended to the eastern reefs at the tip of Geographical Society Island.

3.2 Intertidal zones

The result of the intertidal zone workflow is a raster showing land (pixel location always classified as land), water (pixel location always classified as water), and areas that have sometimes been classified as land and sometimes as water (Figure 3.2.1). These latter regions, when located along the shoreline, are interpreted to be intertidal zones. A more precise delineation of the intertidal area can be obtained by defining land and water thresholds based on low and high tide scenes.

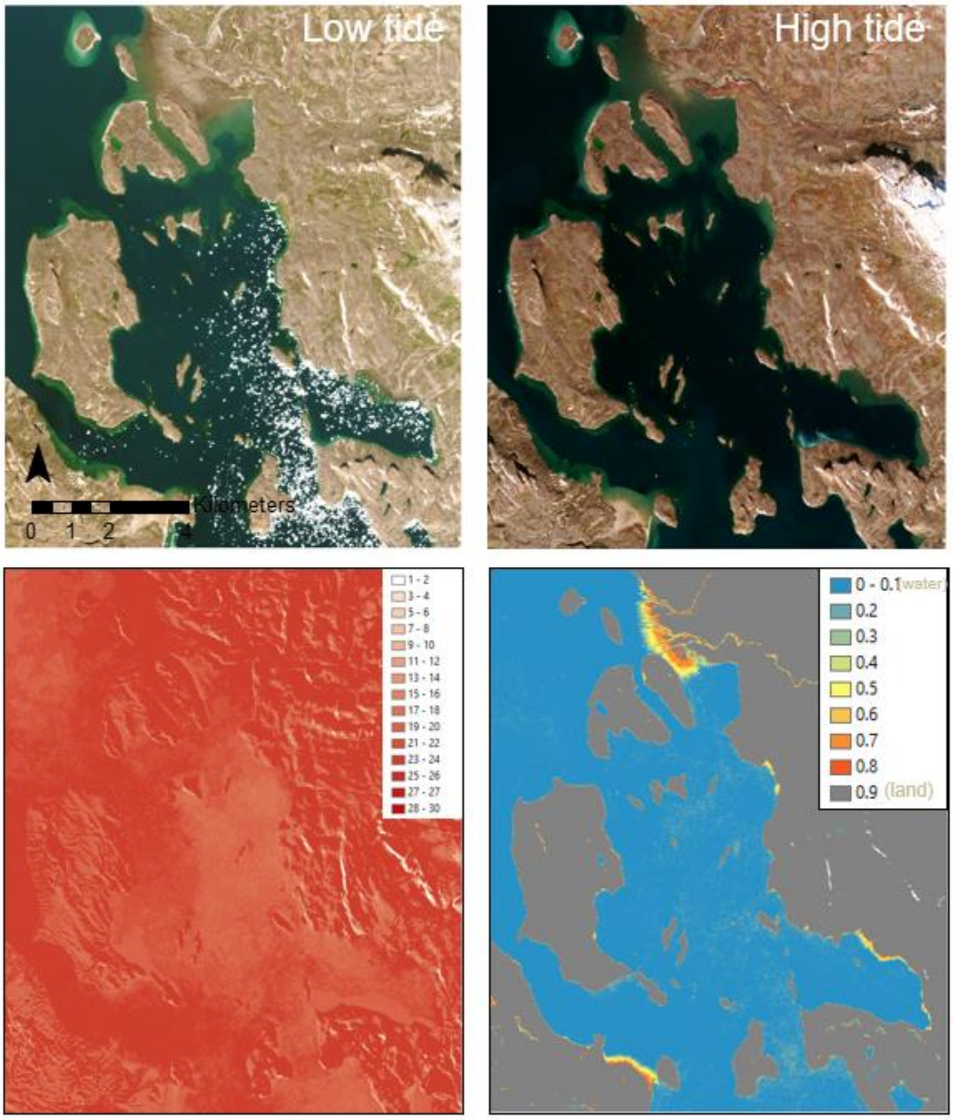


Figure 3.2.1. *Vega Sund region. Upper row: Sentinel-2 scenes showing water coverage during low and high tide. Lower left: for each pixel location, the number of pixels included in the mosaic. Lower right: resulting mosaiced raster indicating areas of land, water and intertidal zones.*

The NE Greenland sites of Vega Sund and Ella Ø have a relatively small tidal reach of about 1m. The Vega Sund area has a number of river deltas that have created shallow deltas along the coastline and which result in narrow intertidal zones at the delta mouths, and in some inlets (Figure 3.2.1).

