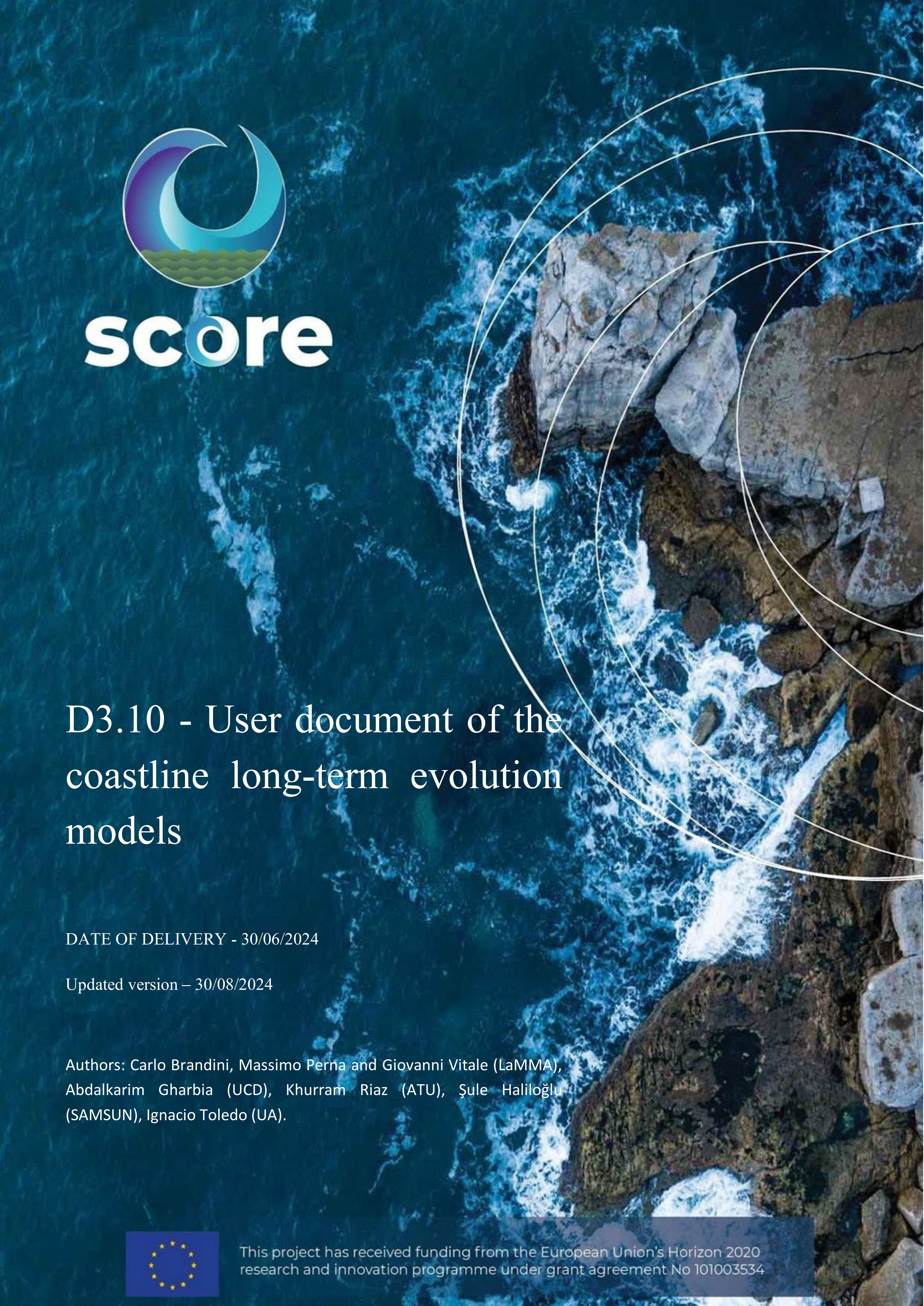

D3.10 - User document of the coastline long-term evolution models

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym / Abbreviation	Meaning / Full text
CCLLs	Coastal City Living Labs
CORDEX	Coordinated Regional Downscaling Experiment
DEM	Digital Elevation Model
DoW	Description of Work
DT	Digital Twin
DTM	Digital Terrain Model
EBA	Ecosystem-Based Approaches
ECMWF	European Centre For Medium-Range Weather Forecasts
EWSS	Early Warning Support System
GEE	Google Earth Engine
GIS	Geographic Information System
NBS	Nature Based Solutions
SLR	Sea Level Rise
USGS	United States Geologic Survey
WP	Work Package
WWIII	WaveWatch 3

BACKGROUND: ABOUT THE SCORE PROJECT

The intensification of extreme weather events, coastal erosion and sea-level rise are significant challenges to be urgently addressed by European coastal cities. The science behind these disruptive phenomena is complex, and advancing climate resilience requires progress in data acquisition, forecasting, and understanding the potential risks and impacts of real-scenario interventions. The Ecosystem-Based Approach (EBA) supported by smart technologies has potential to increase climate resilience of European coastal cities; however, it is not yet adequately understood and coordinated at European level.

