Coastal Erosion from Space

Coastal Erosion Time series in Foppoloburgh (GB)

Coastal Erosion events: in Herja (Spain) in Niles (Ireland) in St. Laurent mouth (Canada)

FINAL Report (April 2019 to March 2021)

Ref: SO-RP-ARG-003-055
Date: 31/01/2021
Customer: ESA
Contract Ref.: 4000126603/19/I-LG

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Signatures

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<tr>
<td>Prepared by</td>
<td>Martin Jones</td>
<td>ARGANS</td>
<td>31/01/2021</td>
</tr>
<tr>
<td>Authorised by</td>
<td>Francois-Regis Martin-Lauzer</td>
<td>ARGANS</td>
<td>15/02/2021</td>
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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
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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1 Executive Summary

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). Having developed 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 2800km of coastlines were observed across 15 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. All products have been validated and an independent validation paper will be released by each participating nation.

The outcome; 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.

ARGANS Limited and its partners have reached the end of a 2-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. The partnership consisted of an EO based information service provider group of Earth Observations and Data experts comprising ARGANS Ltd (UK/Fr), isardSAT (Spain) and adwaisEO (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.

The consortium has developed customer ready co-registered waterlines and shorelines seasonally covering 25 years that have been validated by the leading technical geomorphological experts within the four partner nations. These products can be scaled to cover complete nations worldwide. We have developed a land classification map that describes the coastal strip, including urban waterfronts, marshes, dunes and their inter-annual changes. 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:** 2800 km of coast analysed across 4 nations, spanning over 25 years of satellite imagery.

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

**Global Outreach:** Over 1300 delegates from 30+ nations registered at a series of workshops and webinars.

**Impactful Research:** Peer-reviewed paper published in the 8th International Symposium “Monitoring of Mediterranean Coastal Areas. Problems and measurement Techniques”. In addition, several papers are under preparation to be submitted to leading high-impact journals.

The Coastal Erosion Project aims to demonstrate the value of EO data 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. Then followed a period of design and development to deliver a range of products that 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.
This project has seen the development of 6 processors that have evolved individually and have formed a semi-automatic processing chain which starts with a selection of suitable EO data. 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. These images and then fed through a Waterline processor to extract an instantaneous snapshot of the land/sea boundary before being processed via a shoreline processor to tie the waterlines to known tidal datums. At the same time, these co-registered images are also processed via an IDA processor to derive Bathy-topo Terrain Models and associated features, whilst another processor classifies the coastal strips land cover types averaged over a season. These products were then stored in an FTP server to be 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.
2 Introduction

2.1 Why the project was needed and the funding.

2.1.1 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. 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.

Figure 2.1: Cliff erosion, south of Start Bay (UK)

2.1.2 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.

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 funded for 2 years and has been split into two phases. 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.

2.1.3 The Team

For our project four nations were engaged building a trusted relationship with those institutions who are vested with the responsibility to advise their national systems. In addition, over 2000 linear km of coastline have been observed over 15 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 (IHCantabria) 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.

2.1.4 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 “Master”) 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 Master and the Slave 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.

2.1.5 Outreach

This has been a challenging component of the project since the arrival of the global pandemic COVID-19. The new way of working has very much been via tele-networking; however, a paper was published via the Eighth International Symposium Monitoring of Mediterranean Coastal Areas. Problems and Measurement Techniques Livorno (Italy), June 2020 DOI:10.36253/978-88-5518-147-1.41 and presentations were given at the Living Planet Symposium in Milan pre lockdown. The mandated workshops 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. 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 enables the products to be accessible via a webservice to those authorised.

2.2 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. 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. During this phase it was agreed that each nation would be afforded a dedicated 4 weeks 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. 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.
3 Summary of deliverables

The URD (AD-6) describes the use case, i.e. what the User Group hope to gain from the exercise. This process is supported by one of EVALUATION of the worth or value of the products i.e. an assessment. Does the utility give you something new or novel? Do they change how you think or act in the future? Did they meet your expectation? This is a task delivered by the User Group.

The RBD (AD-8) describes the product requirements. These products need to be VALIDATED i.e. ground truthing where possible and potentially assessed against known wisdom and knowledge. This is a task for Local Expertise and a description of how this was conducted is covered within the PVP (AD-9). In theory the expertise should be independent, however within this project the Local Experts are the User Groups supported by their outreach colleagues.

Although the TSD (AD-7) and associated ATBDs describe the process and theory, it is important to appreciate that the processors are designed based on those technical specifications and they all needed VERIFICATION that the design plan was followed and that they work as planned. This task was conducted by the Service Providers. In a car production line this would equate to a Factory Acceptance Test...” does it work and deliver as designed?”

The value proposition outlined in phase 1 of the study as described within this version 1 of a Technical Specification specifically focused on a processing chain that then delivered intermediate mapping (waterline extraction, land-use extraction and terrain model calculation).

The Technical Specification Document and its accompanying Algorithm Theoretical Baseline Documents were proved fit for purpose and enabled the production of waterlines and derived shorelines to be manufactured. Currently the process is still a little labour and processor intensive but has delivered accurate and repeatable data that has been validated and perhaps more importantly evaluated by an authoritative user community who have been engaged in the design and development process throughout.

The future will be to deliver bespoke (to the decision maker) services such as a Coastal Vulnerability Index to identify those areas of coastline that will be subject to change that in turn will enable a Coastal Risk Index to be assigned, i.e. an assessment of loss, damage or destruction of assets that would penalize coastal communities.
3.1 The User Requirements Document


The User Requirement Document was one of the key documents to establish the direction for the project and was delivered at Milestone 2 as part of the Mid Term Review.

The scope of the project was to develop & demonstrate innovative EO products that would be used by end-users in charge of monitoring (surveyors) and managing (coastal stakeholders) coastal erosion. The surveyors and coastal stakeholders who were consulted to elaborate this document are represented by four champion user organizations (BGS, GSI, MITECO and Government of Quebec). The interest of all champion users organizations represents the requirements of public and private surveyors as well as the requirement of Government Agencies, public and private entities in charge of both Integrated Coastal Zone Management (ICZM) and Coastal Flood and Erosion Risk Management (CFERM). To maximize the use of the outcomes of the Coastal Erosion Project, additional end-users on each of the champion user’s organization countries (United Kingdom, Republic of Ireland, Quebec, Spain) were also approached to express their interest on contributing to the definition of the end-user requirements.

An iterative process was followed to create an individual consolidated URD (AD-6) for each one of the champion user organizations. During the end user kick-off meeting on 3rd May 2019, the URD submitted with the project tender was reviewed and the items that required further details identified. The required steps to produce a consolidated URD by the project mid-term review (i.e. final version of URD) included the production of two versions of the URD. The URD v1 was produced by consolidating and synthesizing the URD v0 submitted with the project tender and is limited to the URD of the champion user’s organization. The URD v2 was an extension of the previous version by including URD from the broader community for each of the four countries to which the champion user’s organizations belong. A large number of other end users additionally expressed their interest on expanding the product requirements described by the champion end-users presented in this document. The list of interested parties continued to grow throughout the project. At the time of writing the URD expressions of interest from institutions have been
received from the following country partners; UK (Environment Agency, UK Hydrographic Office, Coastal Partnership East, WSP Group, HR Wallingford, Univ. Southampton, Universities of Plymouth, Cardiff, Liverpool, Cambridge Birbeck and Edinburgh, the National Oceanographic Centre, Coastal Channel Observatory, Centre for Environment, Fisheries and Aquaculture Science, Scottish Environmental Protection Agency); Republic of Ireland (Office of Public Works (OPW), Ordnance Survey Ireland (OSI), Environmental Protection Agency (EPA)); Spain (Instituto Geográfico Nacional (IGN), Instituto Hidrográfico de la Marina (IHM), Autoridad Portuaria de Barcelona; Maritime Engineering Laboratory, LIM/UPC; Universidad Politécnica de Valencia, UPV; AZTI Tecnalia).

All champion user organization expressed interest on products that represent the coastal change over time of different observable geometries (1D, 2D and 3D) for different purposes. The commonalities and differences among products are discussed in detail within the URD, however a common theme showed a shift from shoreline (1D) products to space (2D) and volume (3D) products. It is interesting to notice that, while end-users are still interested on shoreline indicators of coastal change (35% of products are 1D), there is an interest shift to area (24% of products are 2D) and most evident towards volume products (41% of products are 3D). This shift was expected as the coastal stakeholder community is on the agreement that any policy for coastal erosion should increase coastal resilience by restoring the sediment balance and providing space for coastal processes (EUROSION, 2004).

Spatial scope limited to the coastal zone, but end users also expressed interest beyond coastal zone. Following from the previous point, it was clear that while the shoreline indicators are well within the coastal zone some of the volume products, such as the bathymetries, are of interest for the coastal stakeholder in charge of ICZM of areas further offshore. For example, BGS is supporting the offshore wind industry that is developing on the shallow continental shelf of the Dogger Bank by interpreting bathymetry and subsurface data. Due to the cost of covering the whole region of the Dogger Bank (i.e. about the size of greater London) with traditional marine bathymetric surveys, developers focus their resources to measure bathymetry at locations where there is potential for installing wind turbines and not at the edges of the banks were scientist can extract more useful information. Satellite derived bathymetry could potentially provide bathymetric data in a cost-effective way on the latter areas. Since coastal erosion within the
coastal zone has been identified by coastal stakeholders worldwide as an issue that need urgent attention, the consulted champion user organization agreed on limiting the spatial scope of the products requirements just to the coastal zone.

As noticed by Boak and Turner more than ten years ago, the datum-based shoreline indicator provides a more objective detection technique than the proxy-based shoreline indicators. As Topo-Bathymetric Digital Elevation Models (now renamed as Bathy-Top Terrain Models BM-TM to distinguish them from Satellite Derived Bathymetry, a navigationally validated surface) become more accessible, it is likely to be the preferred shoreline indicator for ICZM and CERM in the future, but their applicability to the analysis of historical trends is more limited (i.e. historical mapped shorelines were mapped using visually discernible features to produce proxy-based shorelines). As a result, both datum-based and proxy-based shoreline indicators are required from the champion user organizations. Interest of End-Users on listed products goes beyond the 25 years historical record.

All champion user organizations expressed a common interest on using the ca. 25 years EO historical database to obtain a time series as long as possible for each EO product. The value of long-time series comes from two perspective. First is the intrinsic value of actual change-data over as long a period as possible. Second is the necessity of long-time series to test, calibrate and use predictive modelling. Quantifying future coastal change in order to assess risk, for example, will necessarily rely on computational predictive models, and such models are only ever as good as the training data available to them. How many more years into the future the described products will be required was also discussed. This is relevant to define the years of interest for the service specification for units currently on operation (i.e. Sentinel 1 and Sentinel 2). ICZM and CERM involve time horizons of 100 years and it is in the interest of all champion user organizations to be able to assess coastal change over a similar time span. Because EO data cover only the last ca. 25 years of coastal change, it is suggested here that the products described here will also be required over the next 75 years (i.e. until 2095) until a complete 100 years EO derived product database becomes a reality. This has only minor consequences to the outcomes of this project, but it is worthwhile to keep in mind that a data gap larger than 25 years still exists.

Coastal State Indicators (CSI) other than shoreline indicators are considered here as a sub-category of the 3D products. The fundamental difference between CSIs and 1D, 2D and 3D
geometrical products is that geometrical products have either a long tradition of use (i.e. shoreline indicators) or surveyors have a mandate to monitor (i.e. elevation, bathymetry) while CSIs are often site and stakeholder specific and therefore more difficult to standardize. Detailed specifications on geometrical accuracies of outputs are aspirational requirement needs for the future, and the champion organizations expect to know of the feasibility, considering results with; (i) available EOs of the last 25 years to assess an average erosion rate at the decadal time scales, (ii) COPERNICUS and commercial higher resolution EOs of last 5 years to monitor erosion and accretion for the management of the coastline by local authorities, (iii) using state of the art sub-pixel resolution techniques.

3.2 The Requirements Baseline Document

This Requirement Baseline Document (RBD, AD-8) presented the requirement baseline for the project and fulfilled the requirement for Milestone 1 of the first phase of the contract with ESA.

It describes the Requirement Engineering, linked to the User Requirement Documents (URD) produced by the authoritative User Group, in the framework of the ESA requirements. The RBD can be access via the https://coastalerosion.argans.co.uk website.

The Requirement Engineering process defined, documented, and maintains the requirements: the requests & requirements are gathered and also a service and products are defined. The following steps were conducted; requirement specification (ESA SOW and URD), the requirement specifications, requirements verification of the processors, the requirements validation of the products and a requirements management section.

The techniques used for requirements specification by ARGANS Ltd and the end-users were threefold: reviews of available documents, interviews of the end-user’s stakeholders and beneficiaries, and brainstorming that was concluded by a workshop in Santander by July 2019. The requirements specifications were drawn concomitantly by the end-users and by ARGANS Ltd, the latter working from the URD versions. The requirements verification was made of a pre-feasibility study with the views of coastal geomorphologists in mind. Requirements validation, i.e. the set of tasks that ensure that the system and the EO-products were built is traceable to
end-users’ requirements has been laid out within the PVP drafted by the authoritative User Group.

With respect to the Requirements management, i.e. collecting, analysing, documenting, tracking, prioritizing, and agreeing on the requirements, this has been performed by versioning the RBD.

The products described in the initial URD were considered in a pure academic manner without reference to the capabilities and limitations of specific EO missions and sensors. However, these EO-products (solutions) were specific to the countries involved (UK, Ireland, Spain and Canada), and to the sites chosen for demonstrations. However, five basic EO products have evolved:

- Four generic EO products at level 2, i.e.
  - two proxy-based shoreline indicators (waterlines, and littoral lines)
  - one subsequent datum-based shoreline indicator (shorelines based on tidal datum and cross-shore profiles, calculated from waterlines), and
  - one plain shoreline indicator (bathy-topo morphology of the shore-bed),
- One statistical Level-3 product (a classification seafront map of the coastal strip).

In addition, time series products have been developed for all of the above.

