



EMODnet High Resolution Seabed Mapping (HRSM)

EMODnet Phase III

Satellite Derived coastlines for Europe

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Summary

EMODnet Bathymetry, started in 2009, aims to provide overview and access to available bathymetric datasets and to a harmonised digital bathymetry (DTM) for Europe's sea basins. The EMODnet High Resolution Seabed Mapping (HRSM) project is part of the overall EMODnet Bathymetry project and has produced a new additional product: a set of coastlines derived from optical satellite images. This has resulted in three coastlines and a dataset that delineates the inter-tidal areas of Europe. The coastlines are given for the three most commonly used levels, i.e. Lowest Astronomical Tide (LAT), Mean Sea Level (MSL) and Mean High Water (MHW). The inter-tidal area is derived as the area between the coastlines at MHW and LAT. These coastlines and inter-tidal areas have been added as an extra layer in the Bathymetry Viewing and Download service (<http://portal.emodnet-bathymetry.eu/>) which allows users to view these and also to download as digital files in shape format. The layer has also been included in the WMS – WFS service.

Disclaimer

The EMODnet satellite derived coastline is a high-resolution geography data set (polyline) that must be considered as an estimate of the location of the coastline generated from a methodology involving optical satellite data and tidal modeling. Although the generation of the product has been done with the utmost care, both elements of the methodology might locally generate imprecise results leading to an inaccurate positioning of the resulting coastline.

In consequences as user of this product, you agree that:

- EMODnet Bathymetry does not provide warranties of any kind express or implied, about the completeness, accuracy, reliability, suitability or availability with respect to the information, products, services, or related graphics for any purpose. Any reliance you place on such information is therefore strictly at your own risk.
- In no event will EMODnet Bathymetry be liable for any loss or damage of any sorts arising from the use of this data and derivatives.
- The provided coastlines datasets do not serve as replacement of official coastlines as produced by the responsible national authorities. They should not be used where official coastlines are required.

Introduction

A coastline is a delineation materialised by a curve that separates the land from the sea. Since, the sea-level changes over time through tides and the weather, the instantaneous coastline also changes continuously. For many applications it is more practical to use the coastline at high-water, since this quantity is more stable and it reflects roughly what many people intuitively would consider the coastline. There are many different definitions of high-water, but it is common practice to use Mean High Water for this purpose. For territorial claims, it is more common to base these on low-water. For territorial claims it is common to use Lowest Astronomical Tides (LAT) (United Nations Convention on the Law of the Sea, 1994) for this purpose. To stay close to common practice, this report and the derived products will use these commonly used definitions. It will facilitate the comparison to other datasets. It should be noted that the term coastlines is often used in a specific context where there are legal implications, in this context one implicitly refers to the official datasets as produced by the authorities. The datasets described here should not be used for this purpose. On the other hand, the satellite derived coastline described in this report uses a single methodology everywhere, ensuring a uniform generation of this product across Europe and thus can be used to compare with other coastline data. In addition, it can be useful where no other high-resolution coastline is available. Moreover, this methodology can take part from the revisit frequency of the satellites used (e.g. sentinel 2 has a revisit frequency of 5 days) allowing the capacity of frequent updates (in case of coastal erosion or anthropic effects).

This document describes the work related to satellite derived coastline that has been carried out within the EMODnet-HRSM project. The first part of the document describes the methodology for coastline retrieval. The following section presents the tidal correction methodology. Finally the results and the conclusions are presented.

Note: The EMODnet High Resolution Seabed Mapping (HRSM) project is part of the overall EMODnet Bathymetry project which started in 2009.

Methods

The identification of a “coastline” involves two general stages: the first requires the selection and definition of a coastline indicator feature, and the second is the detection of the chosen coastline feature within the available data source. To date, there are different techniques and algorithms for coastline detection. Recent photogrammetry, topographic data collection, and digital image-processing techniques now make it possible for the coastal investigator to use objective coastline detection methods. Some of the methods to be explored further are presented below.

Surface water detection from multispectral images

Existing methods for surface water detection from multispectral satellite data use the fact that water significantly absorbs most radiation at near-infrared

wavelengths and beyond. This fact makes it easy to detect clear water employing spectral indices, such as the Normalized Difference Water Index (NDWI), McFeeters (1996).

$$NDWI = \frac{\rho_{green} - \rho_{nir}}{\rho_{green} + \rho_{nir}}$$

where ρ_{green} and ρ_{nir} correspond to the spectral reflectance of green and near-infrared bands. By design, the index values (similar to normalized difference vegetation index (Rouse Jr et al. (1974)) vary between -1 and 1, with water appearing mostly when the index value is greater than zero.

NDWI has been used to distinguish between land and water (Bayram et al, 2008; Kuleli et al, 2011; Almonacid-Caballer et al, 2016) and, hence, detect the coastline from satellite images. This technique was used for example in Donchyts et al. (2016) to study changes in land cover worldwide. The availability of Landsat satellite imagery allows us to study these coastlines from 1984 until now with a pixel resolution down to 15m. The recent Sentinel-2 satellite mission (ESA, 2016) even go up to a pixel resolution of 10m. Based on these images historic trends in coastal erosion can be detected. Recent work to assess the accuracy of satellite derived coastline trends compared to survey data has shown very promising results for a case study of the Sand Motor mega nourishment in the Netherlands. Similar analysis can be made to derive other coastal parameters such as vegetation (FAST, 2017), sand and human infrastructure.

In EMODnet-HRSM, NDWI algorithm is used to derive coastlines for the European waters, this in combination with a tidal model allows, to retrieved coastlines at different vertical datum (e.g. MSL, MHW, LAT).