Around the island of Ella Ø, the steep sided deep fjords resulted in only a few intertidal zones being identified with the satellite imagery (Figure 3.2.2). It was clear during the fieldwork that there are narrow beaches and multiple skerries on the northern central coast of Ella Ø, however the pixel resolution of 10m of the satellite imagery likely hindered the detection of these.

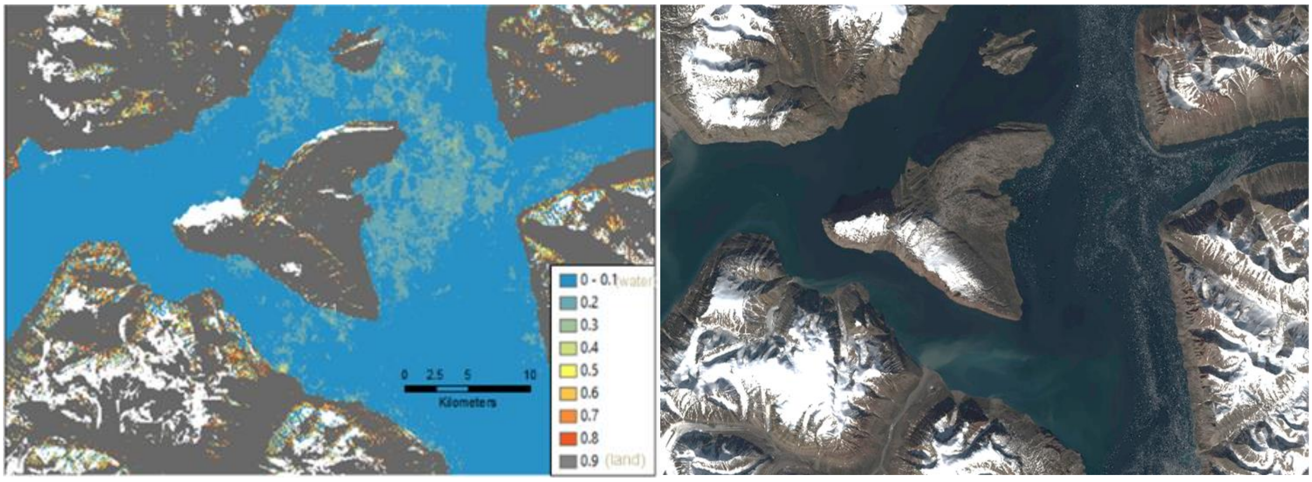


Figure 3.2.2 *Ella Ø site. Left: Mosaiced raster indicating areas of land, water and intertidal zones. Note that sea ice can be misclassified as "land", which can be seen in the central part of the figure. Right: Satellite image of Ella Ø around the time of fieldwork, note the patches of broken-up sea ice visible in the right section of the image (Satellite image: SnapPlanet).*

In contrast to NE Greenland, the test area in Nipisat Sund, Nuuk Fjord, has a much larger tidal range (3-4m). The shallow, gently sloping sound has a larger intertidal zone and numerous small islands that are visible (Figure 3.2.3).

