Coastal Erosion from Space

Final Report (April 2019 to September 2022)

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ARGANS

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Acronyms

BGS	British Geological Survey
CESBIO	Centre d'Etudes Spatiales de la Biosphère
ESA	European Space Agency
EO	Earth Observation
FTP	File Transfer Protocol
GSI	Geological Survey Ireland
HR	High Resolution (EO data)
IHC	Environmental Hydraulics Institute, IH Cantabria
ISPRA	Italian National Institute for Environmental Protection & Research
KO+#	Kick Off (+number of months (#))
LPS	Living Planet Symposium
LULC	Land Use Land Cover
MoM	Minutes of Meeting
MS	Milestone number
PM#	Progress Meeting number
PVP	Product Validation Plan
RBD	Requirements Baseline Document
SAR	Synthetic Aperture Radar
SDB	Satellite Derived Bathymetry
TO	Technical Officer
TSD	Technical Specifications Document
URD	User Requirement Document
VNIR	Visible and Near-Infrared
VHR	Very High Resolution (EO data)
WP	Work Package

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Executive Summary

HTTPS://coastalerosion.argans.co.uk

The purpose of the Coastal Erosion Project was to raise the societal profile of EO derived products, and the professional profile, i.e., to push for the adoption of EO products as a coastal survey means by field surveyors and their patrons (the coastal management authorities, at the international, national, regional or local level, and their civil engineering contractors) as well as by scientists (i.e., the wider community). At the conclusion of the 2-year project an additional years Contract Change Note was awarded, and this report is the summation of the 3 years of development and production. Having designed and updated all the products it was then vital that a validation process could assure users of the accuracy and utility of the derived product set. In fact, over 4000km of coastlines were observed across 21 differing sites to demonstrate that the innovative techniques developed are truly scalable worldwide. The sites chosen were not selected to be easy, but to see what earth observation could provide and this in turn meant we occasionally had to seek out value in novel ways.

What also became clear very early in the project, based on the user requirements being collated from the numerous stakeholders, was the need for multi temporal sampling of the shoreline before and after each event at least quarterly, to avoid aliasing the time-series and confusing temporal erosion for structural on-going erosion. Indeed, this requirement featured heavily within the CCN leading to a bespoke cloud filtering by a new coastal polygon process being developed using the Copernicus API which was supplied via the ESA Network of Resources system. All products have been validated and independent validation papers have been released by each participating nation (Jeagler and Dufresne, 2021; Martinez Sanchez and Gomes da Silva, 2021; Monteys et al., 2021; Payo et al., 2020). Another key tenet identified throughout the initial contract and delivered within the CCN was the need for longer, smoother (interpixel) more continuous waterlines and as a consequence of this requirement the waterline processor has been completely refactored whilst maintaining and improving the adaptive threshold technique for automatically assigning the sea/land boundary.

The outcome is that continuous shorelines can be mapped over decades using the Sentinel and Landsat Mission data to a degree of accuracy that enables changes associated with seasonal variation, storm events and long-term shifts to be monitored confidently and reliably as shown by the validation results.

The ability to derive this analysis is also scalable **now** to deliver regional, national, or global indicators, which is vindicated by all partners applying to the Open Cloud Research Environment to fund and deliver their national coastlines.

ARGANS Limited and its partners have now reached the end of the 3-year project funded by the Science for Society slice of the 5th Earth Observation Envelope Programme overseen by ESA/ESRIN (the European Space Agency/Space Research Institute) which commenced 3 April 2019 with the award of the CCN on 1 September 2021. The partnership consisted of a EO based information service provider group of Earth Observations and Data experts comprising ARGANS Ltd (UK/Fr), isardSAT (Spain) and adwaïsEO (Luxembourg) who delivered to an authoritative public User Group of national representatives from the British Geological Survey, the British government experts, IH Cantabria in Spain on behalf of the Spanish government's Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO), Geological Survey Ireland, the Irish Government experts and ARCTUS representing the Canadian academic world and the local communities of Québec. For the CCN an additional national expert from Italy was added to the consortium, namely the Italian National Institute of Environmental Protection and Research.

The consortium has developed a method to optimise the number of customer ready co-registered waterlines and datum referenced shorelines seasonally covering 25 years that have been validated by the leading technical geomorphological experts within the five partners' nations. These products deliver inter-pixel accuracy, use a locally adaptive threshold method to accurately determine the position of the land/sea boundary precisely and can be scaled to cover complete nations worldwide. Indeed, each partner nation intends to continue this work to provide national coverage. We have developed a land classification map that describes the coastal strip, including coastal features and their inter-annual changes which enable beach width to be determined. Boundaries have been pushed using satellite derived bathymetry

techniques based on a long history of this technology to observe features of interest even in the sediment loaden waters.

Product Scope: 4000 km of coast analysed across 5 nations, spanning over 25 years of satellite imagery.

Expert Analysis: Products validated by coastal experts from leading national institutions.

Global Outreach: 5 workshops and webinars have been delivered, over 10 conferences including Living Planet Symposium, national Geospatial and Coastal Engineering events have been presented.

Impactful Research: Peer-reviewed paper published with several papers are under preparation to be submitted to leading high-impact journals.

The Coastal Erosion Project has certainly demonstrated the value of Copernicus EO data and Landsat mission to derived products to monitor multi scale coastal change in various geomorphological environment. The feasibility phase had wide-reaching stakeholder engagement to capture the requirements of both industry, institutes, and government, local and national. During the CCN many of these requirements were revalidated alongside the experienced gained to date by the lead national institutions, their associated partners in both local and national government agencies and departments. The initial project delivered a period of design and development to manufacture of a range of products that have been improved during the CCN. These products have a global applicability to help coastal managers better understand their areas of responsibility and also enable them to plan how they will mitigate the effects of coastal change. Another key tenet of the CCN has been to move the knowledge threshold from geospatial data products to information of utility to those decision makers responsible for coastal management.

This project and CCN have seen the development of 6 processors that have evolved individually and for the optical imagery have formed a semi-automatic processing chain which starts with a cloud optimised selection of suitable EO data. Optical satellite images are then co-registered via a Geolocation processor to refine their accuracy using commercial VHR imagery supplied under the ESA Third Party Mission agreement. Within the CCN, the addition of national aerial photography libraries was successfully trialled to further improve location accuracy. These images are then fed through a Waterline processor to extract an instantaneous snapshot of the land/sea boundary by means of a locally adaptive threshold process. The next step allies the waterline to a tidal datum via a shoreline processor which uses tidal height along the coast to assess tidal reach via slope and local meteorological conditions at the time. This complete chain has been refactored during the CCN to improve the quality and reliability of each product as identified within QC parameters embedded or within the associated metadata. In the initial project the co-registered images were also processed via an IDA processor to derive Bathy-Topo Terrain Models and associated features, whilst another processor classified the coastal strips of land cover types averaged over a season. Two additional components were also added within the CCN. The first explored how SAR derived wet/dry lines can show erosion rates based on 2 demonstration sites whilst overcoming the ascending and descending path offsets observed. The exact definition of what SAR actually depicts is difficult to define due to the nature of the backscatter returns however the repeatability and number of observations make this data perfect for identifying change. The second looked at evaluating the products using the systems and techniques employed by the partner nations. A full description is included within the section on validation and evaluation. All the products from both the main project and the CCN were stored in an FTP server accessible to the partners to enable validation and further exploitation. In addition to the FTP capability, in tandem a data access portal has been concept tested to provide a web service delivery mechanism during the initial project phase.

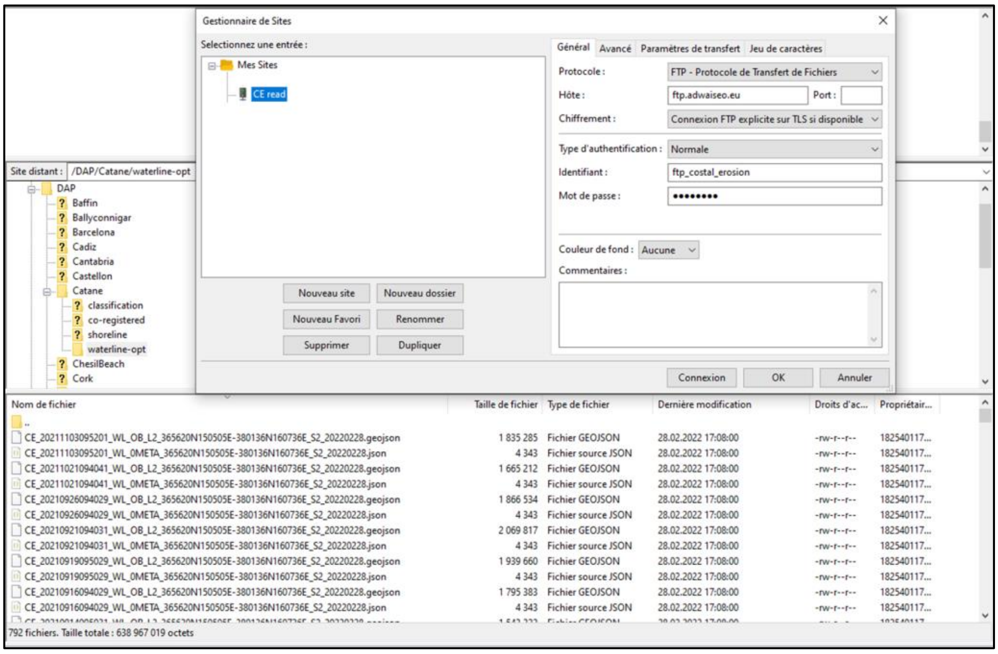


Figure 0.1: Coastal Erosion from Space product storage

1 Introduction

1.1 Why the project was needed and the funding.

1.1.1 The Project.

The Coastal Erosion from Space project, 4000126603/19/I-LG, was commissioned under the Science for Society slice of the 5th Earth Observation Envelope Programme (EOEP-5) of the European Space Agency. The Statement of Work set the challenge to aim at developing innovative EO products and methods in response to authoritative end-user requirements. A further Contract Change Note was awarded in September 2021 with the aim including an additional expert institution from a new country and updating the delivered key coastal state indicators products to the present. As will be demonstrated throughout this report, the relationship between the authoritative professional and technical User Group brought together under the Coastal Change Consortium and the Service Provider Group has been instrumental to ensuring valuable products tuned to the user need have been developed and delivered and the addition of ISPRA has been very good fit.

Figure 1.1: Cliff erosion, south of Start Bay (UK)

1.1.2 The Task

The Coastal Erosion project team was tasked to analyse the erosion of a minimum of 1000 linear km of coast split into 3 different member states and provide the best products suited to end user requirements over the past 25 year. The additional CCN added an additional nation and 5 new sites with an additional 300km per site and the update of the initial sites to the present.

Key to the success of this project was the requirement to develop innovative approaches that best exploit the novel observational capabilities of the Sentinel 1 constellation with S1A and S1B units currently on operation and the S2 constellation with its S2A and S2B, however in order to provide products dating back to 1994 to meet the 25 years of observation the ESA archive of Landsat 5 and 8 as well as ERS and Envisat data were exploited too.