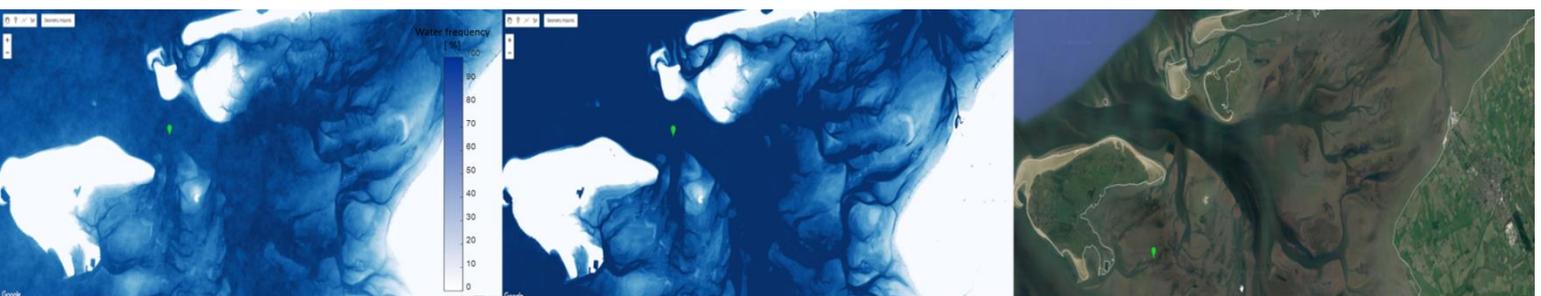


Figure 1 Water occurrence estimated from Landsat 8 and Sentinel-2 images around Nordseeinsel Memmert (Germany), the first image shows the water occurrence computed as a simple mean NDWI value from all images, the second image shows water occurrence estimate using statistical cloud removal method, and the third image the MHW coastline retrieved from water occurrence.

Method for the coastline estimation from optical satellite images

While a single satellite image can be used to detect coastline geometry, a much more robust approach is to combine multiple satellites. This allows capturing not only coastline geometry, but also variations in the coastline geometry due to tidal

water level changes. A number of methods were proposed recently to capture this variation in order to derive inter-tidal bathymetry (Sagar, 2017).

Processing of satellite images at large spatio-temporal scales is a challenging task, due to large volumes of satellite data to be processed, but also, due to variety in the satellite data radiometric properties and formats. In this project, we have used Google Earth Engine platform (Gorelick, 2018) to overcome some of these challenges. The platform allows parallel processing of huge volumes of satellite data in reasonable time and also harmonizes satellite data acquired by different satellite missions performed by NASA and ESA. In this project, we have used a mixture of top-of-atmosphere reflectance satellite images from NASA/USGS Landsat 8 and ESA Sentinel-2 satellite missions, acquired during 2013-2018.

Automated detection of surface water from multispectral satellite images using passive sensor has received significant attention in recent years, Donchyts, 2016 (a), (b), Pekel, 2016. A number of algorithms were developed to make surface water detection fully automatic. The main sources of noise for optical images are:

- a) Clouds and cloud shadows
- b) Shadows due to topographic effects
- c) Atmospheric effects (scattering, aerosols)
- d) Urban areas (complex spectral signal resulting in false-positive surface water)
- e) Snow and ice
- f) Systematic errors (georeferencing and georectification, sensor hardware or software errors, limited radiometric resolution)
- g) Variable thresholds for land/water discrimination when using classical NDWI spectral index
- h) Coastline with a very dynamic morphological changes

To address most of these challenges, we have used statistical methods to process satellite images. In particular, instead of detecting surface water from satellite images using fixed NDWI threshold, the images were processed to represent a probability of land/water boundary, a values close to 1 indicates that a particular pixel is always “wet”, therefore almost sure that location is water. The algorithm shown in Figure 2 was used to process all images from Landsat 8 and Sentinel-2 missions covering EMODnet project area.

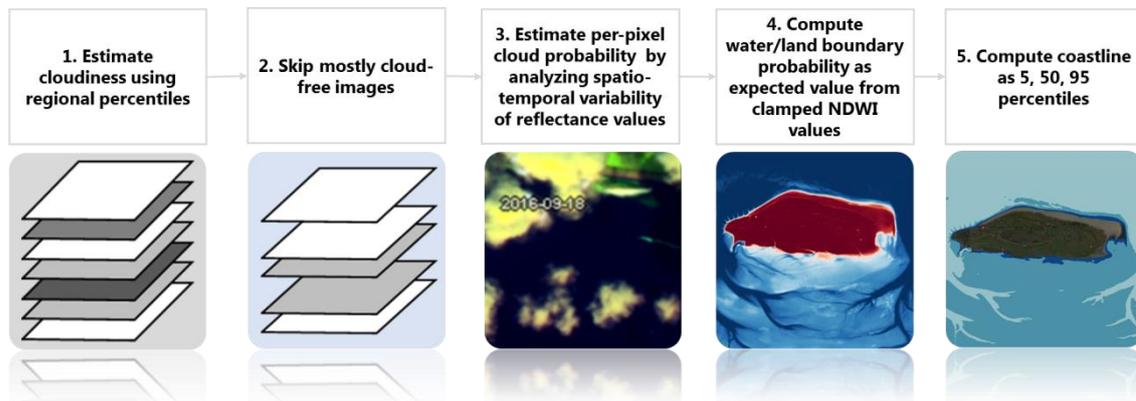


Figure 2 Processing pipeline for coastline detection from optical satellite images, capturing intertidal water level changes

Instead of performing a direct cloud masking for every image, our algorithm first “learns” the overall distribution of reflectance values within observed over every pixel as the first step. Then, a cloudiness metric is introduced for every image covering the area where potential coastline boundary is expected to be located. This metric is then used to filter-out images mostly covered by clouds. Then, a more robust per-pixel cloudiness probability is computed by comparing its values with the spatio-temporal distribution with a small neighbourhood around every pixel. The resulting cloudiness probability is used to estimate the final water occurrence, computed as the weighted average, using cloudiness as weights. The final water occurrence is used to estimate the coastline geometries.