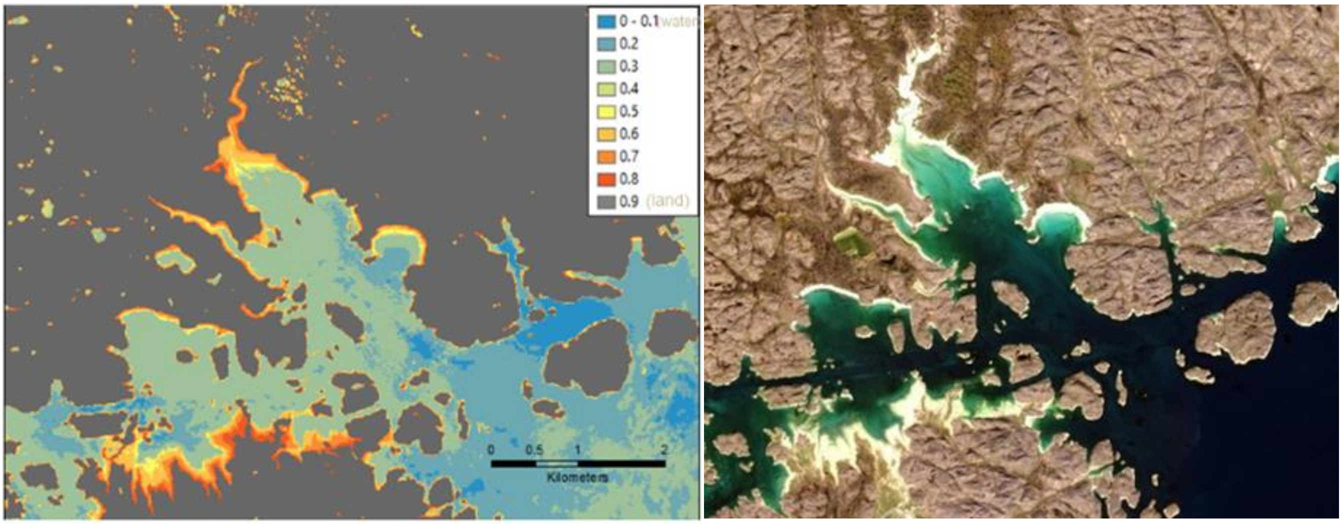


Figure 3.2.3 *Nipisat Sund, Nuuk Fjord. Right: Mosaiced raster indicating areas of land, water and intertidal zones. Left: A satellite image, of Nipisat Sund around the time of fieldwork (Satellite image: SnapPlanet).*

3.3 Coastal classification

Complexity index

To explore the spatial distribution of the complexity of the coastline, a multivariate grouping analysis, and a cluster and outlier analysis was carried out. The grouping analysis showed that 4 groups best represented the variation in the data, but also that the variation was considerable within each of these four groups. This made it impossible to distinguish the four groups statistically at the varying distances (0,1km; 1km and 10km). In the cluster and outlier analysis we found that the spatial autocorrelation was significant, meaning that the areas of high and low complexity are significantly clustered. We used the Anselin Local Moran's I method to further investigate the location of the clustering. In cluster and outlier analysis one very important aspect is to define neighbouring points, since these will be used in the statistical analysis comparing neighbouring observations. For this analysis, neighbourhood distances were calculated to be 2750m using Global Moran's I. The resulting Figure 3.3.1, b, shows clusters and outliers. High value clusters means that high values are surrounded by other high values, relative to each other (pink dots) and low value outliers, where low values are surrounded by high values (dark blue dots).