Time sampling is critical to assess the erosion status of the shores whose dynamics are complex with a quasi-equilibrium built on a series of erosion events and recovery periods superimposed on trends of erosion or accretion depending on the local availability of materials introduced in the ocean. Typically, shoreline retreat is a consequence of processes operating in two distinct scales: i) **Short-term large-scale** morphological change, due to extreme conditions (storm conditions, high impact waves / surges causing break-up of land barriers) that are not rebuilt by natural accretion/replenishment; ii) **Long-term small-scale** morphological change, including natural seasonal cycle of erosion and accretion. EO resolution (VHR) and spatial accuracy is core for coastline shift estimation accuracy in the latter case, whereas HR observations are deemed acceptable for the former. To complete a time-series, all EO missions shall be considered; the best approach being to use same algorithms for all optical EO missions’ data and for all SAR EO missions.

All EO-products have been produced by automated processors, which can be parametrised according to the area of interest, however the prepossessing stage often require human
supervision and intervention, especially when selecting suitable imagery to be processed. These parameters have used a suite of multi-spectral indices (e.g. NDVI, NDWI, MNDWI, etc.) and are represented in a mapping system / projections or geodetic systems, which are configured to the scale and conditions of region of interest. Furthermore, all data has been presented in a format that can be utilised by the Geographic Information Systems (GIS) of choice.

Additional information on the system that should be developed to deliver the service, and some examples of the EO products which have been prototyped, including outputs of the pre-processing steps are published in a separate Technical Specification Document (TSD).

The service providers have embraced these requirements while complimenting them with the coastal monitoring considerations of the scientific and coastal management industries.

The URD mentions explicitly that “detailed specifications of outputs are aspirational requirements needs for the future, and the champion organizations expect to know of the feasibility, considering results with; (i) available EOs of the last 25 years to assess an average erosion rate at the decadal time scales, (ii) COPERNICUS and commercial higher resolution EOs of last 5 years to monitor erosion and accretion for the management of the coastline by local authorities, (iii) using state of the art sub-pixel resolution techniques [to reach the expected performances if not attainable at pixel resolution]”.

The Requirements Baseline Document is a fundamental and definitive component of the projects delivery as it establishes what would be required by the authoritative end users who are the national institutions that deliver the real effects on the ground and then matches these needs in the context of the EO capabilities that exist. It draws out the significant value that EO can deliver (set against more traditional methods) and optimizes the potential product types with this in mind. In effect the RDB set the agenda for rest of the project but in a way that also enabled freedoms to push the boundaries of research and exploitation which continued into the implementation phase 2.

The key findings can be characterized in the following bullets.

- A team of expert and authoritative users (Our partners) were set the task of identifying the problem sets and requirements that they considered need to be addressed.
• These experts were not constrained by the current capabilities that Earth Observation systems currently deliver.
• The URD is both an annex to the RBD and a stand-alone document as the official “statement” of the Authoritative End User Group, it has been published in its own right.
• The analysis process refined these “pure” academic user requirements to “fit” the current capabilities of EO, heavily focusing on the unique attributes of EO exploiting the significant value that EO provides over traditional and currently adopted expensive and labour-intensive methods.
• This analysis has led to five basic product types and the requirement to additionally design and operate these products within a time series, optimising automated processes and processors.

The delivery and improvement of the five product types that have been identified have shaped the second phase of the work moving forward as the project refined their definition and designed automated processes to seamlessly deliver them. By adding the additional time series component, the project has also demonstrated a unique way to observe coastal change and enable traditional modelled approaches to be better understand and re-evaluated. This level of production is only practical and achievable due to the exceptional properties of the Sentinel satellites under the Copernicus programme due to the considerable effort that is placed on the quality control, validation and verification procedures that have been established. Without these procedures being in place the ability to compare over time would be almost impossible. The ability to “blend” these attributes with the high definition that commercial VHR satellite data provides (via the ESA TPM programme) optimises the “best of both” approach and has enabled revolutionary insight and understanding of the coastal change processes to be delivered that would be hitherto unrecognised based on current traditional survey procedures.

3.3 The Technical Specification Document

A Technical Specification Document (TSD, AD-7) was developed and includes the design specifications for each of the EO products, which have been designed to meet the requirements of the European Space Agency (ESA) and the authoritative end-user community within the scope
of assessment and monitoring of morphological changes of 1000 km of coastlines across the four project member states (UK, Ireland, Spain and Canada) going back 25 years.

This document presented; the System Engineering which disseminates the requirement baseline information, producing several functional requirements that were considered in delivering the products that have been identified by academic and professional stakeholders; an assessment of Value Engineering, identifying how EO products compare to existing techniques currently applied to the needs of the coastal management community; a detailed account of the EO products that were developed to meet the user requirements, including a critical review of potential EO solutions and chosen algorithm description; followed by the processors details captured in ATBDs. Finally, the details of EO and auxiliary data procurement were described.

To establish the requirements of the authoritative end-users and thereby shape the design specifications for innovative EO products, a requirements baseline was established through consultation with the group of authoritative coastal managers (and their outreach information collection), who are included as partners on this project.

Independently, these users produced a list of requirements needed to derive effective coastal erosion assessments and monitoring. Created as an academic exercise, this list was not constrained by the current capabilities of current EO technology.

This User Requirement Document (URD) was delivered to the service providers, where its contents were refined to meet both the requirements of ESA (i.e. exploitation of the 25-year archive of EO data) and the capabilities of EO data now and throughout the archive history. This analysis resulted in the Requirement Baseline Document described above.

Importantly, the RBD focused on the unique abilities that EO offers, adding significant and complimentary value to the design of products when compared to expensive and labour-intensive non-EO products currently available to potential stakeholders.

However, this project is based upon selling the value to Coastal Erosion from the Copernicus Sentinels and historical EO missions. It is NOT about replacing current in-situ and ground-based practices performed by competent institutions and authorities, more one of providing complimentary evidence using EO and so the TSD describes the blending and optimizing of the URD need, the RBD to describe the products that were developed and delivered.
A file naming convention was an essential component of the design and development as it is important that folders, documents and records are named in a consistent and logical manner so that they can be located, identified and retrieved as quickly and easily as possible. This proved invaluable for the Data Access Portal pilot demonstration housed within the website. https://coastalerosion.argans.co.uk

It should be noted that many of the products are lines and consequently will be ideally stored in shape files compatible with GIS software like QGIS and ArcGIS.

The relationships that have been adopted throughout the project have been one of constant dialogue between the User Group and the Service Provider Group as well as internally within each sub-group. The team have presented the work at various conferences and had planned to continue this practice throughout the project however the arrival of the COVID-19 global pandemic required plans to be amend and virtual engagement became the order of the day.

3.3.1 The Algorithm Technical Baseline Document

Algorithm Technical Baseline Documents (ATBDs) aim to describe all the research, the state of the art and development behind our processors, all processors’ steps, inputs and outputs are detailed in those documents.

To fully describe our processors, six ATBDs are available in annexes:

- SO-TR-ARG-003-055-009-ATBD-GL in annex A, describe the geolocation processor which allow a perfect overlap of all satellite observations used in the following processors.
- SO-TR-ARG-003-055-009-ATBD-WL-VNIR in annex B, present the Liulezek_CoastL processor. From optical imagery the processor extracts a waterline, computing a vector line representing the instantaneous the land / sea boundary.
- SO-TR-ARG-003-055-009-ATBD-WL-SAR in annex C details the extraction of the instantaneous land/ sea boundary from SAR imagery.
- SO-TR-ARG-003-055-009-ATBD-SL in annex D present the shoreline processor which transform the instantaneous land/ sea boundary into a datum-based reference line using modelled or measured auxiliary data on the sea state and beach slope.
• SO-TR-ARG-003-055-009-ATBD-SF in annex E describe the seafront processor which provide a set of littoral lines extracted from a backshore classification map.

• SO-TR-ARG-003-055-009-ATBD-BM-TM in annex F outline the bathy-morpho terrain model processing. From optical data set the processor provide morphological maps of the seabed’s features.

For all processors, the chosen methodology/model relies on a thorough analysis of previous studies and publications, outlining their progress and limitations. The sketch of our processors is then presented with a physical and mathematical description allowing a theoretical proof of concept. A more detail presentation of processors performances details several tests and their result to compare processors outputs with ground observations. Processors and products validation is performed by the end-user community and their results are presented in section 4.

3.4 The Product Validation Report

The purpose of the validation report was to provide the confidence to the reader that a formal checking process has been conducted from the initiation of production through the delivery of the products and then covering the value and utility of those products for the purposes that the user community initially identified.

This Product Validation Report therefore consists of three sections and follows on directly from the processes and procedures outlined within the Product Validation Plan (AD-9).

• The Quality Process within production (Verification and Quality Control)
• The Product Validation Review by the user community of the products
• The Evaluation Report by the user community on the utility of the products.

These steps tell the complete story from initial downloading of selected images (and why those images were selected) to how the user community have exploited the information and products in support of better understanding coastal erosion processes and designing innovative services to those responsible for monitoring and managing the effects of coastal change.

The key tenet of the Quality Process has been to draw together the Verification steps which are currently identified within each individual processors’ ATDB, identify the Quality Control and
Assurance process adopted. Verification and quality control provide information on the processor’s stability and on the precision of the supplied products.

The Validation and Evaluation compiled by the User Group (BGS, IGS, IH Cantabria and Arctus) is the key component of the report but can also be read as national stand-alone documents.

Verification and quality control are necessary steps in the production chain to check that the obtained EO products accomplish the precision and quality expected and enable those products to be compared to previous studies and surveys. Comparison with in-situ measurements is impossible, as EO products come from an instantaneous but greatly repeated satellite snapshot. Thus, validation checks have been achieved in consistency with results from previous surveys, considering the temporal and the spatial resolution of the EO products. If previous survey results provide different and complementary information, an intersection of common information is needed in order to perform comparison.
4 Processing Chain (Processors and associated products)

4.1 Introduction

This project has seen the development of processors 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 would be the next logical step to creating a fully commercial system, however the current system does produce commercial ready products, albeit in a semi-autonomous and labour intensive fashion.

4.2 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 glob i.e. 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:

CE_YYYYDDMMHHSS_<type>_<category>_<level>_<bbox>_<qualifier>{_<YYYYMMDDHHMM>_<YYYYMMDD>}.ext

where the first date is the acquisition date, to only the accuracy of a minute, and the end date is optional. The final date is the processing date used to distinguish versions of the same product. The <bbox> is the bounding box of the feature as the latitude and longitude of the lower left and upper right corner. e.g. 411021N014826E-413304N023909E. The <type> is a two-character code e.g. WL | SL | BT | LC, the <category> a two-character code e.g. OB (observation-based), DB (datum-based) or MB (model-based). The <level> is a two-character code: L2 (single observation), L3 (multiple observations), L4 (data fusion product). The <qualifier> is used to specify the mission (L5 | L8 | S1 | S3) and datum e.g. HAT_S2 for the highest astronomical tide from a Sentinel-2 image.

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 \_OMETA\_. The naming convention is fully specified in the Technical Specification.

### 4.3 The Geolocation Processor

Landsat 5 and 8 as well as Sentinel 2 were co-registered in order to improve the positional accuracy of each pixel by employing commercial images as the reference (or so-called “Master”) image. These commercial images were provided under the ESA Third Party Mission agreement and are subject to the terms and conditions of that arrangement. There is then a need to identify common points or "tie-in points" that feature in both the master image and are also present in the slave images that require co-registration. These “tie-in” points were generated as a grid with an ability to define the spatial distance between each tie-in point between the master and slave images. The tie-in points were then filtered based on a reliability assessment and a similarity analysis to ensure that only reliable shifts are used. The spatial changes or shifts to the accepted tie-in point are then applied to the slave image. This process is then repeated for all the "slaves" 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.

![Co-registration principle](image)

**Figure 4.1: Co-registration principle**

Two inputs elements of the co-recording model are essential, a master image and a target one. The master image needs to be a very clear image (cloud free, glint free) at a high pixel resolution.
The target image is the one which will inherit the localization precision of the master image, also the resolution, without modifying these radiometric properties.

The capacity to link the two images depends on the identification of similarity points on both entries. The application of the SSIM index on a filtered points grid can measure the similarity between 2 images in a way close to human subjective perception; it starts from the observation 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 master and slave image.

![Image](image.png)

**Figure 4.2: Co-registration process for time-series**

To launch the co-registration process across a time series of images captured over the same location, the same procedure must be applied while keeping the same reference image for all of the simulations in order to provide the best results with less error. In this way we will obtain a better rendering materialized by perfect alignment between all the images (Figure 4.2).

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 core between same points on the master and slave 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 4.3: SSIM index comparison before and after the co-registration process

4.4 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 points in the digital images at which the image characteristics change sharply when coming landward from the sea. They are important as they describe the variation, and dynamic nature of the coast by delineating the land/sea boundary as it changes through time.

Although useful CSIs by themselves as outlined above, 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. This process is described in much more detail later.

The waterline production is affected favourably by increasing beach gradient, water clarity, calm seas, and to a lesser extent by smaller tidal ranges, but these physical components all interplay to differing levels in different regions.

Figure 4.4. Chesil beach, Dorset, UK. An example of a beach of steeper gradient and with increased water clarity in this image

Figure 4.5. Cadiz Bay, Spain. A river plume with increased suspended sediment generates false edges in the affected section of waterline
The 1D proxy-based shoreline indicator (waterline) product is based on EO data for a 25-year period using different spectral properties of optical data sets as reported for studies exploiting data at different resolutions (namely LANDSAT 5 and 8 at 30m and SENTINEL-2 at 10m, but also very high resolution (VHR) (including SPOT, IKONOS, PLEIADES and Worldview at 5m or less). And with a naming convention that captures spatial and temporal information specific to that waterline. (Details of the waterline production process are described more fully in the annex Waterline Processor ATBD in annex B).

Inputs to the waterline processing algorithm:

- Co-registered optical image (High resolution (HR) or VHR)
- Rough coastline from auxiliary data (optional)
- Region of interest (ROI) file containing longitude and latitude in decimal degrees (optional)

A pre-requisite to processing is that reference optical images need to be radiometrically corrected. As we are exploiting a comparative study over decades, all images need to be co-registered from a master image.

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 a spectral index.