After assigning cloudiness metric for every image (patch/tile), the algorithm uses mean cloud frequency estimated by Wilson, 2016 to determine the number of images to skip, significantly reducing noise in the resulting time series, Figure 3. For northern regions (The Netherlands, UK, Germany, Sweden, Finland), the mean cloud frequency is relatively high (~60-80%), resulting in only a fraction of satellite images can be used for processing. While this can be an issue for the analysis covering short periods, we were able to overcome it by using all of the available images acquired during 2013-2017.

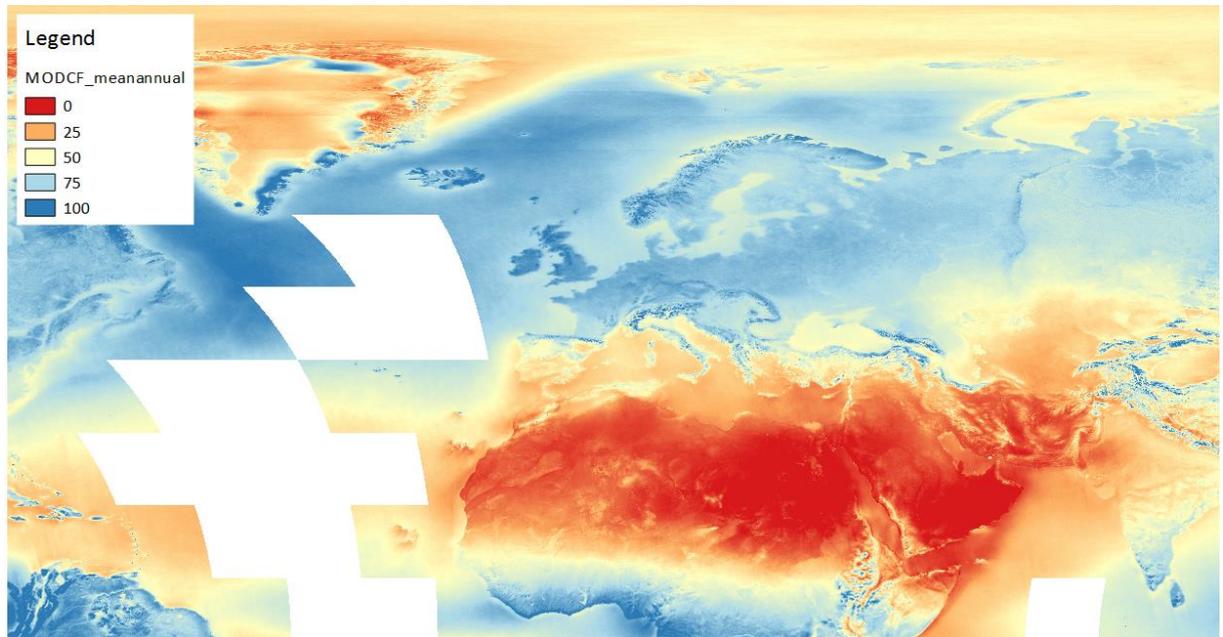


Figure 3 Cloud frequency (0-100) used during step 2 of the algorithm

The Figure 4 shows the final water occurrence estimated using the method outlined above. This spatial resolution of this water occurrence varies between 10m and 30m, depending on the number of Sentinel-2 and Landsat 8 images available for a given area and cloud conditions.

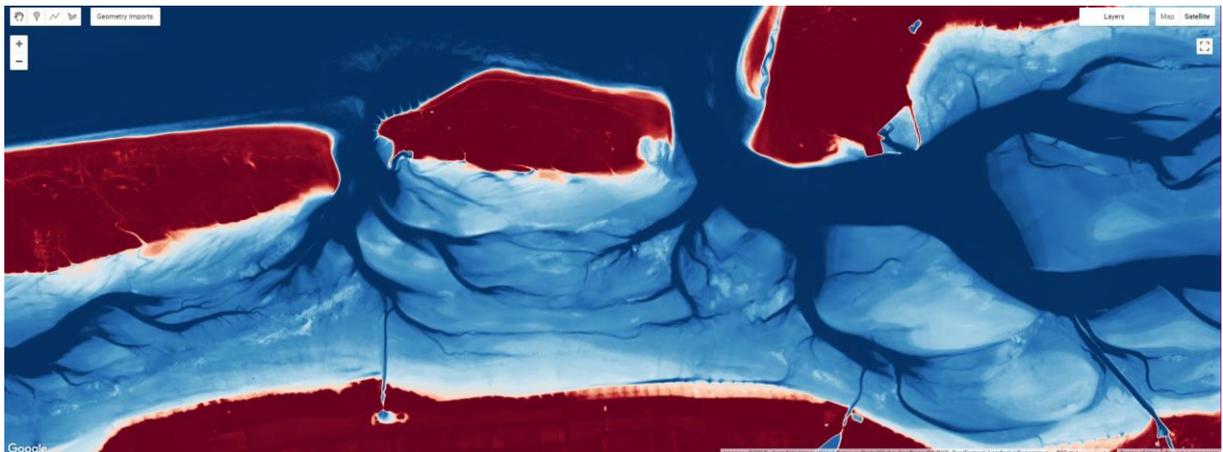


Figure 4 Water occurrence computed as expected value from all NDWI values, using per-pixel cloudiness values as weights (dark blue = permanent water, red = land).

Linking water occurrence to tidal level

In the introduction the coastline was defined as the physical interface between land and water, but this is also the most dynamic part of the coastal zone. Although much of the published literature have studied the problem of coastline position from multispectral images, only a few papers have addressed the problem of mapping the tide coordinated coastline.