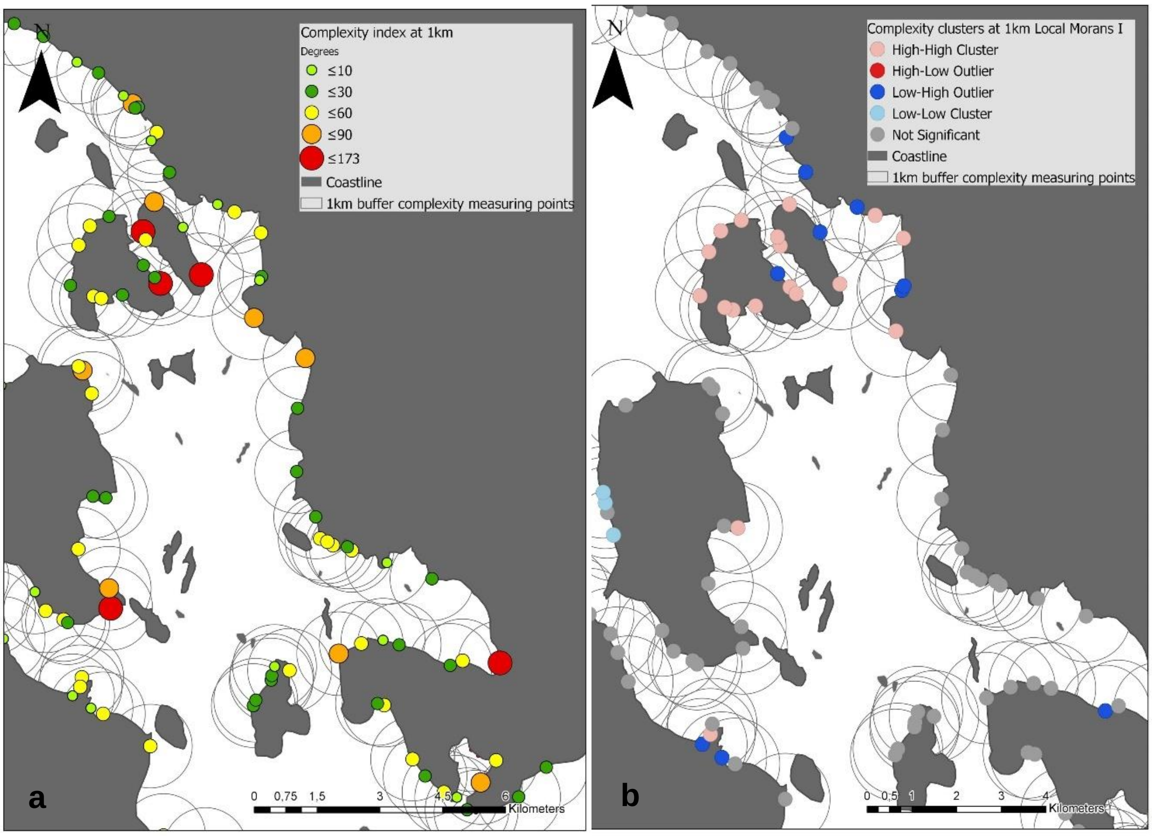


Figure 3.3.1 a & b. *Complexity Index measurements (a) and cluster and outlier analysis (b) in Vega Sund.*

In effect Figure 3.3.1, a, shows the absolute complexity at a defined scale (1km) whereas Figure 3.3.1, b, shows the complexity of each observation relative to its neighbours. In combination these two figures allow us to compare the significance of complexity in the case oil spill emergency response planning, at a regional level.

The complexity index analysis is scale dependant, and therefore the scale selection for the analysis depends on the level of detail needed. For example, in the case of an oil spill emergency response, information on the size and spread of the oil spill would be important factors in selecting the correct scale. It is equally important to determine how much variation exists along the coastline in order to set an appropriate scale for analysis.

Archipelagos

As seen below in Figure 3.3.2, large parts of Vega Sund are regarded as an archipelago. This classification is not excluded, since important information about coastline shape, i.e. complexity index, and coastline content, i.e. surface type information from the supervised classification, can also feed into the oil spill information system.

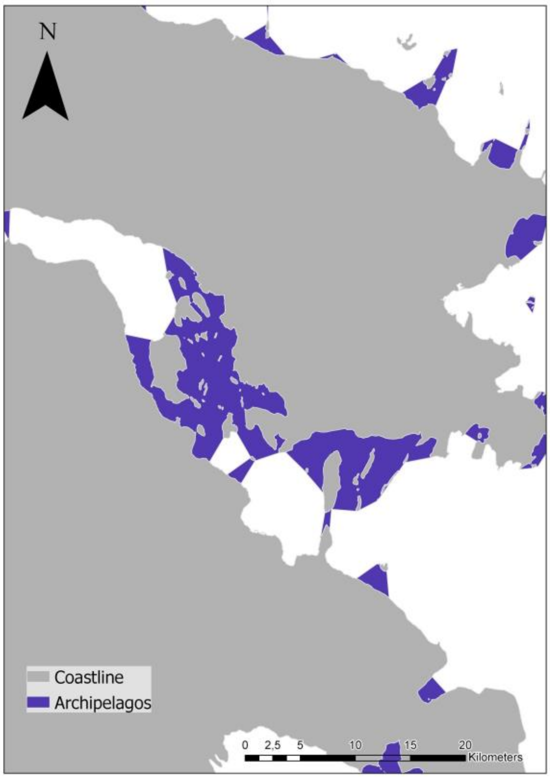


Figure 3.3.2. *Archipelagos defined as group of islands where the ratio of the area of the water to the area of the land is as high as 9:1.*