SCORE is a four-year EU-funded project aiming to increase climate resilience in European coastal cities. SCORE outlines a co-creation strategy, developed via a network of 10 coastal city 'living labs' (CCLLs), to rapidly, equitably and sustainably enhance coastal city climate resilience through EBAs and sophisticated digital technologies.

The 10 coastal city living labs involved in the project are: Sligo and Dublin, Ireland; Barcelona/Vilanova i la Geltrú, Benidorm and Basque Country, Spain; Oeiras, Portugal; Massa (including the coastal area of Marina di Massa), Italy; Piran, Slovenia; Gdansk, Poland; Samsun, Turkey.

SCORE will establish an integrated coastal zone management framework for strengthening EBA and smart coastal city policies, creating European leadership in coastal city climate change adaptation in line with the Paris Agreement. It will provide innovative platforms to empower stakeholders' deployment of EBAs to increase climate resilience, business opportunities and financial sustainability of coastal cities.

The SCORE interdisciplinary team consists of 28 world-leading organisations from academia, local authorities, RPOs, and SMEs encompassing a wide range of skills including environmental science and policy, climate modelling, citizen and social science, data management, coastal management and engineering, security and technological aspects of smart sensing research.

EXECUTIVE SUMMARY

This document is a deliverable of the SCORE project, funded under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101003534.

The D3.10, related to Task 3.5 and entitled "User Document for Methods and Models of the Long-term Coastline Evolution," is a WP3 deliverable, specifically a report describing the methods and models used to study long-term morpho-dynamic processes in a climate-change scenario.

The long-term evolution of the coastline is estimated through the study of local morpho-dynamic processes and climatic projections. Although a hybrid modeling approach would represent the state of the art, it requires a computational effort that is currently too demanding. Instead, a reduced-physics approach has been implemented, focusing on a long-term morphodynamic model. This approach considers the essential processes influencing coastal evolution, without the complexity of fully coupled 2D/3D sediment transport models. The modeling focuses on evaluating long-term shoreline changes primarily through longitudinal sediment balances, taking into account factors such as longshore and cross-shore processes, river sediment supply, and sea level rise.

More than a purely modeling study, the use of these models is crucial for guiding discussions within the Coastal City Living Labs (CCLLs). They serve as tools to facilitate awareness-building, co-creation, and co-design of solutions that can enhance the resilience of coastal cities to the impacts of climate change. As such, these models and tools will be made available to coastal cities, providing a valuable resource for informed decision-making and strategic planning in the face of evolving coastal challenges.

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1. INTRODUCTION

Coastal erosion is one of the major environmental challenges of our time, particularly significant for coastal cities and their ecosystems. The SCORE project (Shoreline Change Evolution Models) aims to address this issue through the implementation of a long-term morpho-dynamic modeling framework. Shoreline Change Evolution Models are crucial for assessing the effects of coastal erosion on urban scales and for developing effective mitigation strategies.

Coastal morpho-dynamics is a complex discipline that requires the integration of physical, geological, biological, and ecosystemic aspects. It is essential to consider the impacts of human activities along the coast, as these influences can accelerate or alter natural processes. Morpho-dynamics does not refer to a single process but to a set of processes operating on different spatial and temporal scales, from small-scale features like bed ripples to larger sedimentary structures such as underwater bars and dunes, extending to regional sediment dynamics.

All coasts, whether rocky or sandy, undergo morphological evolution. However, sandy coasts are generally more susceptible to rapid changes, both at the scale of individual storm events and over multiple years. For this reason, discussions about morphological variations or coastal erosion often focus on sandy coasts, although rocky coasts have been receiving increased attention in recent years.

Beaches play essential roles at socio-economic, environmental, and protective levels. Natural beaches act as dynamic barriers that can mitigate the impact of storms and extreme events on inhabited coastlines. Unfortunately, the natural state of these beaches has been compromised in many European coastal areas, leading to the loss of critical coastal ecosystem elements such as dunes and backshore vegetation. This loss has increased the exposure of coastal cities to the effects of erosion and storms.

Socio-economically, beaches represent an invaluable asset for coastal cities, generating significant economic activity but also leading to environmental consequences. The alteration of coastal ecosystems negatively affects the quality of other ecosystems, both marine and terrestrial. In the era of climate change, coastal erosion combined with sea-level rise results in an increasing impact of storms on coastal cities.