Because of the dynamic nature of the ocean waters and of the near coastal lands we introduce the definition of an instantaneous coastline to point out that line position is relative to a given instant of time (Li et al., 2002). Thus, the coastline needs to be defined in a stable vertical datum in order to be used as a reference coastline. If this vertical datum is defined as the linear intersection between the coastal surface and a desired water tidal level, the coastline is called tide-coordinated coastline (Li et al., 2002).

The tidal amplitudes are often amplified near the coast, while at the same time the spatial variability increases because the tidal wave propagation slows down in shallow waters. Tides are small in some regions, but can also reach extremes of 13 meters in the Bristol Channel or 12.3 meters in Bay of the Mont Saint Michel, for example. Traditionally, corrections for local sea level have been computed from local tide gauges or tidal forecasts. On a global scale the number of permanent tide gauges is not sufficient to interpolate to arbitrary locations. At the same time, satellite-based altimeter observations of sea level do not have a sufficient temporal and spatial resolution to be used directly for correction of dynamic variations of the sea-level

In this project, the correction for sea level variation is based on use of the Global Tide and Surge Model (GTSMv3), which provides instantaneous water level and tide levels with global coverage. To ensure sufficient resolution near the coast, an unstructured grid model is used (Irazoqui et. al. 2018 and Kernkamp et. al. 2011).

As the accuracy of the coastline position extracted from satellite images depends on the range of tidal height at the satellite overpass time (Yu et al., 2011), it is important to link to the tidal height at the time of image acquisition. The availability of GTSM tidal information allows retrieving water level at any time and location and compute satellite derived coastline to a coordinated tide level. The availability of the conversion between these vertical reference frames makes it possible to connect data-sets using different vertical reference frames, and conversion to a reference frame of choice for the user. The schematization of the vertical datum referencing process is shown in figure 5.

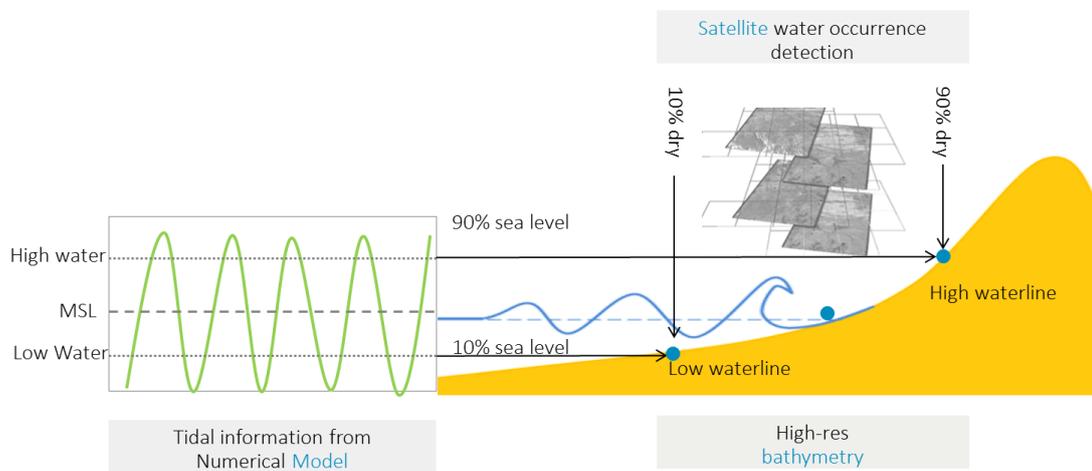


Figure 5 schematization of the vertical datum referencing of satellite derived coastline

Instead of linking to the water level for individual images we used the distribution of water occurrence and the distribution of the local water level to link both. Unfortunately, there was too much noise in the images near the extreme values of the water occurrence distribution, so we had to limit the levels to within the 5% to 95% range. The value of LAT is almost everywhere at a level of more than 95% water occurrence. In the end, it was decided to link LAT to 95%, MSL to 50% and MHW to 95% for the first version of this satellite derived coastline, to describe the maximum tidal range attainable at this time. Future work will aim at more accurate representation of MHW and more extreme levels. The water occurrence grids were contoured on a tile by tile basis.



Figure 6 Coastline polygons for MHW, MSL, LAT estimated as 5%, 50%, and 95% percentiles of water occurrence images.

Validation and example

Because satellite images are acquired only every several days, we assume that over multiple years, the distribution of the actual water level values during image acquisitions converges to the actual distribution of water level values, which usually vary due to tides and surges. The figure 7 shows the actual image acquisitions by Landsat 8 and Sentinel-2 satellite missions combined with water level time series measured at one of the stations at the North Sea, Terschelling. As can be seen from the figure 8, on a longer run, the distribution of the water levels, measured during overpasses of the satellite images, approximates the actual water level distribution fairly well. However, there are some systematic spatially varying errors caused by the sun synchronous track of the Landsat 8 and Sentinel 2 satellites and accurate coupling of the instantaneous coastline to tide level should take this into account.

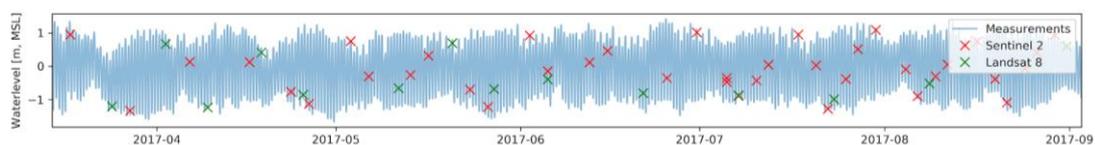


Figure 7 Water level values and times of images acquired by Landsat 8 and Sentinel-2 satellites.