Supervised classification

Ella Ø has a complex coastline with a variety of coastal types. As seen in Figure 3.3.3 a rocky (and steep) coast dominates the southern side of Ella Ø, whereas much more diverse coastal surfaces are found on the western side of the island. Here a combination of sand, fluvial flood plains, unconsolidated rock and other geology/ vegetation are found. This results in a complex and diverse environment, which is very difficult to clean up in an oil spill response scenario.

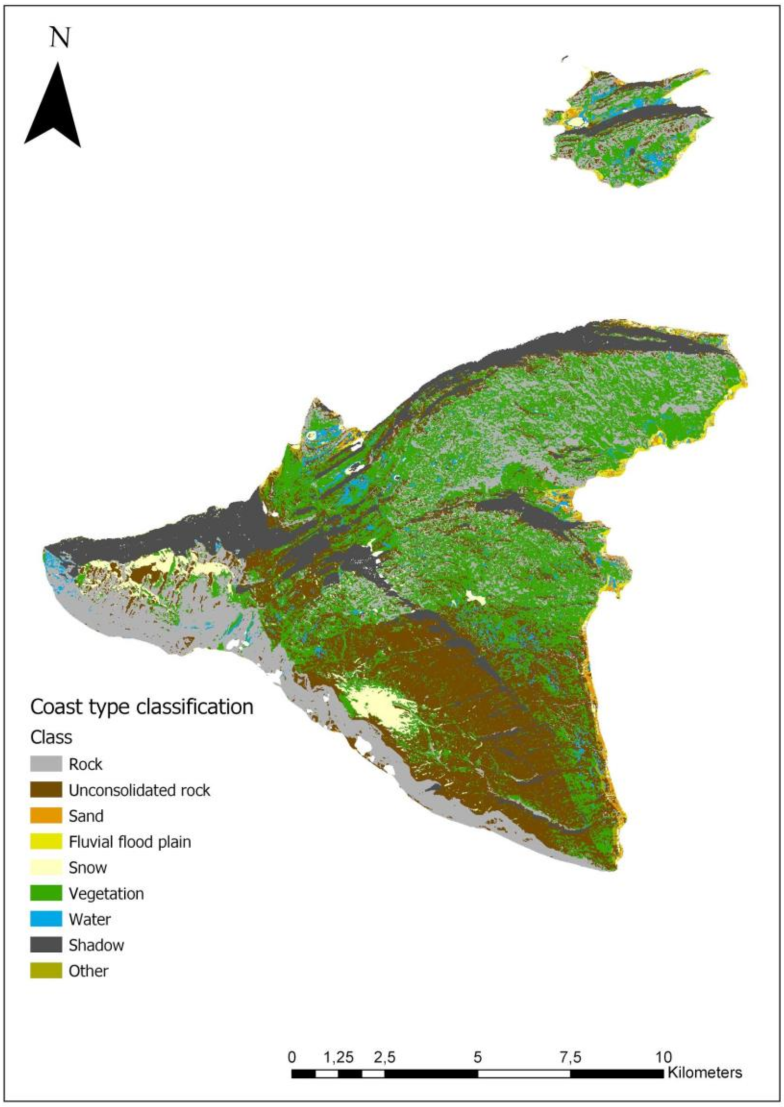


Figure 3.3.3. *Final classification of coastal composition at Ella Ø.*

3.4 Validation

Validation of the supervised classification is important in order to assess the accuracy, plausibility and robustness of the classification. In order to assess the classification, verification photos were taken at the field site, as described in section 2.4. Three example validation photos are shown in Figure 3.4.1.