The user can choose a specific spectral index to apply to the image or by default the processor will compute a BNDVI image. A binary classification performed based on this ratio image will allows extraction of a rough coastline using a fix threshold, this coastline is a “guide” along which a small kernel slides to produce a more precise waterline using an adaptive threshold. Edge detection methods extract the produced waterline, and a vectorization step will save the waterline in vector format.
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 two geometric characteristics of the waterline, the line confinement index (LCI), and the line length (L). 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. This allows for data cleaning and can also be combined with an external QC approach based on a heatmap concept. This approach looks at the repeatability of waterlines in a series, and again assigns a score between 0 and 100, with sections of waterline that overlay/overlap with the other waterlines in the series assigned a higher score, and those that are random or isolated are assigned a lower score.

The waterlines are vectorized and available on a 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.

4.5 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.

On the same way as the optical SAR waterline processor, the SAR waterline is generating 1D lines from every input SAR image. The main steps of the process are: Enhancement, Segmentation, Healing, Vectorisation and Quality Control. 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 4.6. 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, Envisat, ERS 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 order to provide the classification and outlier rejection properly.

The comparison between SAR and optical waterlines can be unfair without understanding the differences between them. The different geometry can produce biased lines or lines that are not really picking up the coast. 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 worse resolution that the Sentinel 2, which will also impact the precision of the lines.

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 4.7.** 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 4.7, 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.
4.6 The Shoreline Processor

The shoreline processor transforms 1D vector waterlines into 1D vector shorelines utilising metocean 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 still 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 1D ESRI Shapefile 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. The waterline is first split into segments, each segment is assigned a slope value and an estimated water level is calculated. This estimated water level is calculated by interpolating a value between bounding tidal measurements locations and factoring in the effects of wave run up. The datum height is also interpolated based upon the waterline segment’s 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 completed, they undergo quality control. Internally, the shorelines are analysed based upon a Line Confinement Index, this determines the ratio between line segment length and the spatial extent/footprint of the line segment. Long but highly confined lines are flagged as erroneous artifacts of the waterline processing that have been carried through to shoreline processing. Externally, the shorelines can be analysed using a heatmap methodology whereby repeating shoreline positioning indicates a high likelihood of shoreline accuracy. The whole process is detailed in the shoreline ATBD in annex D.

The shorelines can also be analysed in GIS software to highlight areas of erosion and accretion, and in some cases estimate change rates. The full methods for this can be found in the GIS Products tutorial (LINK).
4.7 **The Seafront processor**

A map of the various coastal ecosystems is a need expressed in the End-users requirement document. Those maps aim to help in the characterisation of coastal risk management practices, and in the restoration of wetlands. 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 resulting map is then read to automatically extract coastal areas limits. We can identify two or three main coastal areas, the backshore – the use area with main human activities, agriculture, civil works; the intermediate area – optional, it 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, usual zone for accretion and erosion.

![Figure 4.8: Identification of the 3 coastal areas et Barcelona coast, backshore (yellow arrow), intermediate area (red arrow) and littoral zone (black arrow)](image)

The classification is performed using the IOTA² (Infrastructure pour occupation des sols par Traitement Automatique Incorporant les Orfeo Toolbox Applications) processing chain which use
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 have to well represent all the wanted classes taking into account the spectral variability of the land cover. If the classification accuracy and precision rely on the quality of the training data set, a good training data set need to represent all present spectral characteristics present in the image while minimizing the intra-class variance, to have homogeneous class, and maximizing the inter-class variance to have an efficient discrimination of the land cover. The processing chain then compute a classification map according to the spectral characteristics of all classes define in the training data set. The whole classification process is well detailed in the seafront ATBD in annex E.

Figure 4.9: Classification map of Start Bay area for the year 2017

The use of multiple optical imageries through the year allows us to capture some dynamic phenomenon such as 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 ecosystem along the coast bringing knowledge on the various erosive context.
The second part of the Seafront processor read the produced classification and delimit 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 4.11: 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.

4.8 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 on 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 needs 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.

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 were 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).

![Confidence map for the DATE](image)

**Figure 4.13 Iles de la Madeleine Confidence map for the DATE**

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).
4.9 Metadata

Metadata is data that provides information about other 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:

Descriptive metadata is descriptive information about a resource. It is used for discovery and identification. The file naming convention provides sufficient & necessary 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 4.14: Metadata Schema Ontology

Table 4.1: 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:

```json
"GeneralInfo": {
    "ProductName": null,
    "ProductDescription": null,
    "ProductType": null,
    "ProductCategory": null,
    "ProductLevel": null,
    "ProductBBox": null,
    "ProductQualifier": null,
    "LastModifiedDate": null,
    "ProductPath": null,
    "ProductURI": null
},
```
An important property of the metadata is that it incorporates a representation of the processing history. This is provided by including the name and URL of all 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.

This traceability is implemented by chaining metadata such that the metadata of a downstream product contains a link to the metadata of the input product and so on to the source image metadata. Metadata content is described in the Metadata.xlsx table, the current version available on the website documentation page.

4.10 Summary

The project selected 15 sites to study with a range of different and often very complex geomorphologies, in order to test the limits of the technologies.
With an **expansive product scope**, producing over 22,000 products which includes just over 3000 waterlines, **analysing 2800 km of coast.**

Spanning over **25 years of satellite imagery.**
Across **4 partner nations.**

- **Loup:**
  - 1995-2019
  - 122 waterlines
  - 183 kms

- **Mingan/St Laurent:**
  - 1995-2019
  - 216 waterlines
  - 112 kms

- **Outardes:**
  - 1995-2019
  - 233 waterlines
  - 163 kms

- **Start Bay:**
  - 1994 – 2020
  - 153 kms
  - 89 waterlines

- **Perranporth:**
  - 2017 – 2019
  - 56 kms
  - 44 waterlines

- **Chesil Beach:**
  - 1995 – 2020
  - 185 kms
  - 114 waterlines

- **Spurn Head:**
  - 1995 – 2020
  - 310 kms
  - 168 waterlines
5  Validation and Evaluation

5.1  Summary The approach

The adopted validation protocol by the Coastal Change Consortium is a multi-step conformity checking process, performed by both the Service Providers and the End-Users, and is illustrated in Figure 5.1. This validation protocol assesses the degree to which the Earth Observation (EO) products fulfil the technical requirements (reliability, accuracy and precision) as well as the added value of EO products for coastal management purposes. The four steps involved in the proposed validation protocol are: verification, quality control, validation and evaluation. This document contains the results of the validation and evaluation obtained by BGS as enrolled end-user. Validation is defined here as the conformity check process of the EO products technical and functional specifications against a target specification. Evaluation is defined here as the conformity check process of the EO products against user expectations.

Figure 5.1: Validation protocol is approached here as a multi-step conformity checking process done by both the Service providers and End-Users.

The target specifications used to validate the EO products used by the enrolled End-Users are different from the one used by the Service Providers. End-users, have used the aspirational end-user requirements outlined in the User Requirement Document (URD) and summarized in Appendix G, while service providers have used the requirements of what they considered is ...
**feasible** to achieve at present as target specifications for each one of the EO products summarized in the PVP and included in Appendix H. Interpretation of meeting (or not meeting) the end-users and service providers target requirement need to be interpreted differently. If the service providers target requirement is met, the EO products are considered valid because their functional and technical specifications meet the requirements of what is considered feasible. Notice that meeting this feasibility requirement is agnostic regarding the validity of the EO product for end-users. This validity is assessed against the aspirational end-user target requirements. If the end-users target requirements are met, the EO product will be considered valid for the purposes detailed in the URD. Notice that the EO products could still have value for the end-users, even in the case that the end-user requirements are not met. Assessing this value is the objective of the evaluation process.

**Error! Reference source not found.** illustrates the study site locations where the different enrolled end users has performed the validation of the different EO products.
Figure 5.2: Validation sites analysed by the enrolled End-Users; BGS for UK, MITECO-IHC for Spain, ARCTUS for Québec, GSI for Republic of Ireland.
Table 5.1 contains the URL links to the independent end users reports showing the results obtained from the validation analysis in terms of accuracy and in terms of the skill on the analysis of coastal erosion processes of products developed in each end user pilot sites.

The User Groups independent validation and evaluation reports can be found at Annexes I,J, K & L and also at the links provided.

<table>
<thead>
<tr>
<th>End User</th>
<th>Independent validation &amp; evaluation reports</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGS</td>
<td><a href="https://bgs.sharefile.eu/d-s253b85200333343fe8aedd5928d55a5d81">https://bgs.sharefile.eu/d-s253b85200333343fe8aedd5928d55a5d81</a></td>
</tr>
<tr>
<td>GSI</td>
<td><a href="https://bgs.sharefile.eu/d-s7a8ac54633b14dcb9d1d14f3267c4db7">https://bgs.sharefile.eu/d-s7a8ac54633b14dcb9d1d14f3267c4db7</a></td>
</tr>
<tr>
<td>MITECO-IHCantabria</td>
<td><a href="https://bgs.sharefile.eu/d-sad21a07a3e9b4cfe95a8be816e5ffdb1">https://bgs.sharefile.eu/d-sad21a07a3e9b4cfe95a8be816e5ffdb1</a></td>
</tr>
<tr>
<td>ARCTUS</td>
<td><a href="https://bgs.sharefile.eu/d-s1fb310937fe94fd9832adbce4723d47">https://bgs.sharefile.eu/d-s1fb310937fe94fd9832adbce4723d47</a></td>
</tr>
</tbody>
</table>

**Table 5.1: Links for end-user validation and evaluation reports**

For each product type, end users have completed the questions summarized in Table 5.2. For each question, end users have provided a short answer, linked to the evidence cited in the end user validation and evaluation reports. Based on these evidences, end users have provided a score for each question with High (H), Medium (M) and Low (L) as contractually requested in the Annex B of the Statement of Work.
Table 5.2: Service assessment questionnaire (from Annex B of Statement of Work).

Questions on sections B.1 and B.2 are related to the validation results and questions on sections B.2 to B.5 are considered the aim of the evaluation of the products. The utility assessment (B.3) and future outlook (B.4) have been assessed throughout the continuous engagement with the broader end-user’s community who has been consulted regarding; site selection, user requirement specifications and future outlook.

5.2 Summary of end users’ requirements

The four champion user organizations provided a total of 17 EO products description tables. All champion user organization has expressed interest on products that represent the coastal change over time of different observable geometries (1D, 2D and 3D) for different purposes. The commonalities and differences among products is discussed in detail later in this section but here we enumerate a list of salient attributes of the products descriptions as a whole;

- **Clear shift from shoreline (1D) products to space (2D) and volume (3D) products.** It is interesting to notice that, while end-users are still interested on shoreline indicators of coastal change (35% of products are 1D), there is an interest shift to area (24% of products are 2D) and most evident towards volume products (41% of products are 3D). This shift was expected as the coastal stakeholder community is on the agreement that any policy for coastal erosion should increase coastal resilience by restoring the sediment balance and providing space for coastal processes (EUROSION, 2004).

- **Spatial scope limited to the coastal zone, but end users has interest beyond coastal zone.** Following from the previous point, it was clear that while the shoreline indicators are well within the coastal zone some of the volume products, such as the bathymetries, are of interest for the coastal stakeholder in charge of ICZM of areas further offshore. For example, BGS is supporting the offshore wind industry that is developing on the shallow continental shelf of the Dogger Bank region by interpreting bathymetry and subsurface data. Due to the
cost of covering the whole region of the Dogger Bank (i.e. about the size of greater London) with traditional marine bathymetric surveys, developers focus their resources to measure bathymetry at locations where there is potential for installing wind turbines and not at the edges of the banks were scientist can extract more useful information. Satellite derived bathymetry could potentially provide bathymetric data in a cost effective way on the latter areas. Since coastal erosion within the coastal zone has been identified by coastal stakeholders worldwide as an issue that need urgent attention, the consulted champion user organization agreed on limiting the spatial scope of the products requirements to the coastal zone.

- **Constrains imposed by non-satellite derived shoreline indicators on the preferred shoreline indicators requirements.** As noticed by Boak and Turner (2005) more than ten years ago, the datum-based shoreline indicator provides a more objective detection technique than the proxy-based shoreline indicators. As Topo-Bathymetric Digital Elevation Models become more accessible, it is likely to be the preferred shoreline indicator for ICZM and CFERM in the future, but their applicability to the analysis of historical trends is more limited (i.e. historical mapped shorelines were mapped using visually discernible features to produce proxy-based shorelines). As a result, both datum-based and proxy-based shoreline indicators are required from the champion user organizations.

- **Coastal State Indicators are treated as a sub-category of 3D products.** Coastal State Indicators (CSI) other than shoreline indicators are considered here as a sub-category of the 3D products. A list of CSIs has been included as within the Topo-Bathymetric Digital Elevation Model (TBDEM) product description because most of them can be derived from it. The fundamental difference between CSIs and 1D, 2D and 3D geometrical products is that geometrical products have either a long tradition of use (i.e. shoreline indicators) or surveyors have a mandate to monitor (i.e. elevation, bathymetry) while CSIs are often site and stakeholder specific and therefore more difficult to standardize. As many of the listed CSIs can be derived from a TBDEM, by including them as a sub-category of the 3D products we will ensure that will also be included in the critical analysis and feasibility study.

- **Detailed specifications on geometrical accuracies of outputs are aspirational requirements needs for the future, and the champion organizations expect to know of the feasibility, considering results with; (i) available EOs of the last 25 years to assess an average erosion**
rate at the decadal time scales, (ii) **COPERNICUS and commercial higher resolution EOs of last 5 years** to monitor erosion and accretion for the management of the coastline by local authorities, (iii) using **state of the art sub-pixel resolution techniques** [3].