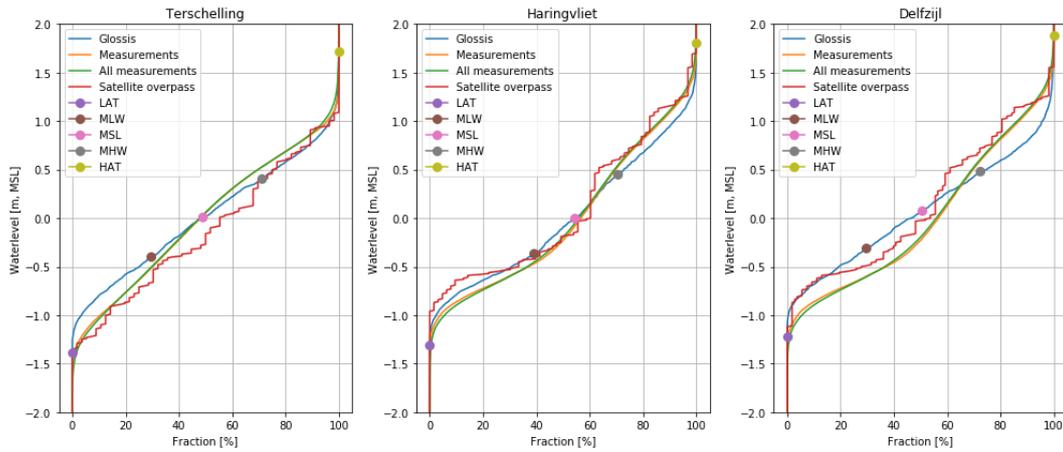


Figure 5 Comparison of different water level distributions for values measured at the monitoring station, computed by hydrodynamic model, and restricted to times of satellite overpasses

Next we compare scaled mean NDWI to LIDAR measurements for a small area at the eastern tip of Ameland Island in the Netherlands. Figure 8 shows the comparison. We performed similar comparisons for various regions, mostly with similar results.

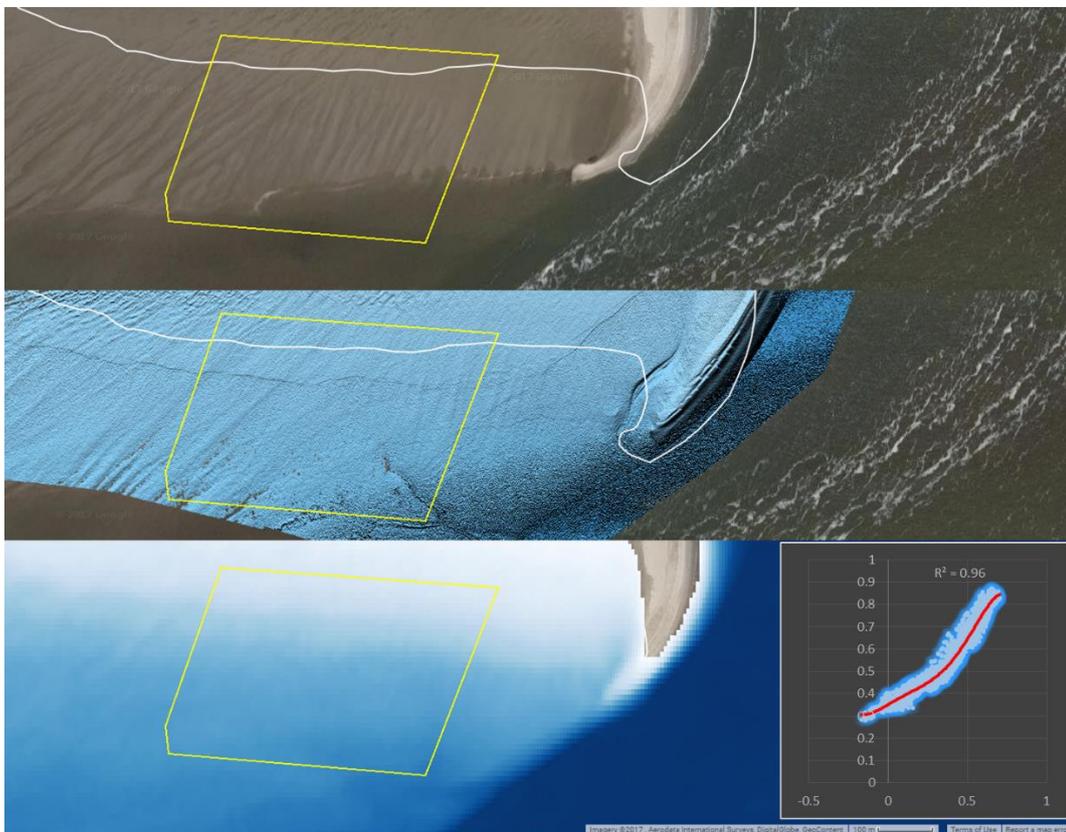


Figure 6. Top panel shows Google base image. Comparison of high-resolution (0.5m) LiDAR DEM (middle panel) to water occurrences or scaled mean NDWI (middle panel) and scatter diagram for the highlighted area.

Post-processing and generation of final products

After land-water detection and contouring, as described above, there are still several steps needed to produce a final set of products. First the data needs to be exported from the Google Earth Engine (GEE). Next, we need to remove water that was detected, but where we do not consider it to be part of the coastline. Then we compute the inter-tidal area as the area between the low water and high-water. Finally, we need to merge the data, since this is computed and exported in GEE, in many rectangular tiles.

Export of polygons per tile

After processing optical satellite data to the level of polygons that together cover the water as detected, we exported the data. Since the GEE computations were organized in small rectangular areas to facilitate parallel computation, this resulted in a large number of files. The figure below gives an overview of the division into tiles. Each tile has an ID, i.e. the number also shown in the figure. For efficiency, the tiles that consist entirely of land or entirely of water were excluded from the computations in GEE. After the export, we added these back into the dataset.