Quantitative assessment of coastal erosion and the combined impact of storms in the coming decades is a complex challenge. The SCORE project addresses the issue by using models that benefit from climate change scenarios simulated through downscaling methodologies, as described in deliverables 3.3 and 3.4. Through these tools, the SCORE project aims to provide reliable predictions and develop effective adaptation strategies to mitigate the effects of coastal erosion on urban areas.

1.1. Scope of this report

The purpose of this report is to provide a user-centric guide on how to approach coastline evolution modeling over climatic timescales. Given the immense complexity of this subject, we have navigated through the selection of various types of models, each with distinct characteristics. Some of these models describe three-dimensional hydrodynamic and morphological processes in an intertwined manner. These state-of-the-art models, such as XBeach (Roelvink et al., 2009), SWASH (Zijlema et al., 2011), and Funwave (Shi et al., 2012), operate over timescales of hours or, at most, a few days, typically simulating the effects of a single storm event. Due to their temporal limitations, these models are not suitable for long-term simulations extending to the year 2100.

To address long-term coastal evolution, we turn to highly simplified, reduced-physics models capable of conducting climate-scale simulations. These models benefit from the high-resolution climate projection data generated by the project for all European coastlines, particularly near coastal cities. These models perform a simple sediment budget along the coastline while keeping the beach profile constant and are commonly referred to in the literature as "one-line models." For this project-deliverable, we have chosen a publicly available model developed by the USGS, COSMOS-COAST, which is part of a comprehensive modeling set that includes various simulation models, wave and sea-level climate projections, and storm surge simulations.

A more detailed description on the reason why this specific code was selected, is provided in D3.9.

In this report, we focus on the application of long-term coastline evolution models. The combined simulation of coastal erosion and storm surge effects will be addressed in the testing phase, where methods described in Task 3.4 (Deliverables 3.7 and 3.8) can be integrated with those outlined in this deliverable. Specifically, the application of the methods is illustrated through the case studies of Benidorm and Massa. More advanced versions of this report may include applications to other cities. Regarding the use of coastal erosion estimates based solely on observational methods, the Dublin case study, conducted by UCD, is presented. A more comprehensive study requires greater integration between observational and modeling components, which will be realized and described in the testing phase (WP3.6).

1.2. Coastline evolution in the climate change era

The coastline is a dynamic interface where the land meets the sea, and its evolution is profoundly influenced by a variety of natural and anthropogenic factors. In the climate change era, these influences are becoming more pronounced and complex. Climate change impacts, such as rising sea levels, increased frequency and intensity of storms, and changes in sediment supply, are accelerating the rate of coastal erosion and altering the natural processes that shape our coastlines.

Rising sea levels, driven by the melting of polar ice caps and thermal expansion of seawater, contribute significantly to coastal erosion. As the sea encroaches further inland, it exacerbates the loss of land and disrupts existing coastal ecosystems. This phenomenon is particularly problematic for low-lying areas where even small increases in sea level can lead to significant land loss.

The increasing frequency and intensity of storms are another critical factor in coastline evolution. Storm surges, high waves, and heavy rainfall associated with these extreme weather events can cause severe erosion, stripping away beaches, dunes, and other protective features. The aftermath of such events often leaves coastlines more vulnerable to future erosion, creating a cycle of degradation that is difficult to break.

Changes in sediment supply, driven by both natural processes and human activities, also play a crucial role. River damming, coastal construction, and upstream land-use changes can reduce the amount of sediment that reaches the coastal areas, starving beaches of the material they need to maintain their structure.

Without sufficient sediment replenishment, beaches and dunes erode more quickly, leading to a loss of natural coastal defenses.

In response to these challenges, it is essential to develop adaptive management strategies that enhance the resilience of coastal areas. This may include the use of advanced modeling techniques to predict future changes and inform policy decisions. By understanding the likely impacts of climate change on coastline evolution, we can implement measures to protect coastal communities, preserve ecosystems, and sustain economic activities dependent on healthy and stable shorelines.

Effective coastal management in the climate change era requires a holistic approach that considers both the physical processes at play and the socio-economic context. It involves not only engineering solutions, such as sea walls and groynes but also nature-based solutions and/or ecosystem-based approaches like dune restoration and the preservation of mangroves and wetlands. By combining these approaches, we can create robust strategies to mitigate the adverse effects of climate change on our coastlines and ensure their long-term sustainability.

1.2.1. Global Coastal Evolution Scenarios

Global coastal evolution scenarios are projections that outline potential changes in coastlines around the world under various environmental and socio-economic conditions. These scenarios take into account factors such as sea-level rise, climate change, human activities, and natural processes. They are developed using advanced modelling techniques that simulate the interactions between these factors over different timescales. In the context of rising global temperatures and accelerating ice melt, these scenarios predict significant shoreline retreat, increased frequency and intensity of coastal flooding, and enhanced erosion rates. Additionally, human interventions, such as coastal development and land reclamation, further complicate these projections by altering natural sediment flows and disrupting coastal ecosystems. By exploring different scenarios, policymakers and scientists can better understand the range of possible futures for global coastlines, aiding in the development of adaptive management strategies that aim to mitigate adverse impacts, enhance resilience, and sustainably manage coastal resources in the face of an uncertain future.