The project was initially funded for 2 years and was split into two phases. On completion a CCN was awarded for an additional single phase, one year period, ie phase three. **The first phase** enabled the User Requirements to be collated and then for them to be refined into the art of the possible based on the existing and archive technologies and the innovative approaches that could be developed within this feasibility phase. **The second phase** moved to implementation where both production and validation became the key tasks. Alongside this work were two additional requirements placed upon the consortium, namely, to develop a pilot data access service and also to broadcast the range of new products, their development, validation and utility via a series of workshops hosted in the four participating nations. The initial plan had been to host these as live events within the partner institutions; however, the onset of the global COVID-19 pandemic required these events to become virtual. This approach proved most popular with in excess of 600 delegates attending the events. **The third phase** (the CCN) supplemented the user requirement based on lessons identified and feedback from the workshops. This phase provides an additional 1500km of coastal products, updated all the previous sites' products to mid-2022, added an additional nation (Italy) to the consortium and delivered improved capabilities as well as an additional workshop, this time more focused on the decision makers in local and national government as well as heads of institutions connected with coastal management.

1.1.3 The Team

For our project **five nations** were engaged building a trusted relationship with those institutions who are vested with the responsibility to advise their national systems. In addition, **over 4000 linear km** of coastline has been observed over 21 different sites representing a range of geomorphological conditions including coastal strips whose main financial incentive is tourism and the need for sand filled beaches.

Representing Spain, the Environmental Hydraulics Institute at the University of Cantabria (IH Cantabria) were selected as they are expert in providing knowledge, evidence, methods, tools and technology relevant to the achievement of the Sustainable Development Goals (SDGs) with special emphasis on the water cycle related SDGs, following an integrated, transdisciplinary, stakeholder- oriented approach in a collaborative framework. They work extremely closely with the Ministry for the Ecological Transition and the Demographic Challenge (MITECO) and, particularly, with the Sub-Directorate for the protection of the coast (SGPC) which aims at protecting the coastal and marine environment and at guaranteeing its free and public use.

Representing the United Kingdom, The British Geological Survey were selected as they are the UK's premier provider of objective and authoritative geoscientific data, information and knowledge to help society to use its natural resources responsibly, manage environmental change and be resilient to environmental hazards. They work extremely closely with the National Network of Regional Coastal Monitoring Programmes of England, a Network comprising 6 Regional Programmes, collecting coastal monitoring data in a co-ordinated and systematic manner to serve the needs of coastal engineering and management as well as the Environment Agency and the Geospatial Commission of which they are a founding member.

Representing Ireland, the Geological Survey of Ireland is Ireland's public earth science knowledge centre and is a division of the Department of the Environment, Climate and Communications. They deal with a diverse array of topics including bedrock, groundwater, seabed mapping, natural disasters, and public health risks. They also work very closely advising the Office of Public Works (OPW), the Irish government office whose primary function is to support the implementation of government policy.

Representing the Province of Quebec, Arctus in association with the University of Quebec at Rimouski, provides advice to the provincial government of the province of Quebec.

Representing Italy (during the CCN only), the Italian National Institute of Environmental Protection and Research acts under the vigilance and policy guidance of the Italian Ministry for the Environment and the Protection of Land and Sea (Ministero dell'Ambiente e della Tutela del Territorio e del Mare). The Institute performs scientific, technical and research functions as well as assessment, monitoring, control, communication, training and education activities.

1.1.4 The Innovation.

What became clear very early within the User Requirement capture work was the need to provide an on the ground accuracy that enabled any changes observed to be assigned to real movement (accretion or erosion) and not within the limits of the observation parameters of the satellite sensor. Each pixel was required to be positioned as accurately as possible and so a pre-processing stage was developed to co-register the optical imagery (both Sentinel 2 and Landsat 5/8). To achieve the desired accuracy commercial images were procured which were then used as the reference (or so-called “Reference”) image. These commercial images were provided under the ESA Third Party Mission agreement and are subject to the terms and conditions of that arrangement. The “tie-in” points between the Reference and the Target image were generated as a grid with an ability to define the distance between each tie-in point. The tie-in points were then filtered based on a reliability assessment and a similarity analysis. A post processing phase was then conducted to ensure that the detection of common points was achieved based on a visual inspection of the imagery, however this process will be covered in depth later in the report. As part of the CCN it was also identified that a greater number of images, if possible, should be used as it was believed that broad image cloud filtering was deleting some possible images with a cloud free coast. Additional requirements also considered ameliorating the problem that the slant angle posed from ascending and descending SAR imagery and despite the “line” identified by SAR not being defined it was repeatable enough to suggest its use in creating change rates. The final hurdle to surmount was to improve the quality of the optical waterlines insomuch as to improve the detection between pixels and reduce the zigzag appearance whilst also increasing the length of the waterline sections from 100s of metres to 10s of kms. All these new challenges have been successfully overcome and delivered in the next product set through refactored processors.

1.1.5 Outreach

This has been a very enjoyable component of the project but since the arrival of the global pandemic COVID-19 it has thrown some challenges our way. The new way of working has very much been via tele-networking and virtual conferences and workshops supported by papers.

Within the CCN a few live events have been attended and presented at including the Living Planet Symposium 2022 and GEO Business 2022. A full picture is included later in section 6.

The mandated workshops in phase 2 provided an excellent opportunity though to showcase the project, the products, the utility of the Sentinel Mission as well as providing an excellent vehicle to engage with decision makers, planners and academics working in this field. In the CCN an additional workshop was delivered that featured a panel discussion of experts from local and national government, heads of institutions and space agencies. The theme was to explore the knowledge and uptake and utility for decision makers.

Finally, the https://coastalerosion.argans.co.uk website is another avenue to explore the project and housed within this website is the Data Access Portal which was delivered in phase 2 to enable the products to be accessible via a webservice to those authorised.

1.2 The Consortium and "ARGANS" approach

The "ARGANS" approach. Project Management has been provided throughout by ARGANS Ltd and from the start it has been important to design a clear plan that has been developed by continuous consultation and dialogue with the partner organisations. Bringing ISPRA into the fold was a relatively easy thing to do as by this time the maturity of the consortium was well developed, and all partners were able to support the newcomer. The bimonthly progress meetings, all recorded as a requirement from the statement of work, proved invaluable, however as the implementation phase commenced a weekly production meeting was introduced. For the CCN this meeting cycle was reduced to fortnightly however this was additionally supplemented by a specific fortnightly meeting to consider the new WP7 "generating information from data". During phase 2 it was agreed that each nation would be afforded a dedicated 4-week package so that the sites for production could be prioritised according to the user need, the auxiliary data could be sourced appropriately, the production or processing chain could run efficiently sourcing the initial imagery, conducting the co-registration, deriving the instantaneous waterlines and then creating the datum referenced shorelines as a package. This procedure was also adopted within the CCN. Associated with this work were the creation of the bathy-morpho terrain models and the seafront classification maps. Within the first 16 weeks of phase 2 the plan that was agreed delivered volume so that the initial validation could take place and this in turn would lead to a refinement of the product specifications as lessons were learned along the route and the Product Validation Review was drafted. The second half of phase 2 drew upon these lessons and the processors were upgraded to improve the products in terms of reliability, consistency and repeatability but also including key quality control indicators and the associated metadata, both features identified within the initial PVR. The second half of phase 2 also enabled more sites (and by default increased linear kms) to be prosecuted and some interesting time series products to be developed to identify where accretion and erosion have taken place. This spiral improvement process proved very successful to both the service group and the user group and so it was also adopted within the CCN to bring those lessons identified forward into the work programme to be developed, coded, tested and then let loose on the production side of the project.

2 Processing Chain (Processors and associated products)

2.1 Introduction

This project initially saw the development of processors that evolved individually and although they theoretically formed a processing chain in that one step had to be concluded before the next commenced, they were more of a workflow. The system at the end of the initial project did produce commercial ready products, albeit in a semi-autonomous and labour-intensive fashion. To create a processing chain that can be deployed on cloud platforms was considered an aspiration at that stage and a large part of this task has now been completed within the CCN. Each step in the workflow has been reviewed and in the majority of cases the processors have been refactored to improve efficiency in processing terms and to add in improvements requested by the partners during the course of the project. The new processors follow a logic that could be linked via orchestration to deliver a production system. It is fair to say that the process will never be completely automatic i.e., at the click of a button following some basic inputs and this is because some stages still require a human judgement to be made. However, the ability to generate datum-based shorelines if auxiliary data is supplied is now much faster, less human intensive and much more continuous, accurate and reliable.

2.2 Naming Convention

The adoption of a strict naming convention was a requirement deemed necessary because filenames should be searchable by Regular Expression (RE) and selectable by wildcard matching. In addition to satisfying this primary implementation requirement, the naming convention was designed to provide the end-user with sufficient information to enable product identification from the filename alone i.e., *what* product, *where* located and *when* acquired.

The standard naming convention for product files is of the form:

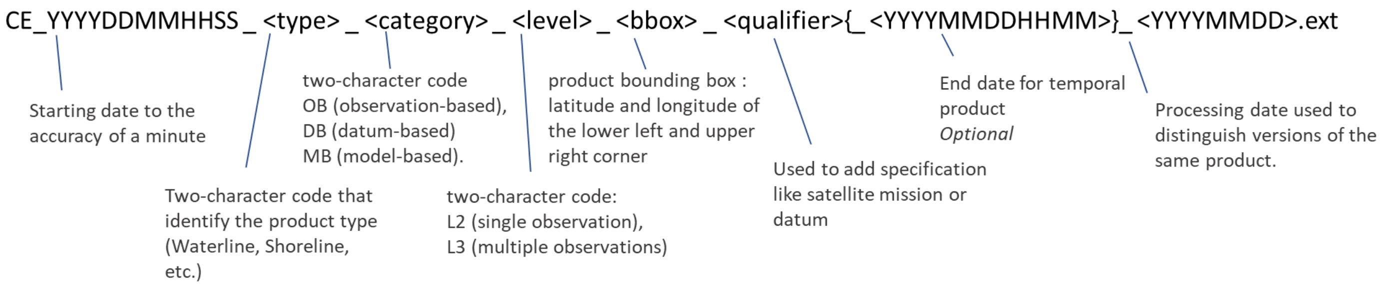


Table 2.1: File naming convention

Filename	Description
CE_<startdatetime>_CR_OB_L2_<bbox>_<qualifier>_<procdate>.tif (ex : CE_202111030952_CR_OB_L2_365728N145959E-375627N161457E_S2_20211206.tif)	Co-registered image
CE_<startdatetime>_WL_OB_L2_<bbox>_<qualifier>_<procdate>.geojson (ex: CE_20200221110959_WL_OB_L2_360021N63636S-370148N53339S_S2_20220126.geojson)	Waterline geojson
CE_<startdatetime>_SL_DB_L2_<bbox>_<qualifier>_<procdate>.shp (ex **:** CE_20160107114452_SL_DB_L2_514705N082412W-515416N075952W_LAT_200928.shp)	Shoreline shapefile
CE_<startdatetime>_LC_FB_L3_<bbox>_<qualifier>_<enddatetime>_<procdate>.tif (ex : CE_201701121114_LC_FB_L3_355559N080140W-371830N052501W_S2_201712081114_20200827.tiff)	LuLc maps geotiff

Metadata files, and product thumbnails if they are required, have the same names as the product from which they are derived but are distinguishable from the filename extension i.e., PNG or JSON. Metadata files also replace the elements _<category>_<level>_ with _0META_. The naming convention is fully specified in the Technical Specification.