There were several challenges encountered, that resulted in a few gaps in the final collection of tiles:

- First, regions in the far north were too often covered in snow and ice, which was aggravated by poor lighting at these high latitudes. This proved too difficult to resolve with current techniques. We therefore omitted Greenland and Svalbard from the coastline estimation. In the far north-western part of the domain, mainly Iceland and the Faroe Islands, the satellite data was too limited by clouds and poor lighting to estimate the coastline at low-water, but results were good at MSL and MHW. We resolved this in the final dataset by replacing the coastline at LAT, with the coastline at MSL here.
- In a few tiles, the computation at GEE was stopped initially and did not produce output as different filters need to be applied to the data. We did not manage to resolve this issue before finalizing the coastline dataset. It should be possible to resolve this in the next version.

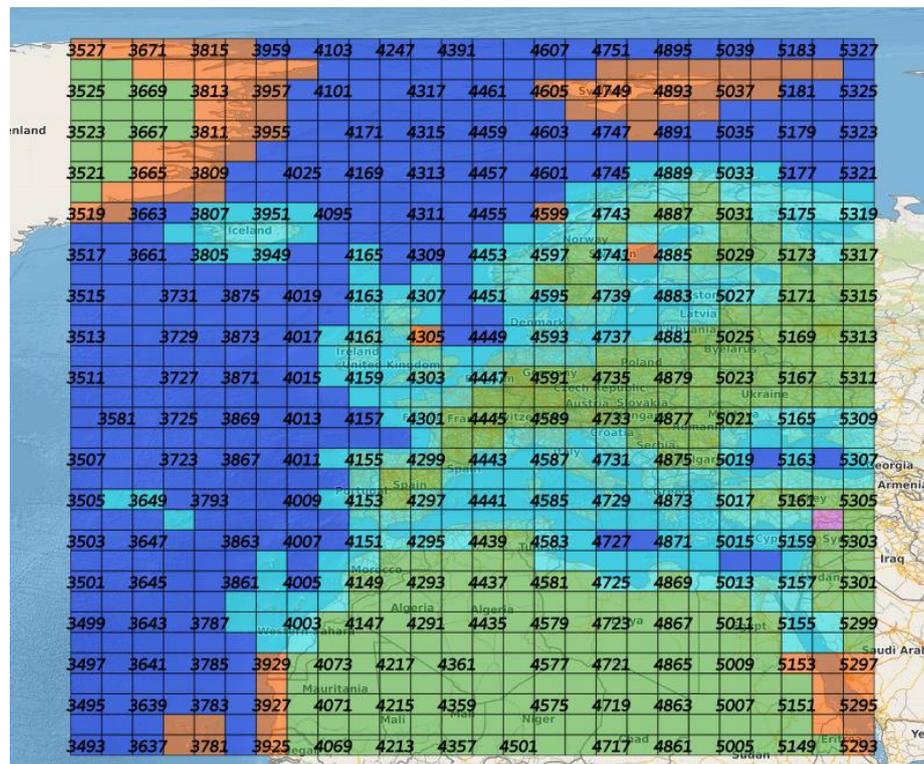


Figure 9. Tiles exported and their status: land only (green), water only (dark blue), part land/part water (light blue), data incomplete (orange)

Filtering lakes

The water detection algorithm does not distinguish between fresh and salt water, resulting in many lakes and other surface water to appear that are not considered to be part of the coastline. It may not be possible to create a clear separation in all cases. The aim of the processing step described here is to eliminate smaller water-bodies that are not connected to open sea. This eliminates many features. We have designed the filtering procedure and threshold to be conservative, i.e. not to delete water-bodies that might be part of the coast line. This implies that the data-set will contain water-land boundaries that we would not consider to be part of the coastline.

The figure below shows part of the Netherlands before and after filtering of small disconnected water-bodies. It can be seen that the North Sea Channel connecting the harbour of Amsterdam to the North Sea is connected to the North Sea in this data-set, but in reality there are sluices near the coast, that separate the water in this channel from the North Sea. Apparently the sluice gates were not detected from the satellite images. In the current version of the satellite derived coastline we have kept these features. In future versions, we may remove the most important internal waters manually.



Figure 7 Example of images before (left) and after (right) after filtering water bodies that do not belong to the coastline

Computation of inter-tidal areas

To compute the inter-tidal area we have computed the set-difference of the area covered at high-water minus the area covered at low water. The figure below gives an example for a part of the Wadden Sea (Netherlands). In the final dataset the parts for each of the tiles were merged into one dataset.



Figure 8 Inter-tidal area (Orange color), computed as set-difference of water at high-water and at low-water

Conversion to Europe wide coastline

Finally, the parts of the coastline per tile were converted from filled-polygons to poly-lines. Figure 9 illustrate the SDC plotted as a line.

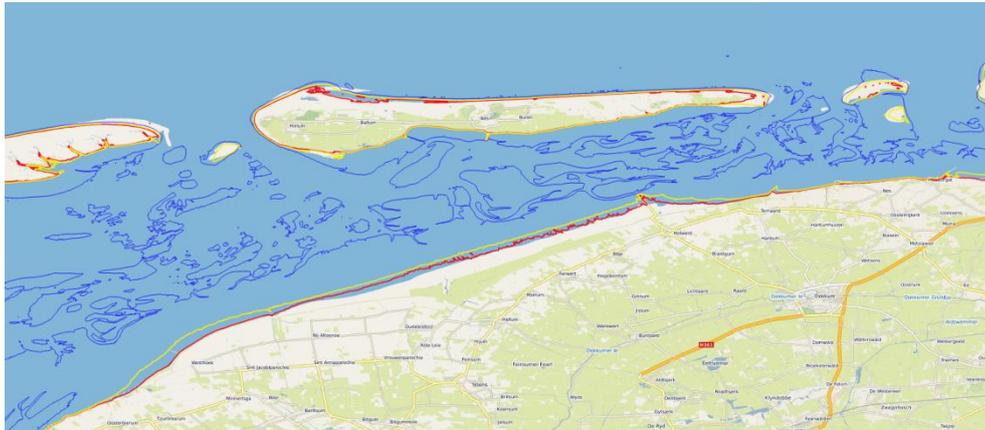


Figure 9 Plotted coastline as poly-line format (Final product delivered)

Coastline comparison

This section presents a visual comparison between the Satellite Derived Coastline (SDC), the coastline derived from Open Street Maps¹ (OSM) and the coastline provided by EMODnet project partners.