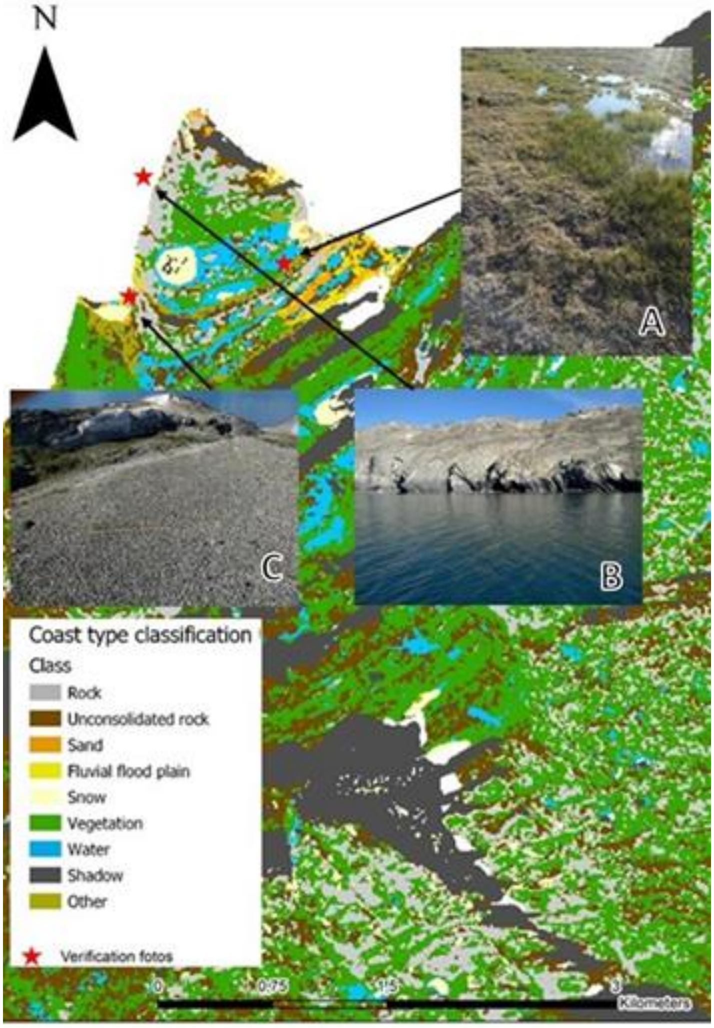


Figure 3.4.1. *Validation of classification, using verification photos. A, shows semi vegetated area, B shows an example of a rocky coast and C, shows an unconsolidated rock beach.*

Photo A in Figure 3.4.1 shows a vegetated area with small areas of clear standing water. According to the classification this location is classified as water. Despite also being vegetated this area is clearly influenced by water. Photo B shows how the rocks directly meet the sea, forming a steep rocky coast, which is also depicted on the classified map.
One challenge when making a supervised classification is that even within each 10m pixel more surface classes are represent. In effect each pixel on the map depicts which of the possible classes is the most abundant within that area of $100m^2$.

Photo C is taken in an area characterised by a loose gravel surface with a certain degree of moisture due to the vegetation. The area is classified as fluvial flood plain, sand, rock and snow. This loose structure of the surface could also be termed as unconsolidated rock. This example demonstrates another challenge with a supervised classification. One has to define classes for classification detailed enough to represent the degree of variation in the environment in question, and at the same time define classes broad enough to end up with an applicable classification for managerial purposes. Thus, the question is how to define robust and applicable class boundaries.

Despite the uncertainties discussed above, the classification generally fits well with the validation photos and a visual inspection of the VHR imagery. For a further quantitative validation to be made, a reference dataset is needed. Unfortunately, such a reference dataset is not available for this study.

A more widespread validation campaign was planned in Vega Sund, however, due to poor weather conditions, only a small fraction of this was carried out. In future studies the planning of validation sampling should take into account sampling area size and spatial distribution relative to the size of the AOI since this will influence the strength of validation data, and overall end product.

3.5 Findings and lessons learned

Many valuable experiences have been gained throughout the entire project; from the ground truthing fieldwork, to satellite data acquisition and data analysis. We hope that these experiences will enable us to adapt our methods for future projects.