2.3 Pre-processing

In order to provide accurate and reliable time series our process need to provide as many products as possible at a high positional accuracy. On optical data, cloud cover is the most important drawback, even if thanks to Sentinel-2 A & B cooperation we can expect an image every 5 days at certain latitude, the cloud cover decreases the temporal resolution.

Our new data selection process derived during the CCN includes a cloud filtering step that considers an AOI polygon and calculates the cloud cover percentage within the polygon. According to the cloud cover percentage over our area of interest the image will, or not be downloaded according to a chosen threshold. This cloud filtering step allows us to retrieve every suitable image that can be processed, and this improvement has helped satisfy a user request to optimise the number products derived.

Table 2.2: Image selection based on cloud cover

		
Cloud cover : 0,21 %	Cloud cover : 45,08 %	Cloud cover : 20,11 %

2.4 The Geolocation Processor

To ensure the spatial accuracy, Landsat 5 and 8 as well as Sentinel 2 were co-registered in order to improve the positional accuracy of each pixel by comparing a commercial image as the reference (or so-called "Reference") image. Very high-resolution commercial images were provided under the ESA Third Party Mission agreement and are subject to the terms and conditions of that arrangement. In addition, during the CCN the opportunity was taken to test the use of aerial photography to improve the location accuracy and for the UK sites the National Aerial Photography of Great Britain was supplied under OGL licence from the UK Geospatial Commission to BGS for our use. This data set is orthorectified using highly accurate airborne GPS/INS with ground control points. The orthorectification only uses the central portion of each frame (1km x1km), reducing artefacts such as sun glint or cloud. Orthorectification is performed on the DSM for areas of true ortho and this leads to an overall positional accuracy will be better than +/-1.25m RMSE. https://apgb.co.uk

The co-registration process first creates a grid of tie points from an image's band, or stack of bands, based on its spectral properties. The tie-in points are then filtered based on a series of validation techniques that explore the pixel value similarity to ensure that only reliable shifts are used. The spatial shifts for each accepted tie-in point are then calculated and applied to the target image. This process is then repeated for all the target within the time series of the same tile.

In order to get a good comparison between images, we must ensure a perfect overlap and alignment of the images, therefore, a co-registration process is a prerequisite to enable any comparison of features that can be extracted from an image such as shorelines.

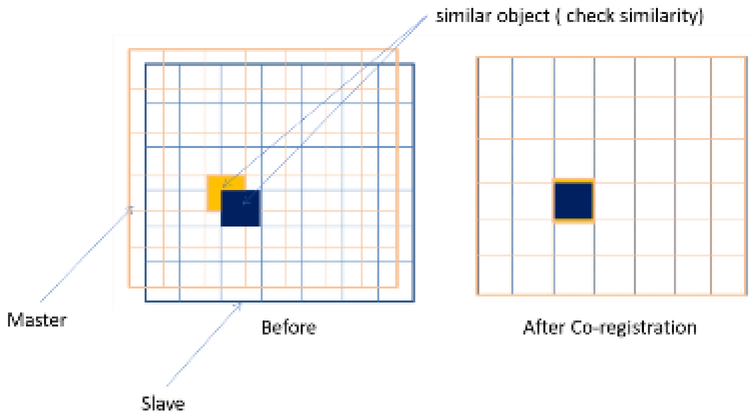


Figure 2.1: Co-registration principle

The capacity to link the two images depends on the identification of common points for both entries. The application of the Structural Similarity Index (SSIM) on a filtered points grid can measure the similarity between 2 images in a way close to human subjective perception. The principle of the index is derived from the idea that human vision is strongly adapted to the analysis of structural information and therefore aims to effectively measure the alterations of this information between the source image and the reconstituted image. This step identifies objects that are both present and identifiable in both the reference and target image.

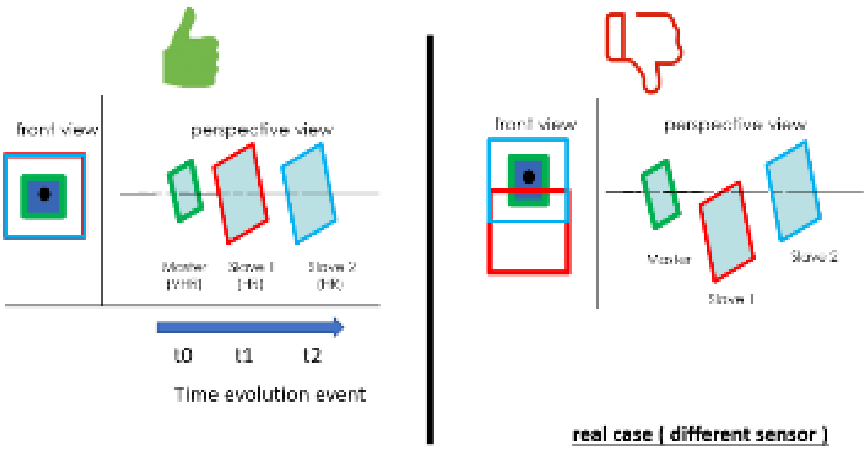


Figure 2.2: Co-registration process for time-series

To launch the co-registration process for all images captured over the same location, the procedure must be applied while keeping the same reference image for all iterations in order to ensure a similar increase in spatial accuracy and similar final position. In this way we will obtain a better rendering materialized by perfect alignment between all the images (Figure 3.2).

The geolocation improvement for a set of images is established using a SSIM index approach. The history of quality changes before and after the model application allow us to visualize the improvement with two scales of measurement comparing SSIM score between same points on the reference and target image.

1- change compared to the average:

On figure 4.3 the 50% of similarity is outlined by the red line. In relation to this reference, it is clear that after geolocation all the points which are below this limit have completely passed to the upper level.

2- change in relation to the 70% and 100% interval:

Before the correction of the image, we notice that this interval was almost empty (5% of the points in this interval), unlike the state after, the majority of the points are located in the interval 70% -100% showing a better similarity between chosen points.

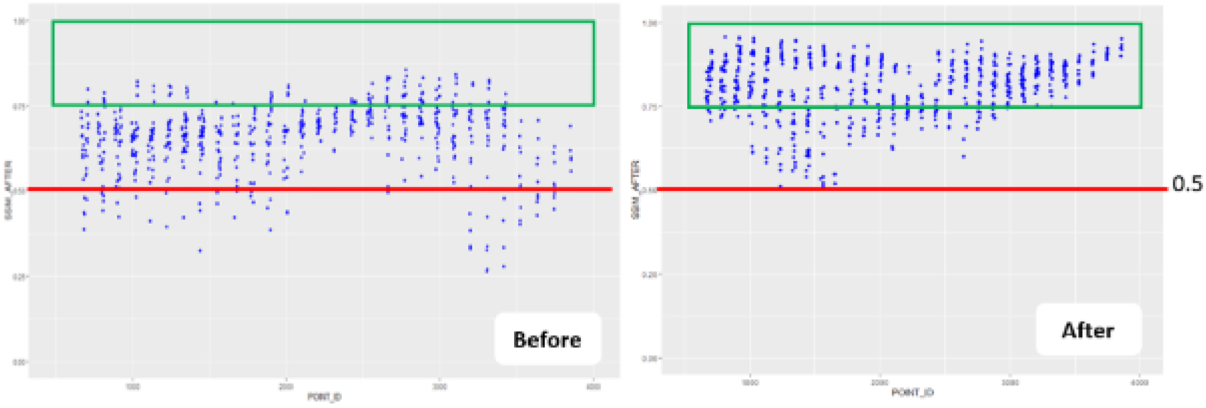


Figure 2.3: SSIM index comparison before and after the co-registration process

2.5 The Optical Waterline Processor

The overall objective of the Coastal Erosion from Space project is to retrieve Coastal State Indicators (CSI) which describe the dynamic state and evolutionary trends of coastal systems.

The waterline is a 1-dimensional (1D) Earth Observation (EO) product generated by identifying the limit between land and sea in the digital images. Using an adapted spectral index (based on geomorphological conditions) the process identifies the spectral variability between land pixels and water pixels. Waterlines describe the variation, and the dynamic nature of the coast by delineating the land/sea boundary as it changes through time with weather condition and/or tidal level.

Figure 2.4. Chesil beach, Dorset, UK. An example of a beach of steeper gradient and with increased water clarity in this image

Figure 2.5. Cadiz Bay, Spain. A river plume with increased suspended sediment generates false edges in the affected section of waterline

The 1D proxy-based waterline product is based on a 25-year EO data set combining Landsat-5 at 30m Landsat-8 at 15m and Sentinel-2 at 10m resolution.

The waterline process needs as inputs an optical image (co-registered for the coastal erosion project), a rough global coastline to guide the process (optional), a region of interest (optional) and a set of different parameters to optimize the waterline identification (e.g. the spectral index).

Spectral index testing is performed on a subset of the co-registered images prior to processing, to select the best performing indices for the series of waterlines. Normalised Difference Vegetation Index (NDVI), Blue Normalised Difference Vegetation Index (BNDVI), Green Normalised Difference Vegetation Index (GNDVI), etc., are tested as they perform differently according to the type of land cover and local specificities of the study locations.

Waterlines are computed from EO optical products (HR and VHR) using a locally adaptive thresholding method based on the spectral index histogram by section of coast.
A binary classification performed based on this ratio image will allow extraction following a "guide" coastline along which kernels are produced (75 x 75 pixel by default) to calculate a locally adapted threshold. To transform raster features into a vector file the gdal contour method implements a Marching Squares algorithm to draw a line through pixels using the neighbouring pixels value to estimate the position of the line.

Details of the waterline production process which has been significantly updated within the CCN are described more fully in the annex Waterline Processor ATBD in annex B.

An internal quality control (QC) score is applied to every waterline and included as an attribute within in the shape file product. The score looks at four geometric characteristics of the waterline, the line compactness (LC), and the line length (LL), and either line eccentricity (LE) for closed segments, or line rugosity (LR) for open segments. A segment is considered closed if the first coordinate of the geometry is equivalent to the last coordinate. The score is between 0 and 100 and is given to each segment of the line. The higher the QC score, the higher the confidence that the line is not erroneous.
The waterline products are available on an FTP server Data Access Portal as ready-to-use products with an accompanying metadata file. The metadata file includes a comprehensive log of the processing history and information to ensure the products are traceable and repeatable.
The waterlines may be extracted annually or seasonally according to erosion rate to develop regular monitoring tools; and around storm-events to improve short-term response and emergency works.