The OSM coastline has been derived from Open Street Map ways tagged with `natural=coastline`. This data contains all the detail available in OSM. For small scale maps (small zoom levels) it might be too detailed and therefore slow to use and not well readable. The OSM coastline projection is in WGS84 (EPSG:4326) or web Mercator (EPSG:3857). The coastlines can be obtained as lines and/or land polygons and/or water polygons.

Within the EMODnet-HRSM project, one task was to gather official coastlines for the European waters. Information about coastline has been gathered per country, the data comes in different coordinate systems and at different spatial resolutions. This data set is also used for the visual comparison and we will refer to it as “Official Coastline”.

The visual examination after the retrieval process showed that the SDC coastline is generally in good visual agreement with OSM and the official coastline. The comparison suggests that the discrepancy between the SDC and the other data sets remains within the pixel size in sandy beaches. This comparison therefore bodes well for future attempts to detect coastline changes of larger magnitude than the pixel resolution (10 m).

There are areas where there is a bigger discrepancy between the SDC, OSM and the official coastline. For example, in areas under land reclamation or human intervention the coastline changes rapidly over time. Resolution and accuracy of OSM coastline is variable since it is the result of many contributions by many people

¹ Coastline in OSM is defined as the mean high water spring line between the sea and land (with the water on the right side of the way). https://wiki.openstreetmap.org/wiki/Map_Features

and from many sources. In the other hand updates in the official coastline might not be as fast as the changes due to human interventions. To illustrate this example we present Figure 10. The figure shows Luka Ploče in Croatia, where SDC gives a more detailed contour of the Port in that area.

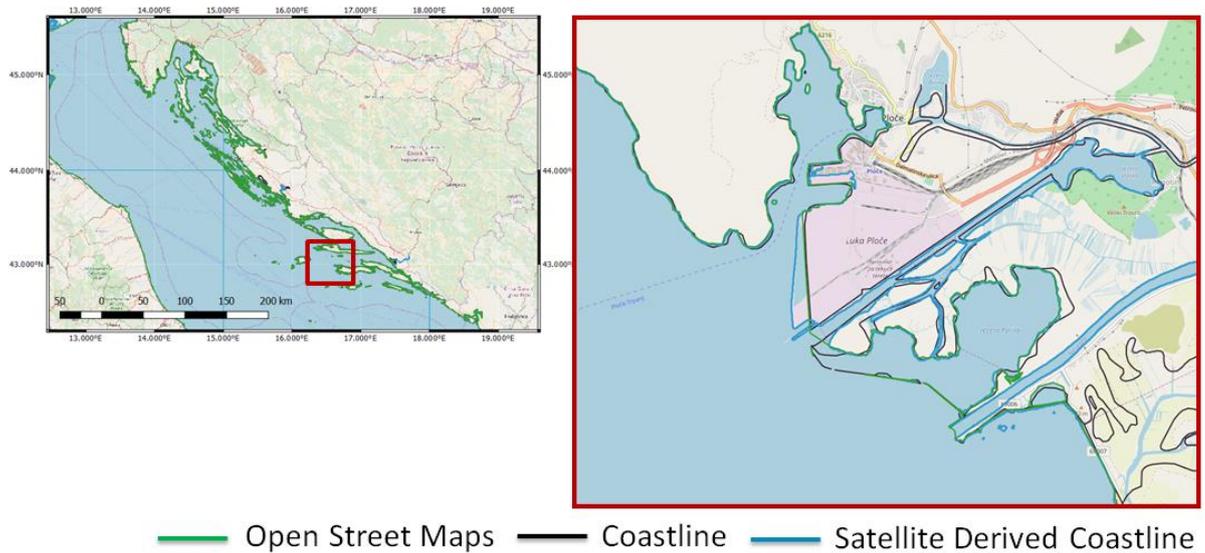


Figure 10 Croatia (Luka Ploče): comparison between SDC (high water), OSM and coastline from official sources

The fact that the biggest discrepancy while comparing the coastlines were consistently observed at intertidal areas, indicates that the current tide level, possible effects of storm surges and the beach slope, play and important role. Figure 11 present the comparison between the different coastlines in an intertidal area. The chosen case is situated in the Netherlands. Terschelling is one of the islands situated in the Wadden Sea. This area is the largest unbroken system of intertidal sand and mud flats in the world. Morph dynamics is very active here, so coastline changes rapidly. The beach is also very flat, so that small differences in approach lead to large spatial differences. The difference between the SDC, the OSM coastline and the official coastline can reach a difference up to 650 meters.