### 1D: Waterlines and shorelines

<table>
<thead>
<tr>
<th>SUMMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>- End-users are interested in 1D products of type shoreline indicators (SI) for both legal interest and to monitor standard of protection change over time.</td>
</tr>
<tr>
<td>- These type includes; proxy-based (PSI) and datum-based (DSI) shoreline indicators</td>
</tr>
<tr>
<td>- PSI has been used historically (i.e. previous Satellite data era) and impose some restrictions on which proxies are used as SI</td>
</tr>
<tr>
<td>- Proxies used for PSI varies with country partners and has changed over time</td>
</tr>
<tr>
<td>- Tidal level used for DSI also varies with country partners and has changed over time</td>
</tr>
<tr>
<td>- Landward Extent of SI within estuarine environments varies with end user duties</td>
</tr>
<tr>
<td>- All end-users have expressed interest in analysing the full historical ca. 25 years archive of satellite data and also exploring what is feasible with higher accuracy satellite data</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FEASIBILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>- EO can reliably use to: (i) the drawing of the instantaneous interface between the water and drier materials of the land, so-called “waterline” (WL) in the following paragraphs, and (ii) the drawing of the “seafront” (SF), where marine ecosystems (sand, silt, encrusted rocks, algae, seaweed...) change to land ecosystems cliffs, seawalls, dunes, ...); difficulties being:</td>
</tr>
<tr>
<td>- The mix-up of wet materials and still water on SAR images, which trigger errors near tidal flat, in estuaries...;</td>
</tr>
<tr>
<td>- The masking of the waterline by buildings on the shore or cliffs on SAR images;</td>
</tr>
<tr>
<td>- The confusion between land and sea in areas such as saltmarshes;</td>
</tr>
<tr>
<td>- The wave run-up on the beach which provides an instantaneous waterline which is different from one part of the beach to the other as EO sensors are scanners, and represent a WL at a temporal scale of a few seconds when we look at coastal erosion at the scale of months, years, nay decades;</td>
</tr>
<tr>
<td>- The errors due to the localization of immersed sand bars (and shoals) instead of the most shoreward waterline because of wave breaking, on optical images.</td>
</tr>
<tr>
<td>- <strong>A waterline derived from EO is not only prone to observation errors, but cannot be considered as an isobath or a contour line (isohypse), due to:</strong> (1) the waves reaching different height on the shore at different points (wave set-up of the surf zone, wave run-up of the swash zone), and (2) the tide height being different along the shore because of the shore morphology; as such it is critical to have an error/uncertainty budget.</td>
</tr>
</tbody>
</table>

EO waterline information into geodetic and tidal datum (‘contours’ / isobaths or isohypses), these data need to be complimented with the following data/considerations:

- **Sea state conditions** (with reference to geodetic datum – from an official geodetic network): tidal heights (usually from tide predictor as there is little chance to have a tide gauge nearby), atmospheric pressure offshore, and onshore-offshore wind speeds;

- **Sea state variability**: to correct from wave set-up, which depend on wave breaking fields on offshore bars or the low tide terraces, to be observed on EO or to be derived from wave forecast delivered by meteorological offices and ‘expected’ bathymetry of the offshore and nearshore areas; to assess the wave run-up amplitude on the shoreface, which depends on wave swash or breaking on the beach face, to be calculated from LUTs supplied by surveyors or with models of the surf zone (knowledge of the position of the bars, the depths of the troughs, the slope of the terraces, the location, height and size of steps, the incident wave spectrum and the energy transferred by breaking waves to the shoreface); to assess the shoreface slope along the shore to derive the contour line at the nearest tidal datum from the waterline which has been drawn on EO: it relies anew on a priori knowledge of the foreshore bathymetry, which is supposed to change with coastal erosion, that occurs at timescales from minutes to decades.
2D: Land use, land cover and habitats maps

- End-users are interested in 2D products of type land use and land cover and habitat mapping
- Land use and land cover maps are required to characterize the receptor for standard coastal risk management practices
- Habitat mapping is required to monitor the implementation of coastal sand dunes or wetland restoration projects. Wetland restoration is becoming a common adaptation option to reduce risk of coastal flooding and coastal erosion
- Classes required for land use, land cover and habitat mapping varies among end-users
- The spatial scope also varies with end-users’ duties and responsibilities

3D: Topo-Bathymetric Digital Elevation Models

- End-users are interested in 3D products of type Topo-Bathy-metric Digital Elevation (TBDEM) Models, elevation transects (ET) and Coastal State Indicators (CSI)
- TBDEM is a raster product, ET is a vector product and CSI are a combination of vector and raster products
- TBDEMs are required to produce Datum Based Shoreline Indicators and also assess volumetric sediment change
- ET contains the elevation along transects perpendicular to the coastline from the backshore to the foreshore
- CSIs requirements varies among end users and can be derived from 1D, 2D and 3D products

Benefits

- This 2D EO products are the outcome of a transformation of images with continuous dynamics (e.g. light or radar reflectance) to images with discrete dynamics (e.g. labels of classes, in finite numbers for the taxonomy, usually 10 to 20) or quasi-discrete dynamics (e.g. probability that the input is a particular class, each class being a 2D feature) — a transformation, called a partition, which, if not based on edge detection as for 1D products, is based on similar principle, i.e. looking at discontinuities yet getting rid of most of them vide an optimal smoothing filter when clustering the data while segmenting the images.
- The result of image segmentation is a set of segments that collectively cover the entire image, each of the pixels in a region being similar with respect to some properties, and adjacent regions being significantly different with respect to the same characteristic(s). The interfaces between segments, i.e. the contours, build-up 1D products, and we are mostly interested in the contour that represents the border between land ecosystems and sea ecosystems.
- Whereas edge detection, which is usually applied to retrieve waterlines, is mainly based on thresholding, segmentation is based on thresholding + a further step of data clustering that takes care of the spatial continuity of expected segments. As such, 2D EO products increase the contextual of the image, i.e. the size of the neighborhood of each pixel in which we look for a single class, and the contours are smoother, but also thicker because one accepts more variability of properties on one side or the other.
- Contours’ thickness is not related to contours’ positioning, whose accuracy is translated in the scale of a map. It manifests the scale of observation of objects. 2D EO products’ observation scale, and the related 1D EO products that are derived from them, is lower than the scale of the 1D EO products which are directly computed on EOIs.

SUMMARY

- In UK, habitat creation achieved as part of coastal managed realignment schemes has been estimated to provide environmental benefits valued at between £680 and £2,500 per hectare, including carbon storage benefits. Furthermore, the Climate Change Committee (2013) advised that 6200 ha of coastal habitats created nationally by 2030 (costing £10-15M per annum) would save £180-£380M in capital and maintenance costs on coastal flood and erosion management over the long-term when compared to the cost of replacing/maintaining hard defences.
- Monitoring change of land cover and land use will allow to assess any change on the vulnerability to coastal flooding and coastal erosion
- To assess the efficacy as a coastal risk management of replacing hard structures by soft engineering and revegetation of the backshore
- To inform their management decision and to design regular maintenance and emergency works

SUMMARY

- Assess geomorphic change and volumes of sediment eroded and deposited by subtraction of two independent DTM surfaces to produce a DTM of Difference (DoD), with each grid cell value representing a measure of the vertical elevation difference
- Monitoring dredging activity and environmental awareness
- Monitoring an active coastal erosion in an urban area
- Monitoring estuary dynamics
- Monitoring coastal erosion, sea level and submerged landscapes
- Complement monthly subaerial beach profiles along the alignment of a gas pipeline buried on the beach towards a proactive management that prevents the exposure of the pipeline
- Assess the efficacy of sand extraction actions for navigational purposes and to estimate the sedimentation rates in the beach in order to plan new actions
Coastal State Indicators (CSI)

- Coastal state indicators (CSIs) are a reduced set of measurable parameters used by coastal managers as benchmarks to support management processes.
- They are designed to provide evidence of trajectories of change and to inform timely management interventions [4].
- The coast yields multiple benefits to coastal inhabitants, and depending on their responsibilities, coastal managers will be interested in different sub-sets of CSIs.
- CSIs are often framed within Source-Pathway-Receptor (SPR) or similar risk analysis frameworks (Marchand et al., 2015).
- Coastal geomorphology is a crucial component, representing the pathway that modifies the severity of marine hazards (e.g., surges, extreme waves) as they are experienced by ‘receptors’ on the coast.

Feasibility

- On the Appendix, we summarized a list of CSIs that represent the pathway of different coastal environments and can be derived from the 1D, 2D and 3D products described in this document.
- This lists examples of shoreline indicators that are currently in use, and that provide the reference accuracy to which the URDs request.
- Importantly, the definition of these indicators is not always consistent, and the observations do not always match the process or geographic feature that it targets.
- These indicators are based on physical, morphological or biological changes with the waterline as a reference.

5.3 End User specific validation and evaluation summaries

5.3.1 United Kingdom

Table 5.3 summarizes the evaluation scores (L: low; M: medium; H: high) for each section of the Annex B in the SOW for all product produced at UK study sites and the highlights of the overall evaluation assessment are presented below. The full-service assessment sheet with the detailed per product assessment is included in the BGS report ref OR_20_04.pdf.

<table>
<thead>
<tr>
<th>Section</th>
<th>Product</th>
<th>WL</th>
<th>SL</th>
<th>BMTM</th>
<th>LL &amp; LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1</td>
<td>Adequacy of the User Requirements Document (URD) requirements (including accuracy)</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>M</td>
</tr>
</tbody>
</table>
Table 5.3: Evaluation scores for all products: United Kingdom

5.3.1.1 Waterlines: Optical & SAR

WATERLINES, derived from both OPTICAL and SAR images, has received a HIGH score on the overall evaluation for the following main reasons.

Required accuracy is comparable to UK OS VectorMap District and is considered valid. The WL has shown to be accuracies on the order of 1:20 000 to 1:40 000 which are comparable with the accuracies of OS Vector Map District (1:15 000 to 1:30 000). Although the accuracy
requirements for waterline products specified in the URD end-user in the URD were not accomplished, those requirements were mainly aspirational, and the products are still useful for many of the purposes of BGS’s practices.

**Required updating frequency of waterlines have been fully accomplished.** The required updating frequency specified in the URD was from events scale (pre and post storms) to monthly scale and this requirement have been accomplished. The variation on the number of products among sites, is not due to changes on the frequency feasibility but on the limited project time to produce all possible products. The frequency of SAR WL production is much higher than requested with an average of 216 lines per year.

**Required temporal range of waterlines have been accomplished.** The URD specified 25 years of historical record has been reached for the optical waterlines that covers a period starting in 1994 to 2020.

**Quality control indexes were developed and provided for each product:** these indexes were required by the end-users and allow the automatic identification of the waterlines that may be the result of detection errors. Quality flags has been provided for all WL products (optical and SAR).

### 5.3.1.2 Shorelines; Optical and SAR

The overall service and product performance, for the SHORELINES (OPT & SAR) are evaluated by BGS as MEDIUM for the reasons expressed on sections B.1 to B.4 and summarized below.

**The SL has shown to have accuracies equal of inferior to the original WL from which has been derived.** Although the accuracy requirements for waterline products specified in the URD end-user in the URD were not accomplished, those requirements were mainly aspirational, and the products are still useful for many of the purposes of BGS’s practices (i.e. SL-MSL has been able to capture beach erosion near a vertical cliff and beach accretion).

**Required updating frequency of shorelines have been fully accomplished.** The required updating frequency specified in the URD was from events scale (pre and post storms) to monthly scale and this requirement have been accomplished. The variation on the number of products among sites, is not due to changes on the frequency feasibility but on the limited project time to
produce all possible products. The frequency of SAR SL production is much higher than requested with an average of 216 lines per year.

**Required temporal range of waterlines have been accomplished.** The URD specified 25 years of historical record has been reached for the optical shorelines that covers a period starting in 1994 to 2020.

**Quality control indexes were developed and provided for WL from which SL are derived but has not been included in the SL.** These indexes were required by the end-users and allow the automatic identification of the shorelines that may be the result of detection errors.

### 5.3.1.3 Littoral lines and backshore classification maps

Littoral lines (LL) and backshore classification maps (LC) have received a MEDIUM score on the overall evaluation for the following main reasons.

**LL and LC frequency requirements has been met.** The requested updating frequency was aspirational and varies from one month to a year. We have received a littoral line for year 2018 and yearly backshore maps for two years.

**Confidence on classification results is high for littoral line but medium to backshore classification maps.** A visual inspection of the LL for year 2018 suggested that the LL delineates the edge of the foreshore and backshore correctly but the backshore classification map shows significant variation between year 2018 and year 2019 that seems to be attributed to the classifier errors instead of actual changes of the backshore type. As we did not have the LL for year 2019 to assess how changes on the classification might have affected to the LL location, we have evaluated both (LL and LC) with medium score.

**Metadata and attributes descriptions provided facilitates user confidence assessment.** A confusion matrix has been provided as part of the metadata of the backshore classification map. Adequacy of land uses, and coverage have been partially accomplished (i.e. tuned to better resolve the intertidal area) and classes description has been provided. BGS required classes descriptions similar to the Environment Agency habitat descriptions for CASI and LIDAR habitat maps but assumed that some modification might be needed. The habitat descriptions provided were: Urban; house; Crops1; Crops2; Forest; Sandy Beach; Rocks; Mudflats; Sea. These classes
seem a good trade-off between classes required and what it was feasible. The intermediate raster habitat map has been provided (i.e. not the vector format requested) but this format has found good enough for the analysis of backshore type along the littoral line.

5.3.1.4 *Bathy-Topo-Morphological Terrain Models (BTMT)*

BTMT, has received a LOW score on the overall evaluation for the following main reasons.

The end user required a seamless (i.e. no data gaps between topography and bathymetry) Topography and Bathymetry Digital Elevation Model of the coastal zone (backshore, foreshore & nearshore) but the product received only includes the foreshore and nearshore. The raster BTMT product received contains 5 bands with different elevation metrics (Band 1: Z_mean; Band 2: Z_median; Band 3: Z_90pct_min; Band 4: Z_90pct_max; Band 5: Z_90pct_range) with all elevation relative to the surface elevation at the time of satellite image from which the BTMT has been derived.

The accuracy requirements for bathymetric products (0.1 m vertical, 1 m horizontal) were aspirational and has not been accomplished due to turbidity levels being too high for the UK study sites.

The frequency required for this EO Product (monthly) was not meet due to cloud coverage and high turbidity values. There were not enough good images per month for the UK study sites at Start Bay, Chesil beach and Spurn Head to meet the requested frequency. The BTMTs provided for which cloud coverage was good enough has been found to have to high turbidity values to extract bathymetry changes with confidence.

Quality control indexes were developed and provided for each product: these indexes, required by the end-users during the project, allow the automatic identification of the bathymetries that may represent erroneous values.
5.3.2 Republic of Ireland

Table 5.5 summarizes the evaluation scores (L: low; M: medium; H: high) for each section of the Annex B in the SOW for all product produced at the Republic of Ireland study sites and the highlights of the overall evaluation assessment are presented below. The full-service assessment sheet with the detailed per product assessment is included in the GSI report ref GSI_ANNEXB_4prodcomb_head_Final.pdf.