The main findings can be listed as follows:

Product	Nipisa, W Greenland	NE Greenland
satellite derived near-shore bathymetry map up to 8 m depth	X	X
intertidal zone map	X	X
coastal complexity		X
eight coastal surface classes		X
robust validation setup (see report)	X	X

Details of some of the challenges encountered in different areas of the project are outlined below.

Challenges in classification

In the classification of the coastal zone we paid attention to a variety of surface material classes. In doing so we encountered some challenges that can be accounted for and avoided in future work. The surfaces we mapped are to some degree influenced by water and other biophysical factors. Since we are working with optical data, the spectral signal variation will vary across the study area. One issue of concern is whether the training areas and validation areas are representative for the variation across the study area, since this will influence the accuracy of the final classification.

Challenges with SDB

In the production of SDB for the study area, the challenges relating to the complicated geography of Greenland became apparent. The high sediment load from melting glaciers obscures the seabed in many areas. This made it very difficult to derive SDB in these regions, as well as limiting the potential extent of the Greenlandic coastline that can be mapped with this method. Another challenge tied into the complex geography is the rapid changes in water depth, caused by the rocky coastline in parts of Greenland. This was highlighted at the Ella Ø study site. In those areas, the

10m spatial resolution of Sentinel-2 data may not be sufficient to accurately represent the bathymetry, and therefore a large scatter is likely to be observed in validation dataset.

Challenges with field work operations

In order to assess and validate the satellite data for bathymetric mapping, intertidal area and terrain classification, in-situ data collection is still currently preferred. The fieldwork carried out in North East Greenland was both expensive and time-consuming. Like all fieldwork in Greenland, it was at times somewhat unpredictable due to difficult weather conditions, localised sea ice conditions and thus lead to some challenges with logistics of the data collection. Whilst the survey team adapted to the dynamic environmental conditions and was efficient in data collection when conditions allowed, nevertheless only a fraction of the original planned data was collected. This highlights the need for a more flexible data acquisition plan for both the ground-based data and satellite data over the study area.

For the in-situ data collection, it is recommended to use high quality instruments, such as a multi beam echo sounder in conjunction with GNSS GPS systems to allow for more complete mapping of the seabed and accurate geographic positioning.

4. Conclusions & Perspectives

As demonstrated during this project, satellite derived information holds an enormous potential for obtaining geo-information for remote and challenging regions, such as North East Greenland. By taking advantage of freely, and/or commercially available satellite imagery, advanced image analysis and local knowledge it is possible to provide a detailed characterisation of the coastal zone in arctic waters. The demonstrated methods have the advantage of being cost-efficient, objective and without the risks associated with traditional survey methods.

The derived map products have all been developed with satellite-based information and are produced with generic and transferable image analysis methods. This facilitates a larger upscaling of the maps to extend the coverage over large and poorly mapped regions of the arctic.

The developed methods and the derived results of the project will be included in the production of Oil Spill Sensitivity Atlases in the Arctic. An important element of the existing Oil Spill Sensitivity Atlases for coastal Greenland, focuses on the analysis of the oil spill resistance of the coast. Traditional analysis is based on manual interpretation of the general coastal morphology and geology from available topographic maps, available aerial photography and low-resolution satellite images, and how these factors determine how oil from a spill will be absorbed by the coastal materials or washed off. In this regard, the information of interest is the predominantly the slope of the coast's terrain, straight coastlines or small beaches, general geology of rock, boulders, pebbles, sand or sediments.

The classification procedures outlined in this study, using medium resolution Sentinel-2 (10m) and WorldView-2, 2 m resolution satellite images, provides the possibility to apply quantitative and automated analysis methods on large image datasets with increased temporal resolution. Additionally, this allows for automated time-series analysis, thereby reducing the biases introduced by traditional manual digitisation methods.

We expect the coastline complexity index, the surface classification and tidal zone products of the analyses to be useful in the preparation of future Oil Spill Sensitivity Atlases. The complexity index can detect straight or contoured coastlines and identify the risk of concentrations of oil in pocket beaches or other complex morphologies. The surface classification can play a vital role in determining the types of geology types that absorb or repel oil.