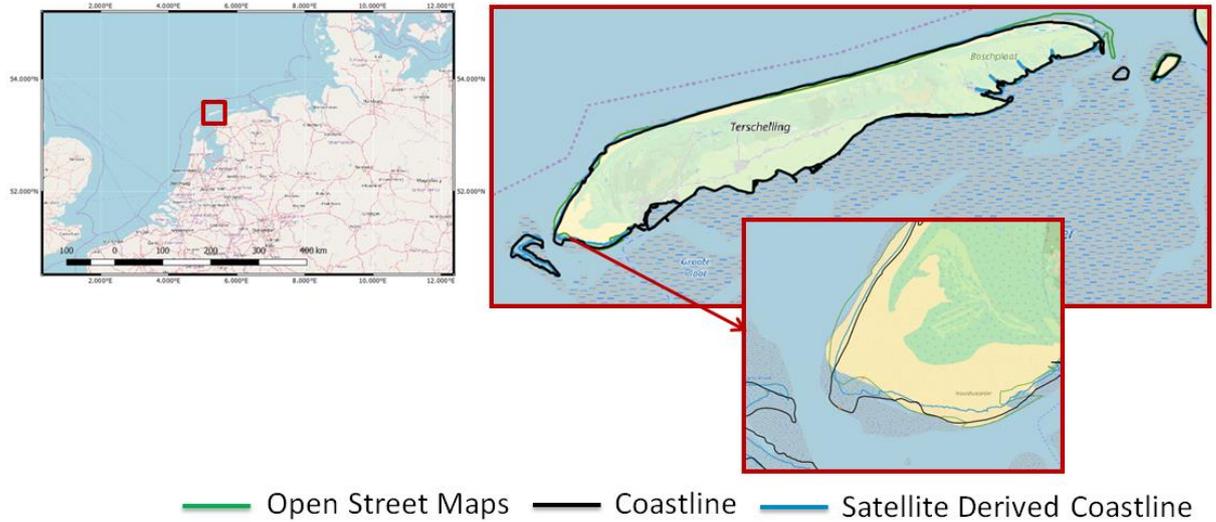


Figure 11 Netherlands (Terschelling): comparison between SDC (high water), OSM and coastline from official sources

Coastline has been defined as a line that forms the boundary between the land and the ocean. Nevertheless are some regions that line cannot clearly be established. Precisely in those regions, the discrepancy between the SDC, the OSM coastline and the official coastline tend to increase. Figure 12 present a peculiar case in Portugal (Aveiro) where SDC provide more detailed information that OSM and the official coastline.

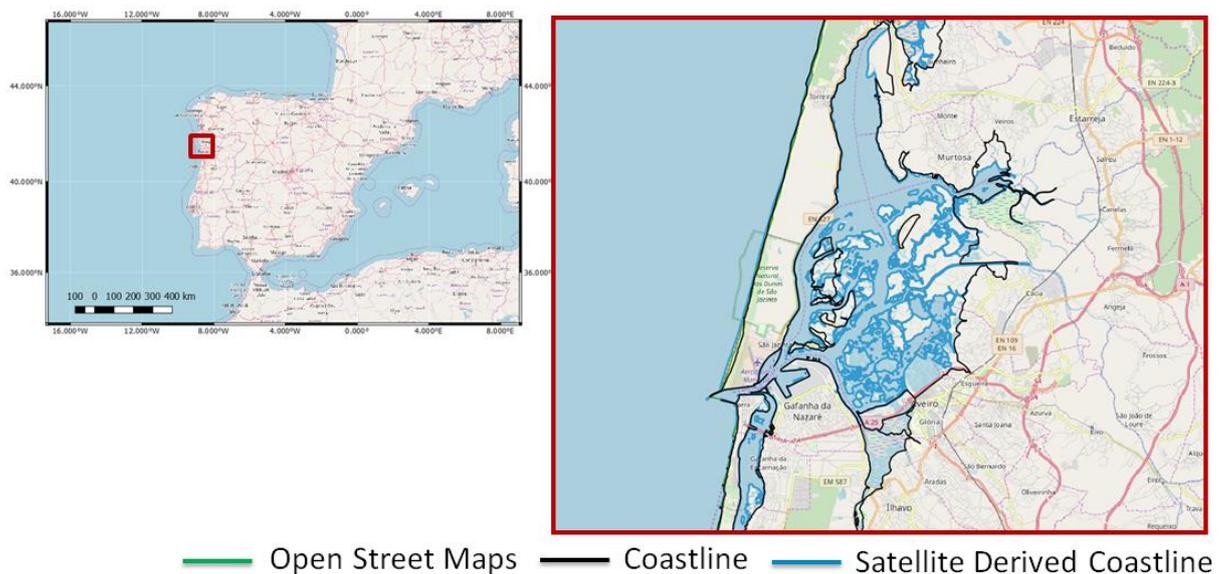


Figure 12 Portugal (Aveiro): comparison between SDC (high water), OSM and coastline from official sources

Conclusions and recommendations

In this report we described the methods used to derive a coastline from optical satellite imagery. In comparison to other sources, the coastline retrieved from satellite images shows good agreement in most areas. It is consistent with the Open Street Map (OSM) and the official coastlines, giving confidence that the interpretation of different positions of SDC shows a real representation of the coastline at different datum. Nevertheless there is room for improvement in the retrieval process; those main issues are listed below

- More attention is needed for the snow/ice problems, as this made coastline detection impossible so far for Greenland and Svalbard. One option is combining with other sensors, for example Sentinel-1
- We did not succeed so far to detect the coastline at low-water for Iceland and the Faroe islands. Perhaps the very high cloud cover and poor lighting conditions are to blame. This needs further investigation.
- NDWI is not robust for very turbid water, and extend analysis to use MNDWI and maybe other indices to improve quality for these regions (in particular, UK) is needed
- A further exploration and improving of the algorithm in urban areas is needed.

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Annex – digital satellite derived coastlines and intertidal areas

The satellite derived coastlines and dataset that delineates the inter-tidal areas of Europe as determined and described in this report are available for viewing and for downloading as digital files in shape format. Therefore these coastlines and intertidal areas have been added as an extra layer in the Bathymetry Viewing and Download service (<http://portal.emodnet-bathymetry.eu/>). The coastlines are given for the three most commonly used levels, i.e. Lowest Astronomical Tide (LAT), Mean Sea Level (MSL) and Mean High Water (MHW). The inter-tidal area is derived as the area between the coastlines at MHW and LAT. The extra layer is also included in the WMS-WFS service.