<table>
<thead>
<tr>
<th>Section</th>
<th>Product</th>
<th>WL</th>
<th>SL</th>
<th>BTMT</th>
<th>LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1</td>
<td>Adequacy of the User Requirements Document (URD) requirements (including accuracy)</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>B.2 Product compliance</td>
<td>Overall product compliance to the user requirements</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Product accuracy compliance to the user requirements</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Confidence in the product quality (including accuracy)</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>B.3 Utility assessment</td>
<td>Confidence in the product quality (including accuracy)</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Impact of the service and products on current end-user practices</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>B.4 Future outlook</td>
<td>Probability of service integration into existing practices</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Desired service and/or product(s) improvements</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Needs for a large-scale service/product demonstration</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>B.5 Overall evaluation</td>
<td>Overall service and products evaluation</td>
<td>H</td>
<td>M</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Recommendations to the European Space Agency</td>
<td>H</td>
<td>H</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.4: Evaluation scores for all products: Republic of Ireland.
5.3.2.1 **Optical Waterlines**

Optical waterlines in the Irish pilot sites covered numerous environmental conditions (tidal regime, wave conditions, coastline type and cloud cover). In general, the waterline products developed cover the geographical area specified in the URD, the temporal range (25 years) and temporal frequency. Full metadata was provided for all the waterlines delivered.

The product’s accuracy levels did not meet the horizontal specifications (1m) but were close to the image pixel resolution of the source data (Sentinel 2, RapidEye and Pleiades data) and is considered in high compliance.

Optical extracted waterlines are considered by the Irish end-user as the most accurate product of all the ones evaluated and deemed ready to be implemented as a service for monitoring coastal change at national level. Sentinel 2 waterlines are accurate to monitor coastal change at near the pixel resolution. A certain degree of post processing is still required to become fully operational.

5.3.2.2 **SAR Waterlines**

SAR waterlines were delivered for all the pilot sites including the Atlantic coast. The temporal range and frequency met the requirements, particularly in the Sentinel 1 products.

The product’s accuracy levels did not meet the horizontal specifications (1m) and were not close to the image pixel resolution of the source data (e.g Sentinel 1). High spatial variability was observed partially due to orbital sensor factors.

SAR waterlines are considered an innovative product and further work is need on the quality control before becoming an operative service. Also, the spatial resolution is a significant limiting factor to monitor change for of less than 40m.

5.3.2.3 **Optical Shorelines**

The results obtained for the optical shorelines are considered of medium quality when linked to the corresponding source waterlines. Coverage met the requirements.

Optical shorelines have appropriate file format and metadata but could be improved in relation to attributes (e.g water level, ancillary data) and quality indicators.
The horizontal accuracy assessment show values near to 2 to 3 times the pixel resolution in the accepted shorelines.

Optical extracted Shorelines are considered an accurate product and, with minor quality control adjustments and better ancillary data, ready to be implemented as a service for monitoring coastal change.

### 5.3.2.4 Land Cover backshore classification

Land cover products were delivered for 4 sites with classification information.

Land cover products did not meet the end-user requirements in terms of temporal range nor frequency. In addition, there was no sufficient information detailing class type.

Accuracy assessment was found to be overall good and contained information useful to monitor change at pixel level.

Land cover-backshore classification is considered a key EO monitoring product but needs further work to become an operational service for a national coverage due to inconsistencies regarding class information and temporal frequency.

### 5.3.2.5 BTMT – Satellite Derived Bathymetry

BTMT products were delivered for most of the pilot sites (all except the Atlantic west coast). The temporal range and frequency was not met partially due to lack of suitable images (cloud cover and water clarity).

The accuracy assessment on the Dublin pilot sites did not pass the end-user requirement regarding water depth accuracies.

Satellite derived bathymetry needs further research to be developed as a service. Confidence levels are low due to significant vertical inaccuracies and high temporal variability in the outputs.

### 5.3.3 Spain

Table 5.6 summarizes the evaluation scores (L: low; M: medium; H: high) for each section of the Annex B in the SOW for all product produced at the Spanish’s study sites and the highlights of
the overall evaluation assessment are presented below. The full-service assessment sheet with the detailed per product assessment is included in the MITECO-IH Cantabria report ref Spain_Validation_Evaluation.pdf.

<table>
<thead>
<tr>
<th>Section</th>
<th>Product</th>
<th>WL</th>
<th>SL</th>
<th>BTMT</th>
<th>LL &amp; LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1 Adequacy of the User Requirements Document (URD) requirements (including accuracy)</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>B.2 Product compliance</td>
<td>Overall product compliance to the user requirements</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>Product accuracy compliance to the user requirements</td>
<td>H</td>
<td></td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>Confidence in the product quality (including accuracy)</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>B.3 Utility assessment</td>
<td>Confidence in the product quality (including accuracy)</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>Impact of the service and products on current end-user practices</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>B.4 Future outlook</td>
<td>Probability of service integration into existing practices</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Desired service and/or product(s) improvements</td>
<td>M</td>
<td>H</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Needs for a large-scale service/product demonstration</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>B.5 Overall evaluation</td>
<td>Overall service and products evaluation</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>Recommendations to the European Space Agency</td>
<td>H</td>
<td>H</td>
<td>?</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.5: Evaluation scores for all products: Spain
5.3.3.1 Waterline

Optical waterlines in the Spanish pilot sites cover various environmental conditions (different tidal range, wave conditions and cloud cover) and under different spatial scales. It is remarkable that the optical products developed proved to be applicable at larger scales, as per the pilot site that covers the whole Gulf of Cadiz. Time series covered the period from 1995 to 2020, a total of 25 years of data, which accomplishes with the user’s requirement of temporal coverage.

Although the accuracy requirements for waterline products specified by the Spanish end-user in the URD were not accomplished (1 m horizontal), those requirements were mainly aspirational, and the results obtained show that the products are still useful for many of the purposes of SGPC’s practices. Some practices, however, still demand higher accuracy, which is expected to be achieved with higher resolution images from future EO missions.

The knowledge on the processing of radar information to obtain coastal products is still limited and SAR products could not achieve the end-user’s requirements. On the other hand, the analysis of waterline (SAR) evolution showed good agreement with those obtained from long term analysis using optical shorelines in Tordera. This highlights the potential of this kind of products to predict coastal change.

5.3.3.2 Shoreline Highlights (SDSL)

The results obtained for SDSL-opt indicate high accuracy, according to the image resolution.

Optical shorelines (SDLS-opt) were delivered in shapefile format as required by the end-user. Regarding the auxiliary data required to derive shorelines from waterlines, a metadata file for each product provides the complete information about the raw data and the dataset used by the processors. Products names are now standard and provide the basic information for the end-user. However, there are some inconsistencies in the shorelines that cannot be automatically detected due to the lack of a confidence index.

Radar shorelines (SDSL-sar) were not developed for the Spanish pilot sites.
5.3.3.3 Land Cover (LC) map Highlights

No LC was developed for those sites where the end-user has specific interest on monitoring changes in land cover, such as Tordera, San Sebastian, Salinas, El Puntal and Maspalomas. LC maps were developed in some of the Spanish Pilot sites with the aim to support the waterline detection in certain areas. However, the Spanish end-user (SGPC) is specifically interested on monitoring the spatial cover of ecosystems and infrastructures, and the use of the products for that purpose could not be tested.

5.3.3.4 Satellite Derived Bathymetry (SDB) Highlights

The analysis of SDB from Barcelona showed that, in some areas of high suspended sediment concentration, it is possible to generate quality bathymetry under certain conditions. Still, accurate SDB could not be generated for all tested pilot sites.

Generally speaking, the sediment concentration in the water is still a challenge to obtain satellite derived bathymetry in areas of significant erosion, and the temporal range and sampling frequency required for this EO Product could not be accomplished.

The accuracy observed in the SDB from challenging sites (like Barcelona) was in accordance with the accuracy obtained in recent studies using satellite information in sites where the sediment concentration in the water is not an issue. However, the accuracy that can be achieved by recent remote sensing techniques is still not enough to allow the fully shift from the use of in-situ measurements to satellite derived products.

Although some results indicate the potential of SDB products, the end-user considers that further research is necessary to relate coastal erosion with changes in those 3D products.

5.3.4 Quebec

Table 5.7 summarizes the evaluation scores (L: low; M: medium; H: high) for each section of the Annex B in the SOW for all products produced at Quebec sites and the highlights of the overall evaluation assessment are presented below. The full-service assessment sheet with the detailed per product assessment is included in the ARCTUS report:

ref: CoastalChangeFromSpace_Validation-Quebec.docx.
### Section B.1 Adequacy of the User Requirements Document (URD) requirements (including accuracy)
- Waterline: H
- Shoreline: H
- Topo-Bathy: H
- Habitat Maps: H

### Section B.2 Overall product compliance to the user requirements
- Product accuracy compliance to: M (H for OPT, L for SAR*)
- Confidence in the product quality (including accuracy): M (H for OPT, L for SAR*)

### Section B.3 Utility assessment
- Confidence in the product quality (including accuracy): H (OPT), M (OPT), L (SAR*)
- Impact of the service and products on current end-user practices: M

### Section B.4 Future outlook
- Probability of service integration into existing practices: M
- Desired service and/or product(s) improvements: M
- Needs for a large-scale service/product demonstration: H

### Section B.5 Overall evaluation
- Overall service and products evaluation: M
- Recommendations to the European Space Agency: H

**Table 5.6: Evaluation scores for all products: Quebec.**

*OPT: Optical product for Waterline and Shoreline, SAR: Synthetic aperture radar product for waterline and Shoreline.*
5.3.4.1  Waterline (optical)

The satellite derived waterline (optical) is available for the 25 years’ time series dataset (1995 to 2019) showing changes of the shore through time. The presence of quality flags helps to select the best segments for the validation analyses. The optical waterline shows a good accuracy to capture changes over large areas (<100km) at a sub-pixel resolution (15m for Landsat and 10m for Sentinel). SAR derived products show large discrepancies due to ascending/descending acquisitions, the lack of metadata and the filtering, which made this product unusable in the frame of this project.

5.3.4.2  Shoreline (optical)

The satellite derived shoreline (optical) shows consistency with in-situ validation data at mean sea level and an accuracy below the pixel resolution. Availability of multiple datums is interesting to assess the coastal vulnerability but the coast features (beach vs cliff) should be considered to mitigate the large discrepancies of inland shoreline.

SAR derived products show large discrepancies due to ascending/descending acquisitions, the lack of metadata and the filtering, which made this product unusable in the frame of this project.

5.3.4.3  Bathy-morpho-terrain-model

The satellite-derived bathy-morpho-terrain-model in particular clear water shows interesting results to monitor changes on shore proximity and sand bars. The atmospheric correction has an important impact on the water-depth assessment, and more work needs to be done to assess its proper parameter. The complex mixture of water constituent in the other area of interest leads to a lot of discrepancies and unrealistic values.

5.3.4.4  Habitat maps

The habitat maps can be considered as the initial condition for the land coverage monitoring, providing a crucial starting point for a long-term monitoring. Still, an independent set of validation should be considered to better assess the accuracy of classification.
6 Outreach and communication

This project, comprising 7 partners from 5 nations, has achieved global outreach:

- Over 1300 delegates from 30+ nations registered with 800 in attendance at a series of workshops and webinars and has presented at the Living Planet Symposium in Milan.

At the recent Final Review, several senior representatives presented their views on this project and a few quotes are provided:

“I would like to congratulate all the team for the successful project which is focused in a very important topic for some countries, including Spain, as it is the Coastal Erosion. I would like to remark a very positive aspect of the project which has been the high involvement of final users in all the phases of the project, mainly during validation and test”. Mónica LÓPEZ, CDTI, E.P.E, Spanish Delegation to ESA.

“Taking part on this Project has enlightened us in the coastal surveillance from space. We are now firmly on the road of a new and promising coastal management paradigm, increasing our chances in successfully adapting our coast to the effects of the Climate Change.” Ana García Fletcher and Roberto Díaz Sánchez, Directorate General for the Coast and the Sea, MITECO

“The datasets being produced under the ESA funded Coastal Change from Space project have great potential application in Ireland and come at a very opportune time as we are establishing a National Coastal Change Management Strategy. The coastal change data can help us recognise areas of greatest change, and thus prioritise the allocation of resources at national and local levels.” Koen Verbruggen, Director Geological Survey Ireland, Department of Environment, Climate & Communications.

- It has also generated impactful research: Peer-reviewed paper published in the 8th International Symposium “Monitoring of Mediterranean Coastal Areas. Problems and measurement Techniques”
• With **expert analysis**: Products validated by coastal experts from leading national institutions that have also published an independent User Requirements Document.
7 Pilot Service Demonstration

The Coastal Erosion web service has been implemented based on the high-level specification detailed in https://coastalerosion.argans.co.uk/src/SO-RP-ARG-003-055-WEB.pdf and is now in beta on the AdwaisEO server at https://coastalerosion.argans.co.uk

The Data Access Portal https://coastalerosion.argans.co.uk/private/erosiondb.php is accessed by using credentials,

```
username: erosion_user
password: iwiHin1o
```

The first stage was to define a product naming convention, now at version 1.4, and a production post-processing stage that ingests products, renames non-conforming products which, for shapefiles, includes calculating the bounding box of the features excluding processor outliers / artefacts to allow the possibility of database retrieval by geospatial co-ordinates, using PostgreSQL postGIS extensions. The second stage was to populate a database with a record for each product enabling SQL query-based access to the product location on the filesystem. To complete backend integration a metadata schema has been devised, including JSON templates, and processors modified to generate metadata files to accompany each product. This last stage is under incremental development until metadata requirements are frozen.

Using SQL, the PostgreSQL database may be queried based on location, date, product type, sensor etc. and return the file location as a URL. To provide non-technical users with means to access products without using the FTP protocol a browser-based GUI has been implemented. The middleware uses PHP to perform database access and display records. The front-end comprised several JavaScript/jQuery libraries to provide value-added functionality, such as the ability to search/sort returned records, to provide graphical status reports of the number and type of products available, and to display shapefiles (waterlines and shorelines) and PNG thumbnails (co-registered data, bathy-topography and feature maps) as overlays using Google Maps API. Care has been taken to follow good practice in UX (User Experience) design e.g. providing user feedback, minimising clicks to target, preventing non-sensical selections etc.