2.6 The SAR Waterline Processor

Unlike passive optical sensors that require the sun's illumination, an active SAR instrument transmits its own microwave signal to illuminate the Earth's surface at an angle. SAR actively transmits microwave signals towards the Earth and receives a portion of transmitted energy as backscatter from the ground. The returned backscatter echo of the scene is received by the instrument's antenna a short time later at a slightly different location, as the satellite travels along its orbit. The brightness amplitude of the returned signal, along with its phase information, is recorded to construct an image of the scene.

In the same way as the optical waterline processor, the SAR waterline is generating 1D lines from every input SAR image. The main steps of the process are: Pre-processing, Enhancing (including Enhancement, Segmentation, Healing, Vectorisation), Quality Control and Change Rate. Each of these processes implements a range of options and are configurable by a range of parameters which can be specified in an input Configuration File.

The quality control is in charge of computing 3 different quality parameters that are used to classify the points of the lines and filter out bad measurements.

- The distance to the reference line
- Angle between the coast and the satellite ground track
- The density of lines
- The classification flag (Good, Proxy, Bad)

Figure 2.6: Waterlines generated from Sentinel 1 between 2014 and 2020 around Start Bay area. Green lines have been classified as "good" whereas the white ones are considered "bad" as the distance to the reference and the density are below the thresholds (50 meters and 2%)

The SAR Waterline processor can process different SAR missions (Sentinel 1 and Cosmo-SkyMed have been integrated in the production). The input images need to be radiometrically calibrated and orthorectified. Apart from the main input product, the QC step needs a reference line in to provide the classification and outlier rejection properly.

The comparison between SAR and optical waterlines can be unfair without understanding the differences between them. Unlike the optical image, SAR is always affected by speckle noise. It is inherent with this kind of data, and this sometimes makes it difficult to separate pixels belonging to "land" or "water". Moreover, the different geometry of the scene and the SAR acquisition (ascending or descending orbits) can produce biased lines or lines that are not really picking up the waterline. To reduce as much as possible this issue, a "collocation" step has been included in the Pre-processing stage. This step co-registers all the SAR images to the same optical image (Sentinel-2). The result is a perfect overlapping among all the SAR images and so this translates to all the WLs derived by them. It has also been seen that for high tide areas, the SAR lines are usually detecting the transition between wet and dry sand. For that reason, is not easy to perform a tide correction for these particular lines. On top of that, the baseline input Sentinel 1 images have a worse resolution than that of Sentinel 2, which will also impact the precision of the lines. For this project, our experience demonstrated that the WL was best extracted using the VH polarization that guarantees better results than VV (as also indicated in literature). Sentinel 1 SAR imagery is also obtainable in a range of acquisition modes and processing levels. Due to coverage High Resolution Level-1 Ground Range Detected Interferometric Wide Swath was used which has a resolution of 20 x 22m. The GRD represents the focused SAR data that has been detected, multi-looked and projected to ground range using the Earth ellipsoid model WGS84. Ground range coordinates are the slant range coordinates projected onto the ellipsoid of the Earth.

Thinking now about the benefits of SAR, the number of lines that can be produced is substantially higher as most of them will not be affected by weather or night. So, the strategy should be to perform data analysis by averaging the different measurement both in time and space.

One successful example can be to analyse the distance to the reference parameter (after performing a monthly running window averaging) It can be used to perform time series and compute change rates for the different points of the line.

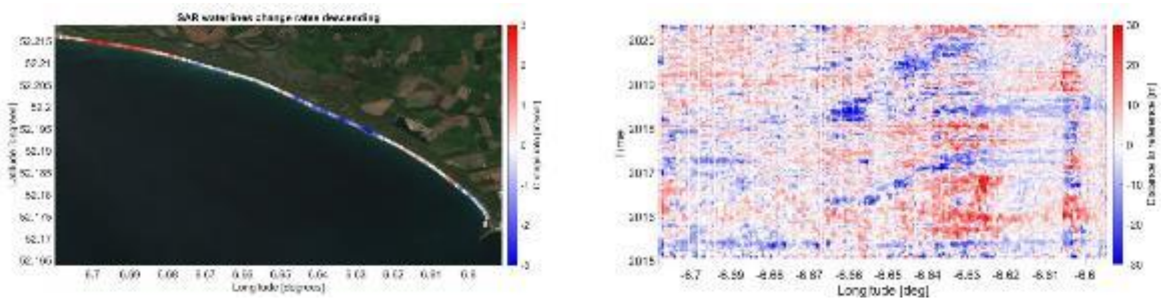


Figure 2.7: SAR Waterline time series and change rates computed around Ballyteige Burrow beach, Ireland from Sentinel 1 2015-2020 period.

By inspection of the example shown in Figure 3.7, we can see different areas along the coast with some features related with coastal change. The top plot represents the evolution of the different lines with respect to the reference. Blue indicates that the coast is changing towards the sea, accretion, whereas red indicates a change towards the land, erosion. By looking at the blue-red patterns, we can identify some specific sections of this coast, between -6.67 and -6.63 degrees of longitude, that present seasonal pattern of accretion-erosion that are shifted in time. This can be explained by the “beach rotation” driven by changes in the wave directions.

Details of the SAR waterline production process are described more fully in the annex SAR Waterline Processor ATBD in annex C.

2.7 The SAR Change Rate Processor

As already said, the comparison between SAR and Optical Waterlines (WLs) could be misleading due to the complexity of the SAR image and the nature of classifying exactly what SAR was observing could seem evasive. Despite that, the SAR technology becomes fundamental and necessary in those countries affected by cloud coverage (UK, Ireland, etc.): in the timeseries 2015-2021 there are thousands of available SAR images set against the few optical ones that are free of cloud cover. Looking at all the produced SAR waterlines, “trends” of movement over time are obvious and to capitalise on this observation and to calculate the erosion change rate isardSAT has implemented a new approach.

The following are the steps for final change rate product production.

Along the same Reference Line (RL) used during the SAR WL processor to calculate the distances $x = (x_1, \dots, x_q)$ from the latter to each WL, a series of polygons are created (see Figure 3.8).

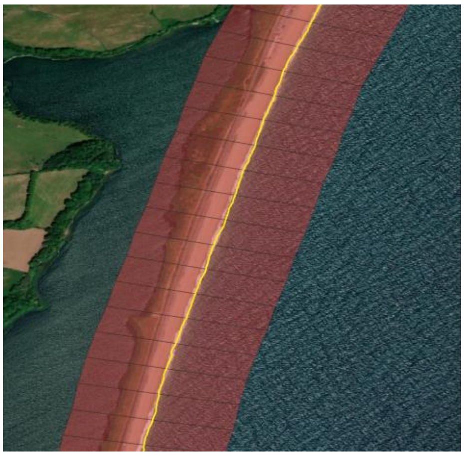


Figure 2.8. Polygons along the RL

They are perpendicular to the RL, and their width w and length across l the RL are tuneable, depending on the user's requests (space sampling). They do not overlap each other except in some complex geometry of the RL (in such case a minimum overlapping is inevitable).

Then to all the WLs a double filtering is applied.

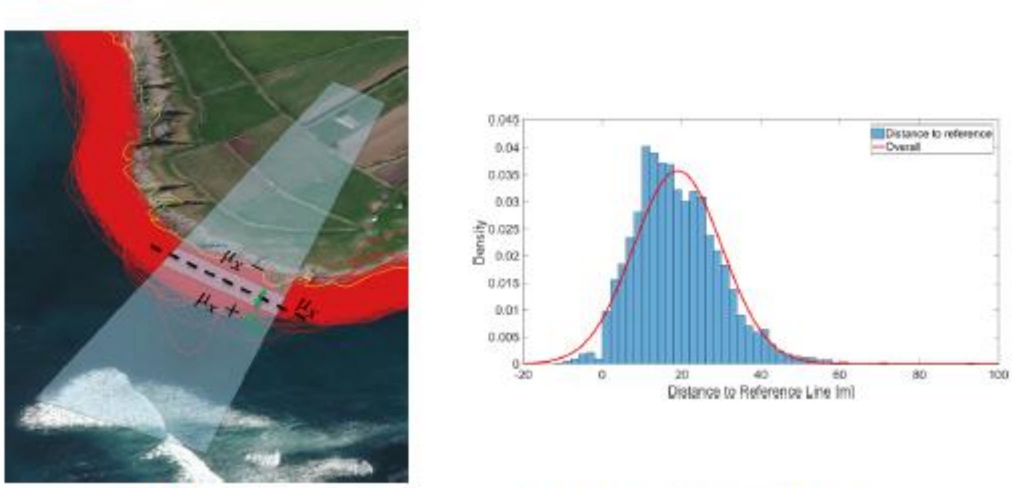
Firstly, only the lines (and their distances from RL) included in the polygons will be used to produce the change rate product.

Secondly, a second filter based on the Gaussian Mixture Distribution (GMD) technique is applied for each polygon. The WL distances are statistically described by a Gaussian distribution, characterized by a mean $\mu_x$and a standard deviation σ_x. The last is compared with an arbitrary value (for example 50 m) and if the comparison is positive, it is used as a threshold for the second filter (Case 1): only the WL distances x_i that satisfy the expression

$$\mu_x - \sigma_x \leq x_i \leq \mu_x + \sigma_x$$

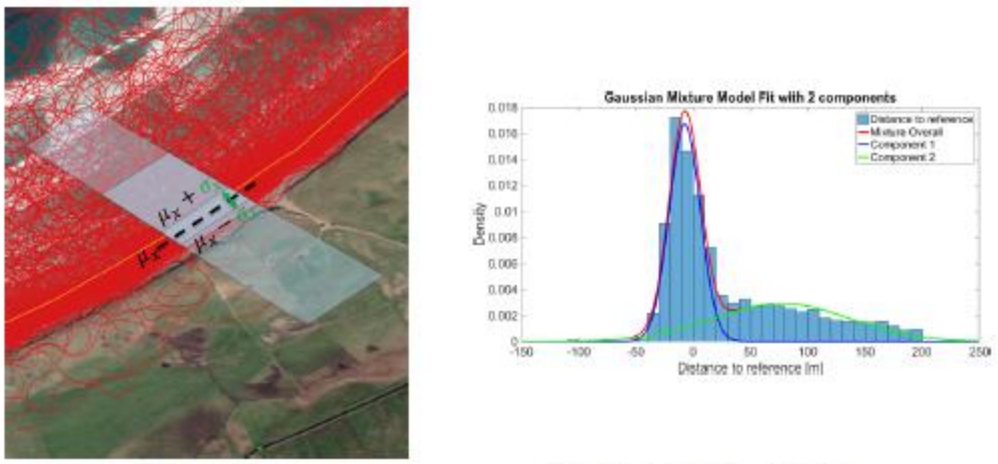
are used for the following change rate product. In Figure 3.9 an example of the GMD filtering is shown, only the WL distances in the smaller polygon are considered for the final product.

In the polygons which have a dispersion higher than the previously set arbitrary value (eg. 50m), the distribution cannot be described by a single Gaussian, so must be described by multiple Gaussians, as shown in Figure 3.10. Only the WL distances belonging to the Gaussian distribution with a larger population are considered, and their mean and their standard deviation are calculated. This new standard deviation is compared again with the fixed value (50m) and, if it is verified, only the WLs that satisfy the relationship above are considered for the change rate product. If the comparison fails, the procedure is repeated for k-times until the standard deviation of the Gaussian with bigger population is less than the specified value.