The tidal zone mapping and SDB would be new features of an Oil Spill Sensitivity Atlas in Greenland. These products have not previously been investigated within the atlas framework. By applying temporal analysis for the tidal zone mapping and novel algorithms for shallow water bathymetry mapping, new critical areas of important marine or tidal habitats that are highly sensitive to oil spills are identified. These highly sensitive areas would otherwise require costly and detailed fieldwork in the remote areas in order to ascertain the same level of detail. To support the infrastructure of operations in the area, the SDB can be utilised for designating possible natural harbours and bays to capture oil residues. This new information would be beneficial to the atlas, as oil spill materials are often saturated into the tidal soils, depending on the geology. Consequently, we recommend the implementation of high-resolution satellite image analysis in the mapping of oil spill sensitive areas and spill removal infrastructure.

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- Joint Arctic Command Head Quarter Nuuk
- Joint Arctic Command Station Daneborg and Ella Ø (Sirius Dog Sled Patrol)
- Joint Arctic Command Station Mestersvig
- Royal Danish Navy, 1. Squadron HDMS Hvidbjørnen (F360)

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Appendix 1: Organization

The project has been conducted by a team of experts, that collaboratively have worked on deriving the presented results in this report.
The team and responsibilities are listed below

Asiaq: Project management; remote sensing analysis and classification of coastal morphology, tidal zones and shallow water bathymetry measurements.

GINR: Coordination of inputs, requirements and feedback with the relevant SEIA scientists of GINR, DCE, and Greenland National Museum; participation in remote sensing classification analysis and setup of channels of data distribution. processing of ground truthing shallow water bathymetry

DHI GRAS: Remote Sensing expertise and sparring on methods of remote sensing classification in the coastal and tidal zone; production of satellite derived bathymetry; quality control and testing of analysis results; provision of commercial satellite data. See more at www.dhi-gras.com

The organizational and financial project setup has facilitated a large degree of knowledge sharing and capacity building between the project partners and its external stakeholders. DHI GRAS - one of the leading global experts within innovative use of satellite remote sensing of the coastal environments and with than 15 years of experience with similar satellite remote sensing studies, has provided specific input and sparring during the project, with the purpose of building up specific remote sensing competences at Asiaq and GINR, which eventually will provide valuable knowledge and expertise for the benefit of a wider group of stakeholders in Greenland.

Appendix 2 Data Distribution

The results of the project are prepared in the ArcGIS software environment, and the project will utilize the server infrastructure of Asiaq to publish the derived maps online. URL to the data is:

Adresse: ftp://ftp.asiaq.gl

Username: coastal_mapping
Password: ea3cb3e769!

Shallow depth bathymetry (SDB) datasets:

- Nipisat Sund: 2m SDB, available as GeoTiff / XYZ file
- Ella Ø: 10m SDB, available as GeoTiff/XYZ file
- Vega Sund: 10m SDB, available as GeoTiff/XYZ file

Appendix 3: Decision tree for final coastal classification

Final classes	**Decision criteria** (Supervised classification, DEM, slope)
1. Rocky coastline	Rocky AND DEM <=20m AND slope >5 Rocky AND DEM > 20m Rocky AND slope >40
2. Unconsolidated rock	Unconsolidated Rock AND DEM <= 10m & slope > 5 Unconsolidated Rock AND DEM > 10m & slope <= 40
3. Sandy coastline	Sand when DEM <= 20m & slope <= 38 Fluvial flood plain when DEM <= 20m & slope >5 & <=34
4. Fluvial flood plain	Fluvial food plain AND DEM < 20m & slope <= 5 Stream AND DEM < 20m & slope > 5 Rock when DEM < 20m & slope <= 5
5. Snow	Snow
6. Other geology/ vegetation	Fluvial flood plain AND DEM > 20m Sand AND DEM > 20m Stream AND DEM > 50m & slope > 5
7. Streams	Stream AND slope <= 5
8. Shadow	Shadow
9. Unclassified	All other pixels