To summarise the delivered functionality is provided by:
• Naming Convention, encoding metadata.
• Post-processor, parses filename metadata – correcting if necessary.
• Database, stored metadata, and links to product location on the filesystem.
• Browser-based user interface enabling the user to select products based on location, date range, type and, in the case of shorelines, the datum used.
• Visualisation of data products overlaid on a Google Maps satellite view background.
• Downloading of data products and associated metadata file.

The UX uses an intuitive ontology, based on the shared user experience with the shopping cart motif, that in tests is capable of use by an inexperienced user without the need for tutorials.

The implementation of this functionality satisfy the requirements of a Pilot data access portal (DAP).

NOTE: Using FTP and lftp -c mirror is the recommended means of access for expert users and the data dissemination service provided to satisfy the SoW. The web-based UI (user interface) is a demonstrator of what would be available to end-users in a service provisioning context; it is a proof-of-concept (POC) rather than a production ready web application.

An operational web service would be re-factored using, for example, React.js/Redux.js, replacing Google Maps with a FOSS (free and open-source) Geoserver and rely less on client-side and more on server-side scripting. Additional POC functionality being developed includes notary stamping of products, via blockchain, and access control.
8 Roll out Analysis

8.1 General Overview  This project set the challenge to bring innovative solutions to exploiting Earth Observation in order to support those engaged in coastal management and operations.

What has materialised throughout the numerous stakeholder engagement sessions is that those charged with the responsibility for the coastal zone, and probably more importantly those who hold and spend tax payers money on mitigation engineering and all the other connected task associated with coastal zone management are public bodies whether institutions of state or local government.

Therefore, the approach adopted throughout the workshops has been to expose this project’s achievements not just to the academic community but to practitioners in local, regional authorities and national government.

What stems from these workshops is a simple truth and that is it is mostly likely that any roll out will be sponsored by local communities and national government and not the private sector at least in the first instance.

This leaves two avenues for the next steps; namely to further develop the product set and the production capability whilst simultaneously capitalising on the customer ready products derived from this project.

The Target Audience

The immediate Target Audience is comprised of two sectors each with a different marketing approach. In the first instance further development work to improve both the production capability and efficiency as well as potentially introduce new products sets will be planned to improve the efficiency of the system.

This approach will be spearheaded by arranging presentations and webinars to the National Space Agencies and the DOSTAG representation in particular so they can see the value of the current capability and the additional value of further development.
ESA has requested the immediate key priorities to improve efficiency and they have been forwarded but are added here for completeness.

- **Expand the consortium to France and Italy to deliver to more sites of differing geomorphology.** The expansion in scope in Europe to include areas i. in France (through a cooperation with IGN, CEREMA & SHOM, and also approached via BGS) which are of interest to the government and not covered by I-Sea, as well as ii. in Italy (through a cooperation with ISPRA, CMCC and the Venice Water Authority) in order to increase marketing and co-operation in regions greater than UK, Ireland and Spain.

- **Better automate the production process.** To prepare systematic and automatic production of the datum-based shorelines (simplest ‘information’ of value because the waterlines are just ‘data’) and to set-up a webservice, as we intend to do on OCRE or through the NOR; this task will require a review on how we access the relevant auxiliary data or develop ways to mitigate a lack of these auxiliary data. This will bring some development and implementation in the production chain and strengthen the position to the market.

- **Improve models using EO.** To have a pilot study using the EO-products through the design of an action plan for flooding prevention (e.g. PAPI - *programme d’actions de prévention des inondations* or the UK *Flood and Coastal Erosion Risk Management Research and Development Programme*) that local authorities will publish, in order to parametrize CFD models for sediment transport such as the TELEMAC-3D (non-hydrostatic model on a unstructured mesh), SISYPHE (sediment transport and bed evolution module of the TELEMAC modelling system), TOMAWAC (wave propagation model for coastal areas) or similar models from DHI or DELTARES which are used by the civil engineering firms that design the prevention plan on behalf of local authorities. This also has the potential to introduce a coastal engineering player.

The second approach is to deliver the customer ready products by approaching and explaining the value to local authorities, regional and national governmental agencies.
The initial approach will first target the four consortium partner nations who are funded to manage their national coastlines, i.e., UK (or England and Wales), Ireland (possibly joining up with NI), Quebec (and all Canada) plus Spain and her overseas territories.

It is clearly hoped that the partner nations will appreciate that in a relative short period their full national coastlines can be covered, looking back 25 years, with the possibility of a seasonal or annual monitoring service moving forward. This approach would enable a tremendous national foundation baseline to be attained and maintained. The service would then naturally be rolled out across Europe and beyond.

In addition, based upon the proposed future research work identified above it would be natural to include France and Italy at this stage.

Based upon this approach it is envisaged that five possible services could be provided.

- **The 5 yr Sentinel service** (all appropriate S2 images delivering all WLs and SLs and Seafront Maps) costed per 100km (England is likely to be 15 tiles still to do so about 2000km), or costed per 1000km
- **The 25 yr Landsat service** (all appropriate L5 & L8 images delivering all WLs and SLs and Seafront Maps) again costed per 100km with a reduction if over 1000km is required.
- **The 25 yr Combined** (S2,L5&8) service with a further reduction if one buys both.
- **The annual update service** (all S2 WLs per year and SLs – could be averaged for a winter solution and a summer solution).
- **An VHR annual update service** (combining a mix of civil data and commercial VHR data for those smaller sites of specific interest that would warrant this additional cost).

We also know the area of the four consortium nations.

- For **Ireland** there are 9 tiles (we have serviced 4.5) so this should take approximately 3 months to complete the combined service.
- For **England** there are 19 tiles (we have serviced 5) and this should take 9 months with the same team employed above. Clearly the benefits of being a commercial SME means that we could recruit very rapidly if production is required in parallel.
One could do the same for **Scotland, N Ireland and Wales** which adds another 20, 6 and 5 tiles respectively or 18 months.

For **Spain** (including Islands) there are 32 tiles (we have serviced 6) so this would mean 15 months, however this is assuming the full coastline is required.

For **Quebec and Canada** - it’s just huge so again I think an average year’s contract could deliver 20 average tiles of effect.

One of the key next steps is to cost the value of owning these data compared to traditional methods of field survey and also the cost of the long term plans and their sea defence budgets so that expenditure on EO based products can be seen in context.

In addition, each nation has a very bespoke and often complex system for managing the coastal zone, and various networks of appropriate institutions would be required to be in place.

For example, within the UK the Geospatial Commission oversees the national mapping agency (Ordnance Survey, a government owned company) and more specifically the Public Sector Geospatial Service (PSGS) which is worth £100m per year. This service pays for and enables public bodies to demand the mapping and geospatial services they require to run their departments. Both BGS (one of the Coastal Change Consortium partners) and the UK Environment Agency (the government body jointly responsible for managing coastal change and flooding) are customers of the PSGS and therefore could fund future EO products. In addition, the 6 Coastal Change Observatories of England have a joint role bringing the local knowledge and responsibility to coastal management. These bodies are directly connected to local government and are represented within the PSGS by the national department for local government and the Local Government Association. Finally, the Geospatial Commission has its own funds (ca £40m a year).

To enable an active lobbying and marketing of the value that has been afforded via the Copernicus Sentinel Missions a leaflet will be designed and distributed, however the main tool will be arranging a series of presentations and webinars that will be supported by the [https://coastalerosion.argans.co.uk](https://coastalerosion.argans.co.uk) website. This website will not only be maintained and active but will also enable the consortium partners to showcase case studies and be regularly updated.
A policy for releasing the current data set has been agreed and this data will also showcase what can be achieved.

It is hoped that the ESA logo can be deployed on the landing page to advertise who has enabled this progress, however it is recognised that approval is required and this is requested in the full knowledge that ESA would have the right to ask for its removal at any time.

Simultaneously an approach will be made to target developing nations based on the Overseas Development Assistance programmes initial from the four consortium nations but also making use of the association that the partnership has with IGN FI. Within the UK both the national mapping agency, Ordnance Survey, and our partner BGS have an overseas development component. The UKs Foreign & Commonwealth Development Office are responsible for the UKs national ODA effort and they also fund a UKSA activity called the International Partnering Programme. The other nations within the consortium will have a similar set up and these will be approached. The International Development Banks, such as the Word Bank could also be a source of support and they will also be approached.

Finally, the message needs to get to the civil engineering associations that are predominantly funded by state institutions to deliver works and they are in need of data. It is unlikely that they will fund directly, however they add support to the argument for state investment.

The action plan moving forward will feature both bilateral approaches working along a single national partner as well as multinational consortium approaches. In the next paragraphs the individual approaches will be outlined.

8.2 BGS roll out plan.

As expressed on the service and product evaluation sheet assessments, the probability of service integration into existing BGS practices is high for all EO products delivered by this project with the exception of the Bathy-Topo-Morpho Terrain models (BTMT) which we have assessed as not been at the same Technology Readiness Level (TRL) than the other products (Figure 1). At present the WL, SL, LL and LC products TRL is assessed to be at TRL7 or inactive commissioning

\[\text{TRL}^1\]

level: product has been tested and factory trials done using inactive simulants comparable to that expected during operations. To reach the maximum operational level (TRL9) will need first to go through active commissioning (TRL8). Before this active commissioning can be roll-out the question of how this new technology should be integrated within all other current coastal erosion monitoring activities need careful consideration. This specific question was addressed during the third session of the UK national workshop and full discussion is available here https://bgscoastalerosion.siteonsite.es/. This is a complex task as illustrated in Figure 2 that shows the slide presented by the Coastal Channel Observatory director during the UK Coastal Erosion Workshop as an attempt to map the products produced within the current monitoring activities in England. The task is complex not only because there are other technologies already been used to monitor coastal erosion but also because the mandate of monitoring coastal change due to coastal erosion is devolved in the UK (England, Wales and Scotland, Northern Ireland). The service and product demonstration provided by this project has focussed mostly in England who has the longest coastal monitoring program of all nations. As BGS provides geoscientific advice to all nations, we would like to extend the service and product demonstration to the other UK nations (Wales, Scotland and Northern Ireland). All nations suffer from coastal erosion at present and are likely to continue suffering the impact of coastal erosion in the future. As each nation has different coastal environments, regulations and access to auxiliary data this extension will allow BGS to effectively assess the adequacy of this new products to the whole UK territory.
Figure 8.1: The aim of BGS roll out plan is to progress the TRL level for WL, SL, LL and LC from inactive commissioning level to operational.

Figure 8.2: Slide presented during the UK Coastal Erosion workshop, by the Director of the Coastal Channel Observatory indicating the how EO products could be integrated with the existing monitoring activities in England.

BGS is actively seeking the progression to TRL9 via; (1) providing geo-scientific advice to our stakeholders and the general public, (2) allocating internal national capability funding to continue the validation and evaluation of all products received and (3) actively responding to tenders.
where we believe EO products could be used to improve current practices. Below we provide some examples of some of the ongoing activities under each category.

**Providing geo-scientific advice to our stakeholders and the general public**

![Image of workshop schedule](image-url)

The video recorded sessions of the UK Coastal Erosion from space Workshop will continue to be openly accessible to the general public via the dedicated online platform: [https://bgscoastalerosion.siteonsite.es/](https://bgscoastalerosion.siteonsite.es/)

**Ongoing research activities**

- CoastalRisk is a modelling environment that simulates daily and longer coastal morphological changes. It is an engineering tool for advanced models seeking to simulate the interaction among coastal conditions and different types of human interventions.
- RIF: The workshop we are developing an integrated modeling tool that will be used to simulate protected areas resilience to coastal erosion and management options along merged coastlines with critical energy infrastructure, such as: Offshore wind farms, Fukushima, England.
- Mindshare Future Research: Eastern England
- The Coastal Change Network: As part of the Coastal Change network, our aim is to develop applications of coastal monitoring and management to inform coastal management plans. We will do this through volumetric analysis of historical data, such as by examining 30 years of ESA Sentinel-2A HiRes data, and Sentinel-1A and -2A interferometric synthetic aperture radar (InSAR) data, to derive coastal change information. In addition, we will develop and evaluate new methods to quantify coastal change, developing new oil spill techniques to address these problems.

**Contact**

If you have any questions, please contact Andreas Pardo-Garita.
The official Coastal Erosion website will continue to be advertise as part of the ongoing research activities of BGS as part of the Coast & Estuaries programme. We will continue disseminating the results from the ESA Coastal Erosion project among differences audiences. The example above shows an schedule online lecture for members of the Geological Society in Scotland.

Alloacting internal national capability funding to address challenging science problems and delivering tangible societal benefits

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2 https://www.bgs.ac.uk/geology-projects/coasts-and-estuaries/
NERC Requirements: LTSM2

- Contributes to delivering on the ambitions of the NERC Delivery Plan

**Environmental Solutions**
- Pushing the Frontiers of Understanding
- Productive Environment
- Healthy Environment
- Resilience Environment
- Digital Environment
- Global Environment

Addressing challenging science problems and delivering tangible societal benefits (typically requires partnerships)

BGS is now developing the research plan for the second call second round of Long-Term. Science Multi-Centre (LTSM³) programmes to start in April 22. The aim of the LTSM program is to enable a more ambitious, integrated approach to research challenges that require large-scale, long-timeline insights and more than any one National Capability Provider can deliver alone. The total budget for all projects under this 2nd round is ca. £8m pa; £40m over 5 yrs. There is one project specifically focused on coastal geohazards of which BGS is participating. The ESA Coastal Erosion project outcome are very timely and are being used to develop this large five-year program.

**Actively responding to relevant tenders**

BGS is leading a proposal that has brought together UK engineering consultants and researchers to develop a methodology to assess historical coastal change in England and Wales for Defra⁴. The Department for Environment, Food and Rural Affairs (Defra) is commissioning a project with the aim to establish a national updatable online platform of historical coastal change to better inform future coastal management decisions that are robustly based on strategic and objective evidence of coastal change. If successfully funded, this proposal will provide the appropriate discussion platform to effectively integrate the EO products not only BGS existing practices but more broadly among UK end-user’s community.

⁴ https://www.procurement.co.uk/tender_details/64ba2591-0cdf-4c90-9ef2-67519a5b058a
### 8.3 IH Cantabria roll out plan

The following table (extracted from the User Requirement Document - URD) presents the products required by each end-user. The end-users also requested Coastal State Indexes, as secondary products derived from those primary ones.