(a) Second filter (b) Statistical distribution of WL distances

Figure 2.9. Case 1



(a) Second filter (b) Statistical distribution of WL distances

Figure 2.10: Case 2

Once the selected WL have been filtered, for each WL the mean distance from it to RL is calculated for each polygon. Additionally, to reduce the noise as much as possible, a moving average filter is applied to smooths the mean distances. The span for the moving average is 5.

Depending on the user's request, it is possible to create a specific time sampling (weekly, monthly, yearly, etc.) starting from the acquisition's day of the previously selected WLs.

In each polygon, a linear regression is applied to all the mean WL distances, previously filtered out, within the user specified time sampling period. The change rate for that polygon, in that time sample is the slope of the regression line. It gives the amount of change of the coastline over time, and it will be provided to the end user in *m/year*, *m/month* or *m/week*, depending on the user's request.

2.8 The Shoreline Processor

The waterlines alone do not provide a proxy for the intersection between land and sea. But when combined with various auxiliary data, the waterlines can be transformed into shorelines, which describe the trends of that physical intersection spatially and temporally. The shorelines are needed to map and study the dynamics of the land/water interface whether visible or not to the human eye.

The shoreline processor transforms 1D vector waterlines into 1D vector shorelines utilising oceanic and topographic auxiliary data from the area of interest. A shoreline is the theoretical line that represents the intersection between land and sea, where the water level corresponds to a defined elevation above a fixed datum benchmark. These defined elevations are generally tidal datums, which correspond to average or extreme values of the harmonic tidal cycle.

The shoreline processor requires a variety of auxiliary data including, measured water levels, wave spectra and measured beach transects. This outputs a vector polyline for every chosen datum for every waterline. Each shapefile also comes with a metadata file outlining processing parameters and history. The processing algorithm uses a simplified geometric model of the foreshore, this splits the coast into a series of beach profiles with varying slope values moving along the coast, but a constant slope value across each profile. Waterline's vertices are first extracted and for each is calculated the direction of displacement and its magnitude based on the nearest slope value and an estimated water level. This estimated water level is calculated by interpolating a value between bounding tidal measurement locations and factoring in the effects of wave run up. The datum height is also interpolated based upon the waterline points' distance between the two bounding datum measurement sites. Using the slope, estimated water level and interpolated datum height, the lateral shift between waterline and shoreline position is calculated using trigonometric equations.

Once the shorelines are produced, they undergo quality control. Internally, the shorelines are analysed based upon the line compactness (LC), and the line length (LL), and either line eccentricity (LE) for closed segments, or line rugosity (LR) for open segments. The score is between 0 and 100 and is given to each segment of the line. The higher the QC score, the higher the confidence that the line is not erroneous. Long but highly confined lines are flagged as erroneous artifacts of the waterline processing that have been carried through to shoreline processing. The whole process is detailed in the shoreline ATBD in annex D.

Shorelines rely strongly on the quality and extent of the auxiliary data provided and within the CCN we investigate ways to decrease the reliance on topographic data. Obtaining ocean data that are relatively complete and accessible in the current sites has been relatively feasible, however beach profiles are more difficult to obtain for the entire length of the coast under study at the needed resolution. To overcome this paucity of slope supporting data two different approaches have been chosen and are tested in various condition to evaluate their pros and cons based on the products available and the coast condition:

1. The MSL evaluation method calculates the slope based on a set of MSL shorelines position calculated for a range of slope value.

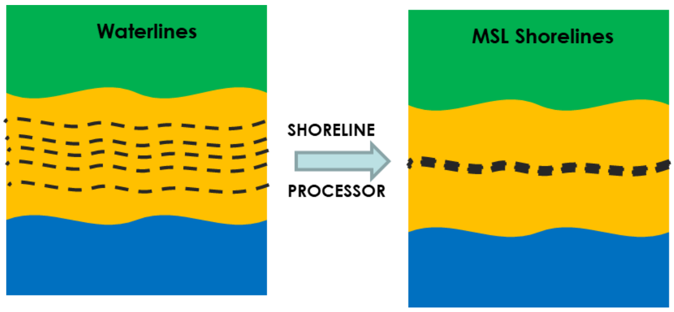


Figure 2.11: Ideal MSL shoreline position

This approach relies on the fact that for a collection of waterlines (close in time) their derived MSL shoreline should be grouped closely together. MSL shorelines are derived using a slope profile consisting of slope values at arbitrary points along the coastline. If the slope value selected is accurate, the resulting MSL shorelines will be positioned closely together. Therefore, for a given point, a range of slope values can be tested with the best determined to be those with the least variation in the position of the shorelines. The amount of variation of distances of shoreline intersection points from the slope point is measured by the standard deviation, a low standard deviation would indicate that the shorelines were closely bunched together as the distances tended to be close to the mean, whereas a higher value would indicate they were quite spread out.

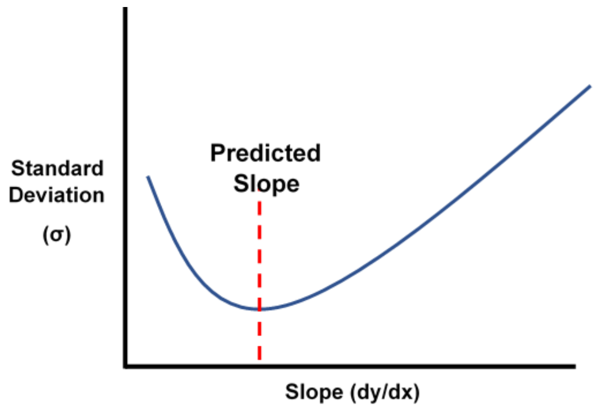


Figure 2.12: Identification of optimal slope value based on standard deviation minimisation

2. The WL2DTM approach aims to build a DTM based on waterline position along the coast. As waterlines are the instantaneous land/ water limit on an EO image we have, within a period, a whole range of various water level heights associated, from high tide to low tide. This method creates a digital terrain model (DTM) by assigning measured tidal heights to waterline positions, through the creation of a point cloud that is then interpolated into a raster surface.

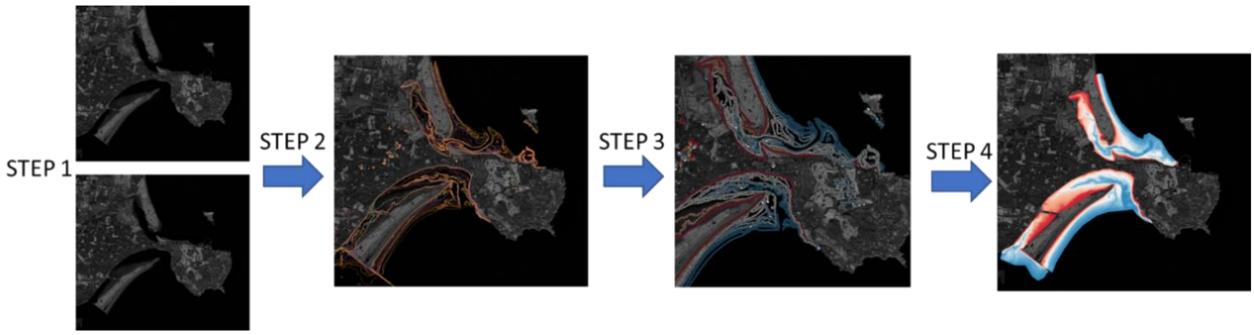


Figure 2.13: DTM calculation using a set of Waterline

The shorelines can be analysed through various time series processes to highlight areas of erosion and accretion, and in some cases estimate change rates.

2.9 The Seafront processor

A map of the various coastal ecosystems is a need expressed in the End-users requirement document. These maps aim to help in the characterisation of coastal risk management practices, and in the restoration of wetlands or other natural coastal defences. A delimitation of the different coastal areas was also expressed in order to access the landward boundary of the littoral. Tests have shown that temporal maps allow a better determination of land ecosystems and their variability, temporal classification are then realised using multiple EO observations through the year or a season.

The seafront processor aims to provide a classification map of coastal habitats and the different limits between coastal ecosystems using co-registered multispectral satellite imagery. First a classification map of the area is computed using a supervised classification processing chain. Multiple imageries are used to provide information on the spectral variability of a class to the processor allowing a more accurate classification. The classification is performed using the IOTA2 (Infrastructure pour occupation des sols par Traitement Automatique Incorporant les Orfeo Toolbox Applications) processing chain which uses supervised classification algorithms. A first step is therefore necessary to build the training data set for the learning step of the algorithm. The training data set must represent all the wanted classes taking into account the spectral variability of the land cover. The classification accuracy and precision rely on the quality of the training data set. A good training data set needs to represent all spectral characteristics present in the image while minimizing the intra-class variance, to have a homogeneous class, and maximizing the inter-class variance to have an efficient discrimination of the land cover. The processing chain then computes a classification map according to the spectral characteristics of all classes define in the training data set. The whole classification process is detailed in the seafront ATBD in annex E.

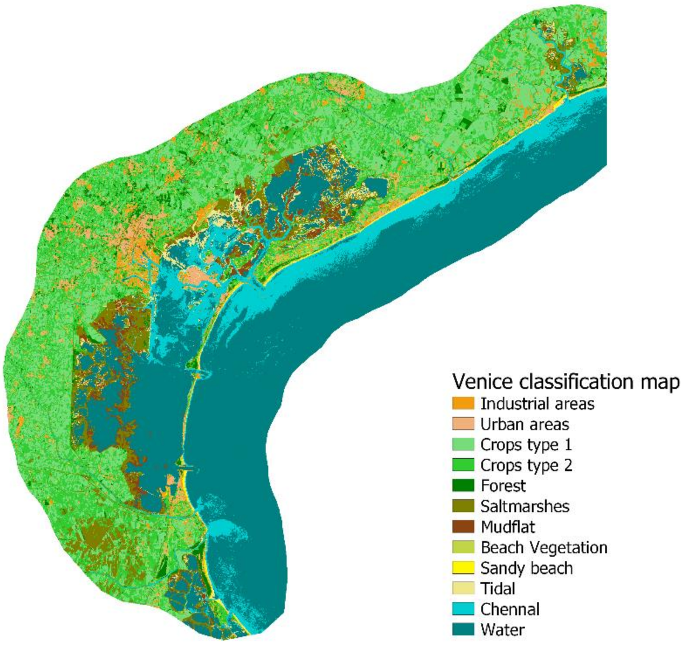


Figure 3.14: Land cover map for Venice lagoon for 2019

The resulting map is then analysed to automatically extract coastal areas limits. It is possible to identify two or three main coastal areas, the backshore – the use area with main human activities such as agriculture, civil works etc; the intermediate area – optional, it is a buffer zone, protecting the backshore with some dunes, vegetation, wetlands, etc.; and the littoral area – the most dynamic part with beaches, cliff and tidal area, and the usual zone for accretion and erosion. The identification of those area allows a refined analysis of various coastal feature like dunes movement or cliff collapsing.

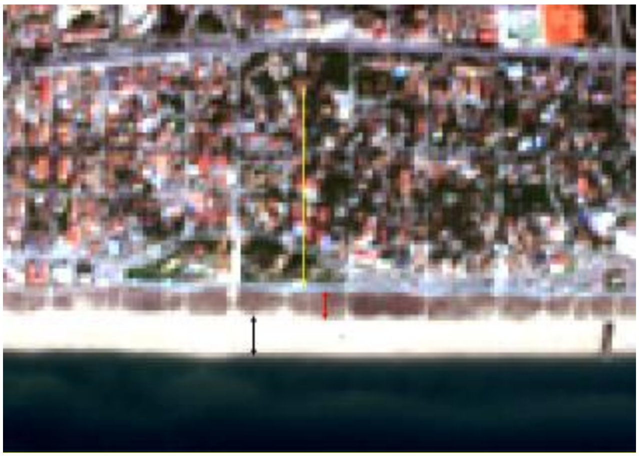


Figure 2.14: Identification of the 3 coastal areas et Barcelona coast, backshore (yellow arrow), intermediate area (red arrow) and littoral zone (black arrow)

The use of multiple optical imageries through the year allows the capture of some dynamic phenomenon such as the tidal area and thus to support the shoreline processor by providing a zone of high probabilities for the waterline and shorelines position.

The classification maps provide valuable information on the different ecosystems along the coast bringing knowledge on the various erosive context.

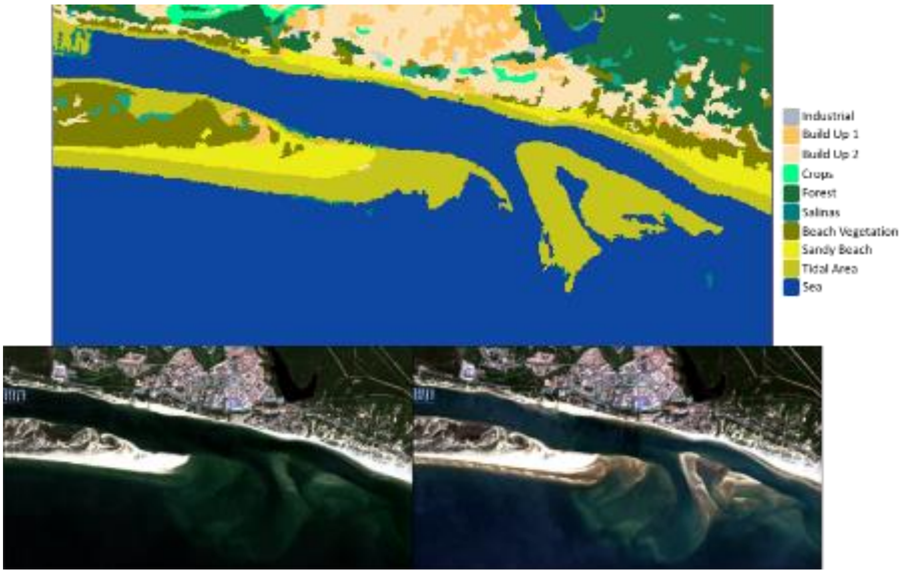


Figure 2.15: Identification of the tidal area in Cadiz Bay

The second part of the Seafront processor reads the produced classification and delimits the boundaries between the coastal areas. As the classification is made using several images through time, the extracted littoral limits are not representative of the position at a given time but indicates a most probable position for the time scale used. The seafront ATBD in annex E also details the littoral line processor.

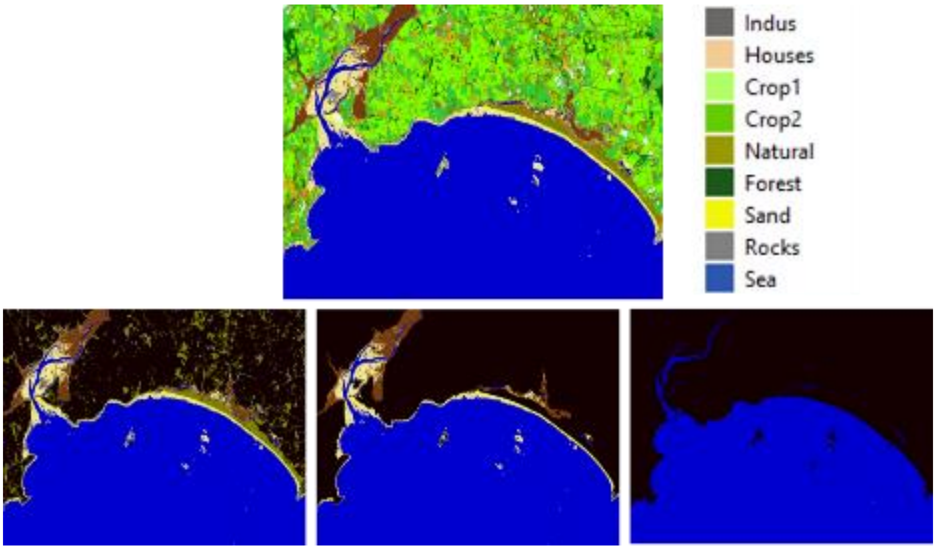


Figure 2.16: Cork Classification and masks associated with the littoral limits

The produced littoral limits provide knowledge on the type of environment around the coast and can “guide” shorelines by framing their possible positions. A shoreline in the backshore area should not be possible except for the case of an extreme storm with a massive erosion.

2.10 The Bathy-Morpho Processor

Bathy-morpho terrain models (BMTMs) have been chosen by the end-users as one of the products to be delivered as they provide bathymetric data in a cost-effective way in some areas. To fulfil the objectives of the Coastal Erosion Project a different approach from that of the well-established Satellite Derived Bathymetry methodology has been chosen. In the latter, a single product is delivered, which provides navigational safe depth values. In this project, the objective is to provide information about the trends that can be found in coastal areas, and to provide information about the coastal features to monitor coastal changes.

BMTMs is a part of remote sensing that is useful to determine depths and other seabed features of coastal marine environments by measuring the reflectance of the sea bottom extracted from the upwelling sunlight signal. Two different approaches exist: empirical models and physics-based models. The former requires a prior knowledge of the seabed depths and is not suitable when looking to measure change on a regular basis. This is because empirical models are based on the exponential attenuation of light set by the Beer-Lambert law and they consist of calculating the various unknowns in the equation from comparison with field measurements, which turns out in an uninteresting approach for our purposes. The latter physics-based method has therefore been chosen as the one to follow in this project. If the estimation of BMTMs is based on the calculation of depths solving the equations using in-situ data, this method will hamper us from detecting the possible trends that could exist in the coastal environment. For that reason, the physics-based model is the chosen approach. They are derived from full equations of optical radiative transfer. In this case, in situ data is not needed because the model attempts to capture the full physical process of light transfer without any unknown scaling factor to be calibrated. One advantage is that they are far more robust in terms of transferability between different waters and atmosphere optical properties. As four different countries are involved in the Project with different geomorphological characteristics in their coastal areas, this seems like the best approach to follow, and this approach supports the applicability of the method in other sites and countries in the future.

When using the physics-based method, the inversions to obtain depth are done at a pixel level, so the images need to be properly processed, paying special attention to the atmospheric effects correction and the glint correction, as they are the main factors that affect the generation of BMTM models. The key to bathymetric estimation is to relate the reflectance of the water column to its depth, so the correction of the atmosphere effects becomes the main source of error, as well as the presence of particles in the water column. The model should capture the variation of the optical properties of the water and its constituents, and also the benthic reflectance. However, we have to consider a fundamental uncertainty related to the physics-based model used in the project, but it can be extended to empirical methods as well, and this is that similar reflectance can be consistent with different depths, ie a strongly reflective seabed in deeper clearer water could look similar to a less reflective seabed with murkier water. Besides, water clarity in terms of water constituents is also a known issue when estimating depth values using satellite data, as the presence of high concentration of particles such as coloured dissolved organic matter (CDOM) or suspended particulate matter (SPM) will not allow the photons to reach the bottom, so the depth will be estimated considering the information provided by these water constituents instead of the bottom reflectance.

For solving these issues, the Image Data Analysis (IDA) software based on Hedley et al. (2009) is used. This software is a modified inversion scheme as proposed by Lee et al., 1999. It considers that bottom reflectance spectrum could be one of many different curves resulting from the linear mixture of a few most common substrate types (sand, live and dead coral, algae and seagrass). Even though we are working in areas where coral is far from being present, coral has a similar reflectance to brown algae (Hedley et al., 2001), so using these six different types of bottom is recommended for general production work, as it is the case of the present Project. This approach was used in several papers, such as Hedley et al., 2009; Hedley et al., 2012 and Hedley et al., 2018. The algorithm proposes an efficient subdivision of the parameter space (any parameter of interest) once the real range of variability is known. For example, consider changes in the reflectance as a function of depth: it can be observed that in the first depths, small changes can lead to greater diminution in measured reflectance; however, at greater depths, small changes lead to lesser impacts in the measured reflectance, therefore, the algorithm proposes a more detailed subdivision of the depth in shallow areas than in deeper ones.

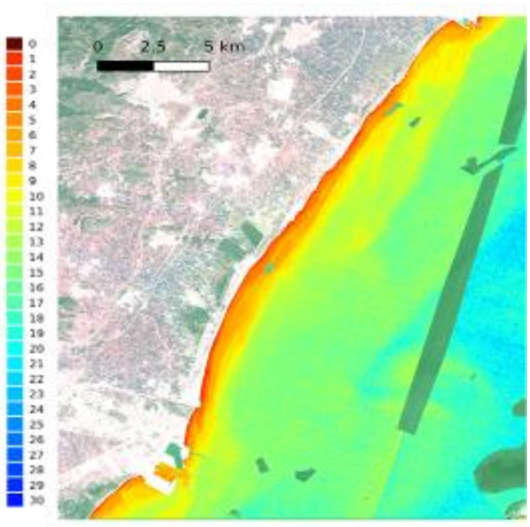


Figure 2.17 BMTM for Castellon

Besides, to provide information about the water clarity (water constituents) that will hamper photons to reach the bottom, a confidence map is provided together with the BMTM map. As explained, in those areas where high concentrations of CDOM and SPM are present, photons will not reach the bottom and the estimated depth will correspond to the depth where those particles are present in the water column. To inform the end-user of those areas presenting high concentrations of water constituents, the confidence map is calculated using the concentrations of SPM and CDOM estimated using Han et al., 2016 and Kutser et al., 2005, respectively. The atmospheric corrected reflectance of each image is used to estimate those two biochemical products, and considering the characteristics found in each area for each country, empirical thresholds have been defined to provide a three classes confidence map: good values (1), for those areas presenting low concentrations of these particles, attention values (2), for those areas presenting mean concentrations for both variables, and bad values (3), for those areas presenting high concentrations of CDOM and SPM, or negative reflectance values (Figure 4.13).