<table>
<thead>
<tr>
<th>Name</th>
<th>Champion</th>
<th>Details</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proxy-based Tidelines</td>
<td>BGS</td>
<td>Table 6</td>
<td>1D</td>
</tr>
<tr>
<td>Datum-based Tidelines</td>
<td>BGS</td>
<td>Table 7</td>
<td>1D</td>
</tr>
<tr>
<td>Topo-Bathymetric Digital Elevation Models</td>
<td>BGS</td>
<td>Table 8</td>
<td>3D</td>
</tr>
<tr>
<td>Habitat map</td>
<td>BGS</td>
<td>Table 9</td>
<td>2D</td>
</tr>
<tr>
<td>Bathymetric change in the nearshore</td>
<td>GSI</td>
<td>Table 13</td>
<td>3D</td>
</tr>
<tr>
<td>Coastal DEM</td>
<td>GSI</td>
<td>Table 14</td>
<td>3D</td>
</tr>
<tr>
<td>Waterlines to shorelines</td>
<td>GSI</td>
<td>Table 15</td>
<td>1D</td>
</tr>
<tr>
<td>Elevation transects</td>
<td>GSI</td>
<td>Table 16</td>
<td>3D</td>
</tr>
<tr>
<td>Land cover changes</td>
<td>GSI</td>
<td>Table 17</td>
<td>2D</td>
</tr>
<tr>
<td>Vegetation line</td>
<td>GSI</td>
<td>Table 18</td>
<td>1D</td>
</tr>
<tr>
<td>Bathymetry changes on beaches</td>
<td>MITECO</td>
<td>Table 26</td>
<td>3D</td>
</tr>
<tr>
<td>Shoreline changes on beaches</td>
<td>MITECO</td>
<td>Table 27</td>
<td>1D</td>
</tr>
<tr>
<td>Land cover changes</td>
<td>MITECO</td>
<td>Table 28</td>
<td>2D</td>
</tr>
<tr>
<td>Nearshore bathymetry</td>
<td>GoQ</td>
<td>Table 32</td>
<td>3D</td>
</tr>
<tr>
<td>Sediment volume changes</td>
<td>GoQ</td>
<td>Table 33</td>
<td>3D</td>
</tr>
<tr>
<td>Shoreline/Waterline</td>
<td>GoQ</td>
<td>Table 34</td>
<td>1D</td>
</tr>
<tr>
<td>Land-Use and Land-Cover and habitat maps</td>
<td>GoQ</td>
<td>Table 35</td>
<td>2D</td>
</tr>
</tbody>
</table>

Table 8.1: EO products name, champion user organization, link to table with detailed description and type of product.

Table 8.2 shows the products considered to be developed in the Requirement Baseline Document (RBD), that means, the final products that service providers agreed to develop on the basis of the requirements:

<table>
<thead>
<tr>
<th>Products</th>
<th>PRODUCTS TYPE</th>
<th>Current situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>i) Feature-based shoreline based on the mark of high tide.</td>
<td>1D</td>
<td>Delivered for other partners.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not requested by Spain.</td>
</tr>
<tr>
<td>2) Feature-based shoreline based on the vegetation line or civil works (seafront).</td>
<td>1D</td>
<td>Delivered for other partners.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not requested by Spain.</td>
</tr>
<tr>
<td>3) Wet/dry edges on the shore, i.e. waterlines (border between land and water at the time of a snapshot).</td>
<td>1D</td>
<td>Delivered for the Spanish pilot sites.</td>
</tr>
<tr>
<td>4) The cross-shore profiles, which is an intermediary product.</td>
<td>1D</td>
<td>Calculated to obtain the shorelines in areas where no topobathymetry was available. But not delivered as product.</td>
</tr>
<tr>
<td>5) Shorelines based on tidal datum, waterlines, and cross-shore profiles.</td>
<td>1D</td>
<td>Delivered for the Spanish pilot sites.</td>
</tr>
<tr>
<td>Requirement</td>
<td>Format</td>
<td>Status</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>--------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>6) Seafront based on thematic classification of ecosystems = the interface</td>
<td>1D</td>
<td>Delivered for other partners pilot sites. Not requested by Spain.</td>
</tr>
<tr>
<td>between marine and land habitats</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7) The map of the shore by land and marine ecosystems’ classes.</td>
<td>2D</td>
<td>Requested but not delivered.</td>
</tr>
<tr>
<td>8) Seafront based on thematic classification of ecosystems but on a series</td>
<td>1D</td>
<td>Not delivered. Not requested by Spain.</td>
</tr>
<tr>
<td>of EOs from same satellite mission to smooth the seasonal effect.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9) The map of the shore by land and marine ecosystems’ classes using a</td>
<td>2D</td>
<td>Not delivered. Not requested by Spain.</td>
</tr>
<tr>
<td>series of EOs from same satellite mission.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10) Outputs of calculation on time series of previous shorelines derived</td>
<td>CVI</td>
<td>Not delivered, but analyses showed the potential of the primary</td>
</tr>
<tr>
<td>from snapshots from same EO mission.</td>
<td></td>
<td>products to be used for that purpose.</td>
</tr>
<tr>
<td>11) Outputs of calculation on time series of previous shorelines derived</td>
<td>CVI</td>
<td>Not delivered, but analyses showed the potential of the primary</td>
</tr>
<tr>
<td>from snapshots from different EO missions.</td>
<td></td>
<td>products to be used for that purpose.</td>
</tr>
<tr>
<td>12) Bathy-topo morphology changes based on SDB (vs. a reference DEM-DTM).</td>
<td>CVI</td>
<td>Not delivered. Although the primary product, the bathymetry was</td>
</tr>
<tr>
<td>13) Bathy-topo morphology changes based on Wave Fields analysis (vs. a</td>
<td></td>
<td>developed for some pilot sites.</td>
</tr>
<tr>
<td>reference DEM-DTM).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14) result of data fusion of BTM/SDB or BTM/WF on a data sets of snapshots</td>
<td>3D</td>
<td>Not delivered.</td>
</tr>
<tr>
<td>in the Δt time interval.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15) Result of data fusion BTM/SDB and BTM/WF on a data sets of snapshots</td>
<td>3D</td>
<td>Not delivered.</td>
</tr>
<tr>
<td>in the Δt time interval.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16) result of data fusion BTM/SDB and BTM/WF on a data sets of snapshots</td>
<td>3D</td>
<td>Not delivered.</td>
</tr>
<tr>
<td>from different EO missions in the Δt time interval.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17) outputs of calculation on time series of previous BTMs.</td>
<td>CVI</td>
<td>Not delivered.</td>
</tr>
</tbody>
</table>

Based on those requirements and on the analysis of the services and products provided for the different pilot sites in Spain, it was possible to identify a series of “desired” advances, on which
future research should focus when looking forward to obtaining products that completely fit the needs of the Spanish end-user.

While the results of 1D products showed good accuracy (considering the minimum resolution of satellite data) and have proven to be useful for coastal monitoring purposes, the development of 2D (land cover maps) and 3D (topo-bathymetry) information is more challenging and further research/development on those products is still necessary and would be highly desirable. In the next sections the future outlook and roll-out of the various products is described from the perspective of IH Cantabria. Finally, a section on further dissemination of project results, after project finalization, is included.

1D products future outlook and roll out

Among the products requested in the URD, the 1D products (waterlines and shorelines) from optical sensors were certainly those that showed greatest advances and development. Waterlines and shorelines from optical sensors presented high accuracy and some improvement regarding products obtained from existing tools (based on Google Engine) that usually use simplistic approaches and that have clear limitations due to a non-site-specific methodology for the extraction of the waterlines and due to un-co-registered satellite images.

Based on those improvements respect to previous studies, it would be interesting to extend those products to rest of the Spanish coast. A recent OCRE Research Project Proposal was submitted to extend those 1D products to the whole Spanish Coast. In that project a demonstration case will be conducted to compare Google Engine results to the results based on Copernicus data. This can facilitate the standardization of these activities in the whole country. The ultimate outcome of this project is the enhancement of the ability to assess and forecast shoreline change in the long-term and at a large geographical scope. This is especially relevant in a country like Spain, with a highly anthropized coastal area, supporting an unprecedented tourism industry, and highly valuable natural coastal habitats, threatened by coastal squeeze. This accurate and precise information on shoreline change is critical for the following studies:

- The Spanish national strategy for the protection of the coast (under development by IH Cantabria and to be completed in October 2022). Coastline evolution from the satellite-derived shorelines
in the last 25 years at the national scale will be used to assess coastal erosion risks and to inform
decisions regarding the selection and prioritization of risk reduction measures.

- In addition, this shoreline evolution database will be used to delineate the public maritime-
terrestrial domain along the coast and a further zone where special restrictions apply to private
ownership (defined by the Spanish Coastal Act 1988/2013) and to inform the criteria to allow the
use of such maritime-terrestrial domain.

- Other on-going initiatives that will benefit of this unprecedented long-term time series of
shorelines are the regional PIMA Adapta plans. These regional plans aim to reduce the
vulnerability of the Spanish coast under climate change. IHcantabria is developing the first four of
those plans in Canarias, Valencia, Castellon and Cantabria. Currently, a large amount of resources
has to be allocated to obtain baseline information on shoreline change to inform the plans.

- Finally, the Spanish state-owned port system will invest 1001 Million € in 2021 and 8.700 Million
€ in the period 2020-2024, with climate change mitigation as one of the main blocks of
investment. Additionally, there are hundreds of regional and private fishing harbours and marinas
(there are 268 marinas in Spain, being the third European country in number of marinas) that
undergo continuous enlargements. The Spanish Coastal Act (1988/2013) oblige to assess the
impacts in coastal morphodynamics of all coastal civil works at harbours and marinas. These
assessments will highly benefit from the EO shoreline monitoring based on Copernicus data.

**Future outlook and roll-out of 2D and 3D Products**

As mentioned before, the development of 2D and 3D products are quite challenging, and the
results obtained from these products are not enough yet to allow their fully incorporation in
current end-user’s practices. Because of that, further research/development would be highly
desirable. In that context, the following aspects can be highlighted:

- Land cover maps could not be tested, during the project. LC maps from EO products will
allow the monitorization of dune fields and their vegetation. With that information it is
possible to understand dune evolution what would contribute to coastal protection
action plans along the country. IHCantabria is currently working on the project SANDS (https://sands.ihcantabria.com/) funded by MITECO, which is a demonstration project for the monitoring of North Atlantic Spanish coastal dune systems, combining drone and satellite images. The development of LC maps from EO products for such purpose is of MITECO’s high interest and, at the same time, it is a solid line of research at IHCantabria. Therefore, funding opportunities will be explored by IHCantabria to complete the validation of LC maps from Sentinel and other satellite missions with regards to the coastal dune monitoring.

- The accuracy observed in the SDB from challenging sites (like Barcelona) was in accordance with the accuracy obtained in recent studies using satellite information in sites where the sediment concentration in the water is not an issue. However, the accuracy that can be achieved by recent remote sensing techniques is still not enough to allow the fully shift from the use of in-situ measurements to satellite derived products. This was particularly highlighted by the key end-users that use such information to monitor the changes for dredging and beach recovery, for example. Although the end-users are aware that part of the limitation comes from the image resolution, it is important to know the possibilities of applying the methods developed in this project to higher resolution images, so they can be considered in the future. An improvement in picture resolution would allow the monitoring of estuaries and, particularly, the monitoring of habitat rehabilitation in estuaries (including managed realignment) by means of LC maps from EO products, which is also a line of research of high interest at IHCantabria.

**Future outlook and roll-out of Coastal State Indexes**

Although coastal indexes were not developed and delivered as products, the analyses carried out with the primary products showed the potential of using such information to obtain coastal indexes (e.g. shoreline evolution rates from shoreline products, for example). The end-user is interested on having that type of information for the following reasons:
• Satellite motorization and integration of objective parameters, such as coastal vulnerability index, will allow prompting to continuous evaluation of the coastal zone and to better practice in the decision-making process and management. The development of a data set from remote sensing information for the assessment of coastal erosion derived through an erosion susceptibility assessment for various types of coastal features would be the core of the CVI. The need for CVI is aligned with the implementation of the Plan Nacional de Adaptación al Cambio Climático (National Plan for the Adaptation to Climate Change) and the Estrategia de Adaptación de la Costa Española.

• The SGPS has developed a flood risk management tool in compliance with the Directive 2007/60/EC on the assessment and management of flood risk. It is mainly consisted in Risk-Vulnerability maps at national scale, with profiles every 200 meters for the whole Spanish Coast. Information related to coastal vulnerability to flooding is already available in a web viewer (http://sig.mapama.es/snczi/visor.html?herramienta=DPHZI) but no coastal vulnerability to erosion is publicly available. Coastal vulnerability is currently estimated considering parameters such as population, goods or services, evaluating risk as a function of wave climate and coastal evolution. However, there is no systematic obtaining of a Coastal Vulnerability Index (CVI), or other relevant indicators.

**Future outlook and roll-out of Radar Products**

The validation procedure was applied to products derived from optical sensors. The understanding of coastal information from radar sensors for coastal monitoring purposes is not as advanced as the understanding we have nowadays about optical sensors. Radar products could not be assessed in the Spanish pilot sites, nevertheless, some advances were made in terms of improving the knowledge on this kind of sensors for coastal analysis. Besides, initial analysis carried out by service providers indicate that with those products we can reach long-term changes similar to those obtained from optical sensors, highlighting the potential use of these kind of data in the future. Because of the nature of radar detection (e.g. SAR detection is not sensible to the presence of clouds), the use of radar information represent 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, thus further advances on that topic would be highly desirable for the Spanish coast, where cloud cover is often an issue to optical detection.

**Project Results Dissemination After Project Dissemination**

IH Cantabria has in-house resources for science dissemination, which is one of its core functions as a public research institute. After finalization of Coastal Erosion from Space, project results will be shared both with the scientific community and with the general public.

In terms of contributions to the state of art by means of publication of scientific papers, IH Cantabria publishes more than 50 peer-reviewed papers per year. The results of products validation in the Spanish coast will be part of a paper (currently in development) that will be submitted to the Coastal Engineering journal (www.journals.elsevier.com/coastal-engineering).

Besides, it is expected to develop papers in collaboration with the other partners of the Coastal Change From Space Consortium, to disseminate the general conclusions, results and the dataset. The general public will be engaged through news on IH Cantabria (https://ihcantabria.com/en/comunicacion/noticias/page/2/?et_blog) and UNICAN (https://web.unican.es/en/Pages/default.aspx) websites. Besides, the topics of the project will be presented and discussed during a talk in the session “Café Científico” (Scientific Coffee) organized by the Institute of Physics of Cantabria (https://ifca.unican.es/es-es/educacion-y-divulgacion/cafe-cientifico) in the theatre Café de las Artes in the city of Santander (Spain), during the academic year 2021-2022 (after Sept/2021). These talks are recorded, displayed in a youtube channel (e.g. https://www.youtube.com/watch?v=N0ahcPH9K4E) and shared by means of social medias, what allows the engagement of a broad audience.

Finally, the recording of the workshop hosted in Spain to broadcast the range of new products, their development, validation and utility was recorded and it will remain available at IH Cantabria’s vimeo channel indefinitely:

- Morning session: https://vimeo.com/480714920
- Afternoon session: https://vimeo.com/480717649
8.4 GSI roll out plan

Figure 8.3: Digital shoreline system for shorelines comparison

Further validation work

- The next step will be a joint analysis between shorelines and waterlines, together with their respective co-registered images, to better understand the overall’s performance in relation to changing factors such as auxiliary data, environmental conditions and image seasonality.
- It is intended to further develop the current quality indicators of the shorelines and waterlines to include reference layer’s information.
- Current SAR waterlines will be fully assessed in order to examine its suitability in monitoring coastal change. In addition WL processing on higher resolution SAR data is expected to start in 2021.

Further product development

- Land cover derived products, primarily using Sentinel 2 data, will be further explored in future GSI projects as it is considered a primary product to monitor coastal change and to index other layers.
- It is expected to analyse shoreline change over time using the DSAS toolbox (USGS) to quantify shoreline rate-of-change statistics. Erosion rates (m/year) will also be calculated.
through the evolution of the Sentinel 2 shorelines. GSI has a dataset of vegetation lines from 1995 to 2020, which is used as a reference layer for the validation process.

**Incorporate results into existing GSI mapping services**

- A number of project’s products, including waterlines, shorelines and land cover might be incorporated into current GSI practices of Coastal Vulnerability mapping. [https://www.gsi.ie/](https://www.gsi.ie/)

- Shorelines change derived products (e.g. accretion vs erosion) at national scale will be disseminated through the European portal EMODnet Geology, where European harmonization of marine products, including Coastal Behaviour (WP4) is expected. [https://www.emodnet-geology.eu/](https://www.emodnet-geology.eu/)

**National rollout**

- A National rollout coastal erosion project is currently being considered by GSI. The role of Sentinel 2 erosion products within this project will be assessed shortly to determine implementation, scale, temporal factors and accuracy levels.

**Outreach and disseminations**

- Once the project "Coastal Erosion from Space" is completed, the validated results obtained will be shared publicly both to the scientific community, as well as to companies and the general public.

- In addition, some of the case studies of shorelines and waterlines will be shared through the educational channels in which the GSI takes part, including the outcomes of the Irish stakeholder’s workshop from 2020.

- Evaluation and validation results of the Irish coast are expected to be published in 2021 in a series of peer-reviewed articles, including a special edition in the Journal of Remote Sensing.
Figure 8.4: GSI Spatial map services including coastal products (2021)

8.5 Arctus roll out plan

Québec context

The Estuary and the Gulf of St. Lawrence region is amongst the world regions where the trend of sea-level rise has been the highest. Erosion is aggravated by the loss of coastal- and sea-ice (i.e. longer ice-free period) and increased temperatures (warming conditions) that lead to accelerated thaw cycles. With more than 3220 km of coastline to study characterized by a marked diversity of coast types, it is crucial to develop a preventive management approach to coastal hazards while increasing coastal resilience.

Human activities and climate change exacerbate the impact of flooding and erosion phenomena in Québec, while coastal erosion potentially exposes roads, railways and public infrastructures often located near the shores. This threat to the safety of coastal communities represents one significant economic impact of coastal changes, with no or little adaptation measures planned. Socio-economic risks add to the ecological vulnerability of Quebec coasts, associated with biodiversity loss and coastal habitat modifications.

Although the shift of the littoral line stands out as the main issue, mapping coastal dynamics, mapping land cover and coastal ecosystems, and assessing the vulnerability of infrastructure through time (short and long term) remain top priorities for coastal managers.
Future outlook and roll-out of products

EO proposes solutions to fill the gaps in *in situ* measurement and offer the capacity to analyze time-series prior to *in situ* monitoring. It offers complementary methodology with an operational and integrated approach for coastal change detection and monitoring. Satellite-derived products represent an opportunity to delineate new operating procedures for monitoring, planning, and decision-making not only in the province of Québec, but for all Canadian coastal areas. Exploring and extending products’ development to Canadian Arctic, and specifically to sea-ice, seems extremely promising in the climate change context.

Products developed in the frame of *Coastal Change from Space* project already show promising applications for coastal management. 1D products (waterlines and shorelines) from optical sensors show good accuracy in regard to the relatively low resolution of satellite data. These products reach the Canadian Space Agency application readiness level 6 (ARL-6) (Error! Reference source not found.) and have proven usefulness for coastal monitoring purposes. Additional developments are needed before implementation of a mature and operational product (ARL-8) tailored for the stakeholder. Improvements toward ARL-8 will be investigated in the framework of a Canadian Space Agency funded project (Arctus *CCIER-Climate Change Impacts and Ecosystem Resilience* project, 2019-2021) by extending products to longer coastlines and other sites (*e.g.* Canadian Arctic).
Figure 8.5: Canadian Space Agency Application Readiness Level (ARL) Scale satellite data applications.

While 1D products results demonstrate their possible soon application, further research and development are yet needed for 2D (land cover maps) and 3D (topo-bathymetry) products to reach monitoring and management requirements. Results obtained from these products show that additional efforts are required before full incorporation in end-user’s practices.

Although intricate and challenging, the improvement of such products yet remains promising and highly desirable. Regular update of bathymetry maps in regions where coastal dynamics is very active (e.g., Magdalen Islands) is of high priority for scientific research, security and management. Arctus has engaged R&D in satellite-derived bathymetry (SBD) based on a novel artificial intelligence algorithm that will exploit EO optical time series such as Sentinel-2. The inversion model will be developed for Canadian waters which present distinct optical properties. Such development will be done in collaboration with hydrographic R&D centres (e.g. CIDCO), academic researchers and the Canadian Hydrographic Service. The ultimate goal is to offer high-quality SDB services tailored for Canadian needs.

Near shore land-use and land cover classification is a proper product to assess the impact of the coastal erosion on shore habitats. This product shows good accuracy (kappa coefficient) and confusion matrix. Future development should imply the adaptation of the classification processor.
to Landsat sensors for long-term land cover changes monitoring. Land covers maps would for instance allow to monitor remote locations and any change in time, beneficial to the enormous Canadian territory.

**Dissemination**

The development of a preventive management approach to coastal hazards includes dissemination of results and access to coastal data, but also increasing public awareness. The *Coastal Change from Space* project results will be shared both with the scientific community and with the general public. The results of product validation will be shared with the scientific community through peer-review publications, and collaboration with the other partners of the *Coastal Change from Space Consortium* is expected, to pursue the dissemination of main conclusions, results and the dataset.

Engaging constantly with end-users will also contribute to increase the community's consciousness and understanding of coastal changes. The *Coastal Change from Space* Québec Workshop gathered attendees from academia, not-for-profit organizations, private and industrial sectors, local authorities, and regional and national governmental agencies. More than 90 participants registered, from whom about 40% had no or very little knowledge in Earth Observation. Recorded sessions will remain available and openly available to the general public through the Arctus’ YouTube Channel ([https://www.youtube.com/watch?v=fllRmgHcMQ](https://www.youtube.com/watch?v=fllRmgHcMQ)).

To better disseminate data and products, interactive portals with a good graphical user interface and easy data visualization tools are needed for end-users without advanced programming skills. In the framework of Arctus CCIER project, data dissemination will be achieved using a powerful web mapping platform developed by Cartovista ([https://cartovista.com](https://cartovista.com)). Cartovista has developed web mapping tools allowing the end-users to perform their own spatial analysis by overlaying several layers of information along their coastal sites (infrastructure, roads, erosion rates) including gridded data layers such as topo-bathymetry. Considering the ultimate goal of Arctus CCIER project, *i.e.* to promote the use of operational EO data in the integrated management of coastal zone in Canada, we will integrate the EO products generated in the *Coastal Change from*
Space project (i.e Waterline, Shoreline) in a web mapping tool (Figure 8.6) specifically designed for the end-users, whose are readily familiar with.

Figure 8.6. Example of a web portal design for data viewing and products dissemination to stakeholders (credit: CartoVista)
9 Recommendation

The following list of recommendations are based on the strategic direction that future work might take and followed by some detail based on each processor.

- **Expand the consortium to France and Italy to deliver to more sites of differing geomorphology.** The expansion in scope in Europe to include areas i. in France (through a cooperation with IGN, CEREMA & SHOM, and also approached via BGS) which are of interest to the government and not covered by I-Sea, as well as ii. in Italy (through a cooperation with ISPRA, CMCC and the Venice Water Authority) to increase marketing and co-operation in regions greater than UK, Ireland and Spain.

- **Better automate the production process.** To prepare systematic and automatic production of the datum-based shorelines (simplest ‘information’ of value because the waterlines are just ‘data’) and to set-up a webservice, as we intend to do on OCRE or through the NOR; this task will require a review on how we access the relevant auxiliary data or develop ways to mitigate a lack of these auxiliary data. This will bring some development and implementation in the production chain.

- **Improve models using EO.** To have a pilot study using the EO-products through the design of an action plan for flooding prevention (e.g. PAPI - *programme d'actions de prévention des inondations or the UK Flood and Coastal Erosion Risk Management Research and Development Programme.*) that local authorities will publish, in order to parametrize CFD models for sediment transport such as the TELEMAC-3D (non-hydrostatic model on a unstructured mesh), SISYPHE (sediment transport and bed evolution module of the TELEMAC modelling system), TOMAWAC (wave propagation model for coastal areas) or similar models from DHI or DELTARES which are used by the civil engineering firms that design the prevention plan on behalf of local authorities. This also has the potential to introduce a coastal engineering player.

**The Geolocation Processor:**

- Develop an automatic image selection process based on cloud cover just within the coastal strip.
The Optical Waterline Processor:

- Develop a multiple spectral indices approach to optimise waterlines by harnessing internal quality control data.
- Improve errors analysis both on the extraction model and in noise handling associated with suspended sediment/increased turbidity.
- A sub-pixel analysis, with pixel demixing, to provide valuable information on pixel content. This sub-pixel analysis will allow, in the case of our LiuJezek_CoastL processor, a more precise position of the “true” waterline better boundary extraction.
- Address the white-water problem by use of bright pixel mapping and quantification to assist mitigation against white water false edges.

The SAR Waterline Processor:

- Development of volume change and deformation products over the land, based on the computation of DTM using the interferometric information.
- Development of bathymetry products for intermediate depths (10 to 70 meters) based on the analysis of hydrodynamic surface processes influenced by the sea bottom.

The Shoreline Processor:

- Explore automatic auxiliary data extraction from a MetOcean database/model and extract slope data using a waterline to DEM approach to improve independence form in situ data and increase global scalability.
- Use littoral lines or a dynamic slope model to increase the accuracy of shorelines in areas with soft eroding cliffs.
- Develop line segment building algorithm to improve the performance of the processor in micro-slope environments such as mudflats.

The Seafront Processor:
• Develop a semi-automatic method, using unsupervised classification in smaller ROI to create an unlabelled classification training data set, grouping radiometrically similar clusters.
• Develop a combination of supervised and unsupervised methodology to find a balance between time resources, accuracy and operator manipulation.
• Add regional information in the creation of the training data set to classify the main different regions as cities, agricultural, littoral, etc. to improve the base classification.
• Reduce the inland section, which bring most of the instability, to allow a reduction in wide temporal cover.
• Testing the impact of a more focus ROI over the littoral areas on the accuracy of seasonal classification maps to bring some new information of seasonal erosive regimes and cycles.

The BM-TM processor

• Wave crest and sand bar extraction to aid feature detection.
• Wave field bathymetry estimation.
• Combining the sediment and CDOM confidence maps with a depth of Penetration algorithm
• Use of Hydrolight radiative transfer numerical model to better describe the water properties.
• Addition of automatic cloud and boat mask
• Wave crest and sand bar extraction to aid feature detection.
• Wave field bathymetry estimation.
• Combining the sediment and CDOM confidence maps with a depth of Penetration algorithm.

Germane to all processors

• On Demand production and integration into the C-TEP or other platforms so that customers can access and generate their own outputs.
• GIS facility so that multiple different data sets can be joined to deliver a better understanding of the relationship between existing and planned infrastructure with coastal change observations and predictions.
10 Conclusion

10.2 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 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.

As can be seen from the recommendation section above, there are many identified tasks that will improve the current compatibility and all the indications from this capability demonstration are 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. However, this consortium was not looking for quick and easy wins but 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.

The second, 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, but gain very real world requirements as their professional judgment contributes significantly to how coastal regions are managed.

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.

The decision to co-register the optical images from Sentinel2, Landsat 5 and 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.

This project has seen the development of individual processors 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 would be the next logical step to creating a fully commercial system, however the current system does produce commercial ready products, albeit in a semi-autonomous and labour intensive fashion.

10.3 Summary of end user validation and evaluation assessments

The salient remarks that all enrolled End-Users would like to highlight to the Service Providers and the European Space Agency at this stage of the project 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 (Table 1).
- 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.
- 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 shorelines allowed the assessment of morpho-dynamic processes (beach rotation, accretion and erosion) in different temporal scales and the identification of critical zones.

There are still some limitations that should be highlighted:

• The water clarity is still a challenge to obtain satellite derived bathymetry in the nearshore, what affect 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.

• More product specific improvements have been detailed on the end user product service assessment sheet.

• To obtain high quality products, some auxiliary data (in-situ measurements) are still necessary, yet it requires less in-situ measurements in comparison to the traditional monitoring methods.
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