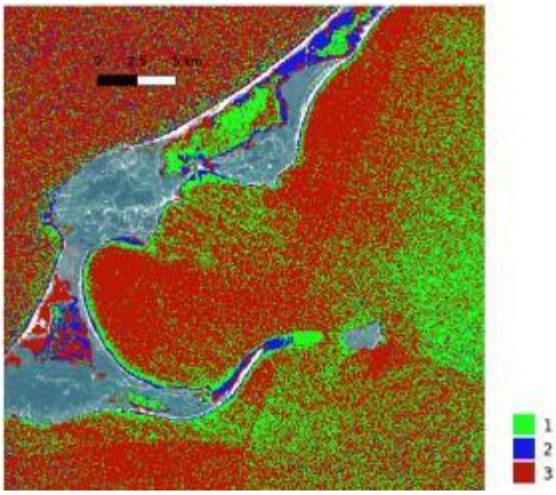


Figure 2.18 Iles de la Madeleine BM-TM Confidence map (1-good confidence, 2-medium confidence, 3-low confidence

Despite proving to provide good results in some study areas, most coastal environments are quite challenging due to the presence of suspended particles in the water column or to the lack of information to reduce the number of unknowns when estimating the depth. Confidence maps have shown its utility to detect those areas with less than 10 m depth were suspended particles have impede the photons to reach the bottom, as light rarely reaches depths higher than 10 m for the studied areas. However, confidence maps should be combined with Depth of Penetration algorithms, to better assess the end-user when validating the BMTM maps. Besides, for those areas with almost constant presence of high concentrations of suspended particles in the water column, BMTMs have proved to be a tool which can only provide information about coastal features such as sand bars, but not to detect depth changes due to coastal erosion/accretion processes. For that, another methodology could be developed using also optical satellites, but taking advantage of the wave field present in the images and the acquisition time gap existing between each of the bands that form the image. (Details of the BM-TM production process are described more fully in the annex BM-TM Processor ATBD in annex F). During the CCN there were no additional requirements to supply BM-TMs as their utility has not been explored by the User Group following their initial review during the main project. Despite slope being a vital component to support change detection over time, the very nature of the seas surrounding areas of erosion and accretion are not conducive to light penetration and any techniques are only qualitative at best.

2.11 Time Series

Within the CCN, how to use shoreline to extract coastal dynamic was a central question. Different approaches have been tested and the time series approach implememnted takes two dates (a starting date and an ending date) to extract how the coast changed in that time range. The time series process computes the area between two lines based on the satellite derived shorelines and creates a vector layer that represent a quantitative change for the chosen time period.

The selection of the shoreline relies on a first visual assessment of the available shorelines for the period of interest. MSL shorelines have proved to be the most relevant ones to illustrate coastal change as HAT and LAT are extreme situations with specific morphologies. Also, as shorelines are derived from waterlines that might represent different coastal morphologies based on the water level, it is recommended that combined shorelines very close in time relatively to the range of the time series are selected to smooth coastal morphology variation. At the end of this first step there are two reference lines (start and end) that are either shorelines or an average line of multiple shorelines. For each line a one-side buffer (on the seaside) is created that is then clipped to keep just the polygons between the lines. Polygons derived from the starting line represent the accretion and the one for the ending line the erosion.

Figure 2.19: Accretion and Erosion polygon created from the starting and ending reference lines.

To obtain a more locally focused information and to enable the quantification of the change and finally the extraction of the change rate we need to calculate the area for smaller parts of the polygon. The polygons are merged on a vertical or horizontal grid to split them equally based on a fix resolution. A calculation can then be made for each part the accretion or eroded area.

Figure 2.20: Time series result showing the beach renourishment between March and June 2015 in Malgrat beach, Torera Spain.

2.12 Metadata

Metadata provides information about other data i.e., data about data. **Geospatial metadata** provides the type of metadata applicable to geographic data and information with features to be described in a metadata repository, or data inventory.

A metadata record is a file of information, usually presented as an XML document, which captures the basic characteristics of a data or information resource. It represents the who, what, when, where why and how of the resource

We consider two main categories of metadata:

- **Descriptive metadata** is descriptive information about a resource. It is used for discovery and identification. The file naming convention provides components to describe the file contents.
- **Structural metadata** is metadata about containers of data. It describes types, versions, relationships and other characteristics of the product. The minimum requirement for all products is traceability to the container of files that includes the Uniform Resource Indicator (URI) of all associated data, i.e. the input image(s) and any auxiliary data files (ADF), and a record of the processor history including name and version.

For most users only the descriptive metadata will be required, which should provide the user with type descriptor, location and date of the product. The file naming components will be mirrored in the database as attributes and providing a **searchable data catalogue**.

The metadata schema developed is based on the Dublin Core Metadata Element Set, with a structure based on the Sentinel-2 SAFE schema. Products produced from Copernicus/EC Sentinel missions are INSPIRE compliant by linking to the metadata of the input image. The top-level structure follows the schema:

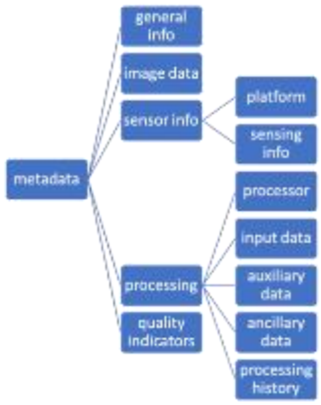


Figure 2.21: Metadata Schema Ontology

GeneralInfo	ProductName	Filename, not including path
	ProductDescription	Short description of product
	ProductType	Type of product
	ProductCategory	Category of Product
	ProductLevel	Single, multiple, or fusion
	ProductBBox	String representation of Bounding Box
	ProductQualifier	Identify platform & datum etc.
	LastModifiedDate	Last Modified Timestamp

Table 2.3: Attributes of the General Info category

Two common structured data formats are XML (Extensible Markup Language) and JSON (JavaScript Object Notation), both used for data exchange. JSON was selected mainly because it is more lightweight, less verbose and easier to read than XML and faster to parse. JSON is easily serialized to return a JavaScript object, which as easily can be parsed using PHP and Python. JSON encodes data as a map and the syntax is as attribute: variable tuples. As illustration the General Info metadata attributes are represented in JSON as presented in Figure


```
"GeneralInfo": {
    "ProductName": "S2B_MSIL2A_20211111T100149_N0301_R122_T33TUL_20211111T121500",
    "ProductDescription": "Co-Registered : Input sensor co-registered image",
    "ProductType": "CR",
    "ProductCategory": "OB",
    "ProductLevel": "L2",
    "ProductBBox": "450213N122739E-460251N135002E",
    "ProductQualifier": "Sentinel-2B",
    "LastModifiedDate": "20211208",
```


Figure 2.22: General Info metadata bloc for a co-registration product

An important property of the metadata is that it incorporates a representation of the processing history. This is provided by including the name of the input files, both satellite image or auxiliary data files, and setting used to run the processors, the processor version, and any ancillary information required to repeat the processing. This is to ensure traceability and repeatability, and important component of the verification and QC procedure.

2.13 Summary

The project incorporating the CCN selected **21 sites** to study with a range of different and often very complex geomorphologies, in order to **test the limits** of the technologies.

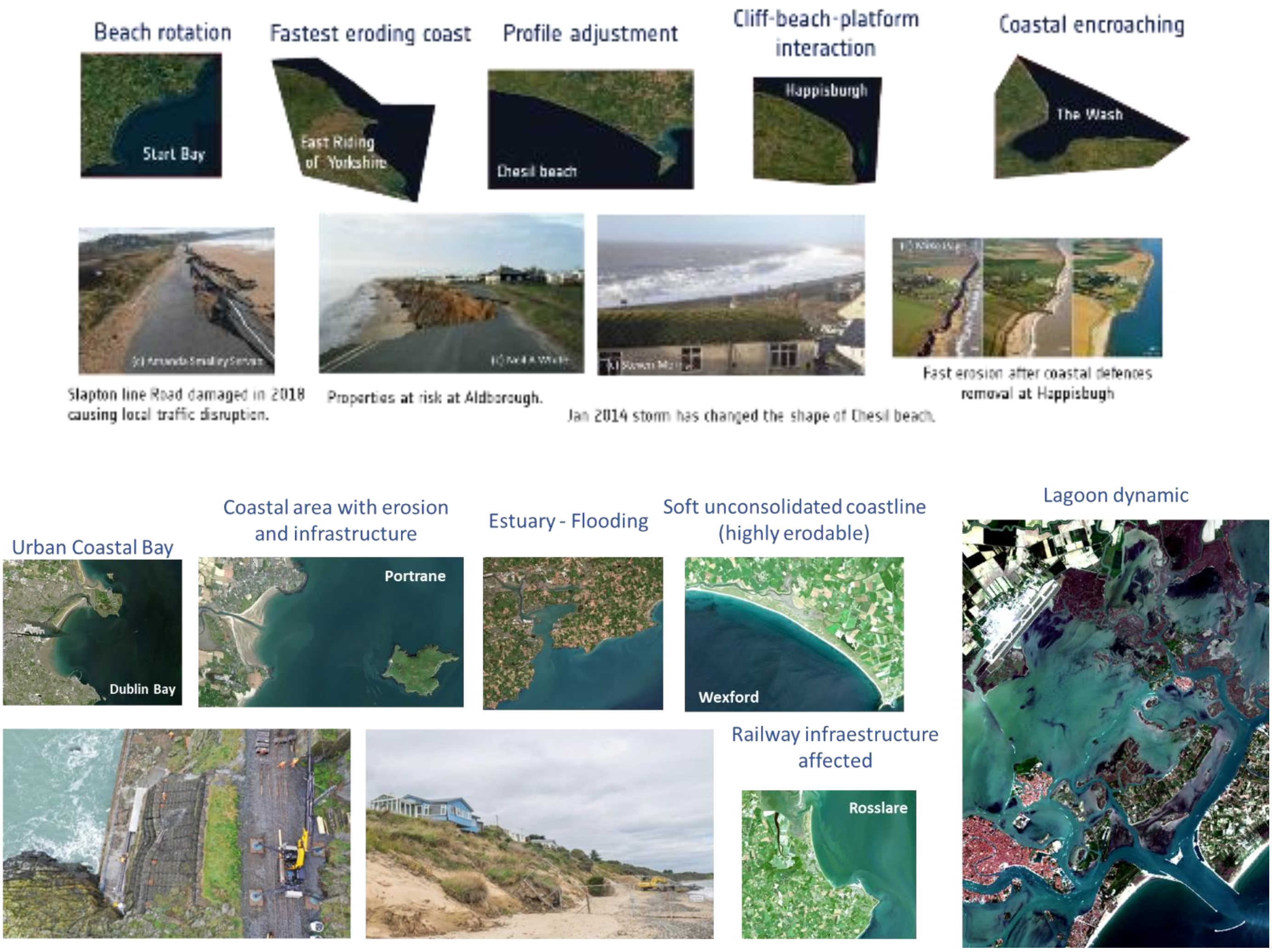


Table 2.4: Structural and morphological description of the study sites

With an **expansive product scope**, producing over 30,000 products which includes just over 5000 waterlines, **analysing over 4000 km** of coast. Spanning over **25 years of satellite imagery**.

Waterford:
1995-2022
157 waterlines
150 kms

Wexford:
1995-2022
161 waterlines
137kms

Dublin:
1994-2022
100 waterlines
267 kms

Cork:
1995-2020
90 waterlines
278 kms

Barcelona:
1994 – 2022
71km
404 waterlines

Tordera:
1994 – 2022
50km
335 waterlines

Cantabria:
1994 – 2022
750 km
380 waterlines

Cadiz:
1995 – 2020
522km
1069 waterlines

Castellon:
1995 – 2019
152km
242 waterlines

Loup:
1995 -2019
122 waterlines
183kms

Mingan:
1995-2019
216 waterlines
112 kms

Outardes:
1995-2019
233 waterlines
163 kms

Baffin:
1995-2021
76 waterlines
2 000 kms

Across 5 **partner nations**.

Start Bay:
1994 – 2022
153kms
157 waterlines

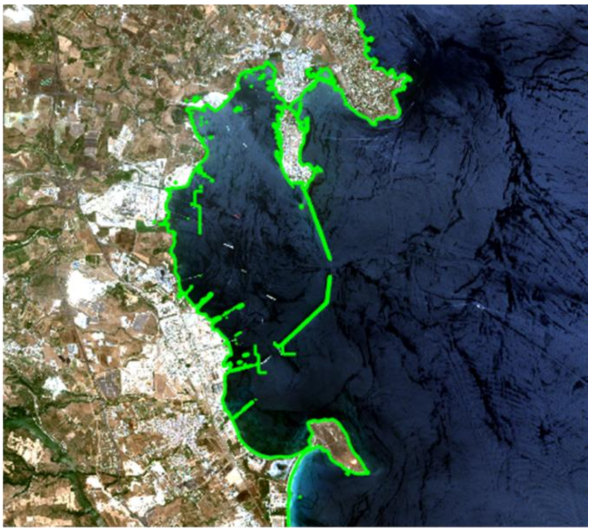
Perranporth:
2017 – 2019
56 kms
44 waterlines

Wales:
1994 – 2022
300 kms
334 waterlines

Chesil Beach:
1995 – 2020
185kms
114 waterlines

Spurn Head:
1995 – 2020
310 kms
168 waterlines

Venice:
1994 – 2022
1 150 kms
714 waterlines



Catane:
1994 – 2022
395 kms
396 waterlines

3 Conclusion

3.1 The key points

Continuous shorelines can be mapped over decades using the Sentinel and Landsat Mission data to a degree of accuracy that enables changes associated with seasonal variation, storm events and long tern shifts to be monitored confidently and reliably if the sampling by observations from satellites is dense enough to describe all the processes at a 10-to-30 m spatial scales, as shown by the validation results. In any case, EO allow a better sampling than the traditional in-situ surveys, thus decreasing the aliasing due to insufficient sampling.

The ability to derive this analysis is also scalable now to deliver regional, national, or global indicators.

As can be seen from the recommendation section above, there are many identified tasks that can still be developed to improve the current system and all the indications from this capability demonstration and the subsequent CCN clearly indicate that improvements and advancements are not only achievable but increase the ability to manage the coasts of partner nations.

However, one obvious and well-known constraint really does show up within this project and that is the location of the sites being observed makes a significant difference into what the optical sensors onboard the Sentinel 2, Landsat 5 and 8 could deliver. Needless to say, the sites with clear skies, calmer weather and clear waters of the Mediterranean rendered much better results across all product ranges both in terms of reflectance from the seabed as well as number of images available (in the order of 3) over the 25-year period.

A second indication is that the geomorphology of the coast plays a significant role in the determination of the datum-based lines. As these shorelines are manufactured from a waterline, i.e. an instantaneous observation of the border between water and land, the shape of the beach at the time that individual waterline was extracted is handed across to the resultant shoreline. This means that in areas with wide beaches of uneven gradient a shoreline based on a low water waterline will have a different shape to that derived from a high-water waterline and this difference must be acknowledge so that “coastal change” isn’t attributed to an information production factor.

A third point worth mentioning, despite being obvious, is that the waterline or instantaneous border between water and land is exactly that – the precise position at satellite overpass and of course waves ebb and flow every minute or so by up to two or three pixels and this variation exacerbates shoreline positional uncertainty especially in very shallow gradient wide beaches and when there is a long fetch in the local sea conditions.

Although the delivery of numerous shorelines which can bracket key events (manmade or natural) is a great leap forward in the understanding of our coastal regimes, the use of auxiliary data that help derive a shoreline from waterlines is definitely an area which can provide improvements. The main two contributors are tide and beach-nearshore slope.

The tide information used within this project has been mostly all observed tide gauge observations. This is due to the sites examined all being within developed nations who have a long hydrographic and navigational background. Most parts of the developing world are not blessed with this data and for those areas tidal models based on simple harmonic constants derived from the position of the moon and sun can be used. But even when working in the current set of sites it must be recognised that tide gauges are established for mariners entering ports. They can be used to represent entire coasts, but this adds an inaccuracy that a detailed coastal model might improve, however detailed coastal models require detail coastal bathymetry and close inshore but not connected to port approaches is not a priority to mariners.

The slope information by and large has been obtained from airborne LIDAR DTMs supplied by the partner nations; surveys being conducted every 2-to-5 years. This data is excellent however the cross-shore morphology seasonally changes, and within a long-time frame there is mostly likely only one or at best two data sets at different time frames. An alternative approach has been researched during the CCN. This approach attempts to extract a DTM from the waterlines when the weather and tide conditions are more or less stationary, i.e. the shore slope does not change too much. Clearly a cloud free region with numerous waterlines that capture a few high and low waters is better. These waterlines being linked to the tidal system also are affected by the issue raised in the previous paragraph, however this approach does easily allow the possibility of an annual or even seasonal slope to be generated. In addition, this process would also benefit those developing areas of the world with very minimal data on coastal slope. The next step would be to validate this approach against the LIDAR based DTMs.

This consortium was not looking for quick and easy wins. The focus throughout has been to test the missions and subsequent processors to derive as much value as possible in order to provide a truly scalable capability that can translate globally.

Another, and possibly equally obvious, conclusion was that by selecting a team of technically expert end users who are right at the heart of advising governments meant that the consortium had the toughest of audiences to please. This has meant that very real-world requirements have been placed and their professional judgment contributes significantly to how coastal regions are managed. This aspect has remained throughout the CCN and is especially important as user and supplier expertise in each other's domain has increased.

It is also fair to say that some products (the waterlines and shorelines) are commission ready now, ie they can be ordered and delivered now by any customer. The other products (Bathy-morpho Terrain Models and Seafront Maps) proved their worth conceptually but need to have more research conducted to exploit their full potential. There is vast amount of information that can be extracted from the seafront maps that has not been achieved during the project timeframe but will be extracted by the partners as they further exploit the data provided beyond the project.

The decision to co-register the optical images from Sentinel2, Landsat 5 & 8 proved invaluable to enable the resultant lines to be validated and demonstrate real changes on the ground and equally importantly across the times series of products. In addition, during the CCN the SAR images have been co-registered against the optical images, and this has significantly improved their reliability and utility.

This project has seen the development of individual processors in phase 2 that have evolved individually and although they theoretically form a processing chain in that one step has to be concluded before the next commences, they are more of a workflow. To create a processing chain that can be deployed on cloud platforms was considered the next logical step to creating a fully commercial system, and to a large extent this has been achieved within the CCN by refactoring all the processors to enable them to be orchestrated and reduce the human intervention and processing time/power required. Having stated that, the role of the human becomes one of quality control and assurance as there are still components where human intervention leads to a more tailored and precise product set. The current system is ready to produce "commercial ready" products, albeit in a semi-autonomous fashion and this capability is now available via the OCRE EO Catalogue. https://www.ocre-project.eu/eo-catalogue. As of writing this conclusion the UK has been awarded an OCRE voucher to continue to map the complete GB coastline, and all the other partner nations, (Ireland, Italy, Spain and Canada) have applied to OCRE for their nations. Within the ESA Global Development Assistance programme under the Disaster Resilience project this capability is also being applied to the coastline of Ghana.

In short coastal management based on products derived from Earth Observation has come of age and a "standard" has been established by the Coastal Change Consortium led by Argans Ltd which has only been possible due to the foresight and support of ESA and the collaboration of expert partners who represent their nations in the field of geology/hydraulics.

3.2 Summary of the validation and evalutation by partners.

The key points that have been derived from the partner End-Users that should be highlighted as the project comes to the end of its feasibility, and demonstration period are:

- The set of selected pilot sites made possible to validate satellite derived products in a wide variety of spatial scales and under different atmospheric and oceanographic conditions.

- Results presented on this document are based on the assessment of a sample of all products received. End users have received a very large volume of products and have been only able to validate a sample of all products received as indicated on the end user specific reports. Even after an extension of 1 year via the CCN this still remains the case, especially as an additional 1500km of coastal products has been generated within the year which will require the next few months outside the project to fully assess.

- All products contain the minimum required metadata. Product metadata is expressed in the product's name and associated metadata file.

- Most of the products, contain embedded relevant quality flags, the shorelines' quality assessment is derived through supplied GIS techniques. Quality flags are an important metadata for the end users which is now included in the product metadata.

- Accuracy of optical waterlines showed good agreement with reference and baseline data respectively in all pilot sites. The co-registration and waterline detection algorithm are ready to become operational. To improve this further will likely require a higher spatial resolution at the pixel level.

- The improved waterlines have provided an interpixel smoothing, much longer lines (in the order of 10 times longer than phase 2 lines) and the increased number available has been of great benefit.

- The shorelines allowed the assessment of morpho-dynamic processes (beach rotation, accretion and erosion) in different temporal scales and the identification of critical zones; however, this is not true for all geomorphological areas and the widest beaches with a very low gradient are the most susceptible to erroneous shorelines being generated.

There are still some limitations that should be highlighted:

- The water clarity is still a challenge to obtain satellite derived bathymetry in the nearshore and affects the analysis of changes and identification of seabed morphology.

- End-users requested a seamless Topography and Bathymetry Digital Elevation Model of the coastal zone (backshore, foreshore & nearshore) but it was only feasible to include the foreshore and nearshore. The interest on the seamless topo-bathy metric model still high among the coastal community.

Significant advances were made in terms of improving the knowledge on SAR derived products for coastal analysis and long-term monitoring. Nevertheless, the development of coastal information from SAR radar sensors is quite challenging. In particular, we have noticed that the accuracy seems to be sensitive to the coast orientation and the orbit of the image (ascending or descending). Because of the cloud penetration capabilities of radar detection, the use of this technology represents a big step in terms of coastal change analysis since it can fill the gaps from optical data and increase the temporal frequency of the time-series. The CCN provided an opportunity to improve the SAR derived lines and research the change that ben derived from these lines.

Finally, to obtain high quality products, some auxiliary data (in-situ measurements) are always necessary, and the quality and time cadence of this supplied auxiliary data has a direct result on the finished products. Steps have been taken within the CCN to decrease the reliance on auxiliary which is both of use to improve the cadence issue but also for product supply to developing nations where auxiliary data is sparse or non-existent.

End of Document