1.2.2. Exploring Future Scenarios for European Coastal Regions

European coastal regions are unique due to their geographical and historical contexts, which influence their vulnerability to climate change. Unlike many other parts of the world, a significant number of European coastal cities are situated along marginal and enclosed seas, such as the Mediterranean, the Baltic, and the Black Sea. These seas have different hydrodynamic and climatic conditions compared to the open Atlantic Ocean, which affect how coastal erosion and sea-level rise impact these areas.

Europe is home to some of the world's oldest coastal cities, rich in historical and cultural heritage. The evolution of these coastlines has been profoundly shaped by human activities dating back to prehistoric times. Early land-use policies like the transition from hunter-gatherer societies to agriculture, have left lasting impacts on coastal dynamics. The development of early civilizations and the subsequent Romanization further altered coastal landscapes through infrastructure development, trade, and urbanization.

Future scenarios for European coastal regions must therefore consider not only natural processes and climate change impacts but also the extensive historical modifications to the coastline. As sea levels rise and storm patterns change, ancient cities like Venice, Istanbul, and Barcelona face unique challenges. These include the preservation of historical sites, the need for sustainable tourism management, and the protection of densely populated urban areas.

Models developed in the SCORE project can simulate the combined effects of these factors, providing insights into potential future changes. These scenarios emphasize the need for integrated coastal zone management that balances preservation with modernization. Strategies may include enhancing natural defenses, such as restoring wetlands and dunes, implementing advanced engineering solutions, and developing policies that promote resilient urban planning.

By exploring these future scenarios, European policymakers can better prepare for the challenges ahead, ensuring that coastal cities continue to thrive while preserving their invaluable historical, cultural and natural heritage. This proactive approach will help mitigate the adverse effects of climate change, protect coastal communities, and sustain the economic and cultural vitality of Europe's coastal regions.

1.2.3. The Impact of Coastline Evolution on Coastal Cities: Challenges and Strategies

Coastal cities face significant challenges due to the evolving dynamics of their shorelines, driven by both natural processes and anthropogenic influences. The primary impacts of coastline evolution include increased erosion, more frequent and severe flooding, and loss of valuable land. These challenges are exacerbated by climate change, which accelerates sea-level rise and intensifies storm activity. For coastal cities, this means not only physical damage to infrastructure and loss of property but also economic disruptions and threats to both cultural and natural heritage.

The historical and socio-economic context of coastal cities further complicates these issues. Many European coastal cities, for example, have intricate historical layouts and ancient infrastructure that are less adaptable to modern coastal defense mechanisms. Additionally, these cities often rely heavily on tourism and maritime industries, which are highly sensitive to changes in the coastline.

To address these challenges, cities must adopt a multi-faceted strategy that includes both short-term and long-term measures. Immediate actions might involve constructing or upgrading sea walls, levees, and other hard defenses to protect against storm surges and coastal flooding. In the longer term, strategies should focus on sustainable urban planning and development, incorporating natural defenses such as sea grass meadows mangroves, wetlands, and dune restoration to absorb wave energy and prevent erosion.

Furthermore, coastal cities should invest in robust monitoring and modeling systems to predict future changes and plan accordingly. This includes leveraging the latest climate change scenarios and morpho-dynamic models, such as those developed in the SCORE project, to understand and mitigate the impacts of coastline evolution.

Community engagement and education are also crucial, ensuring that residents are aware of the risks and involved in the decision-making process. By fostering a resilient and adaptive approach, coastal cities can better protect their populations, preserve their heritage, and maintain their economic vitality in the face of evolving coastal dynamics.

1.3. Climate simulation models for coastline evolutions

Climate simulation models are essential tools for understanding and predicting the evolution of coastlines under various climate change scenarios. These models integrate a wide range of data, including sea-level rise projections, temperature fluctuations, storm frequency and intensity, and sediment transport dynamics. By simulating these complex interactions over different temporal and spatial scales, climate models provide valuable insights into how coastlines are likely to change in the future.

One of the key advantages of climate simulation models is their ability to incorporate different climate scenarios, from moderate to extreme, allowing researchers and policymakers to explore a range of possible outcomes. For example, models can simulate the impact of various greenhouse gas emission trajectories on sea-level rise and coastal erosion. They can also predict how changes in precipitation patterns and storm surge events might affect sediment deposition and coastal stability.

Advanced models, such as those used in the SCORE project, employ downscaling techniques to translate global climate predictions into regional and local impacts. This approach ensures that the unique characteristics of specific coastal areas are considered, providing more accurate and actionable data for decision-making.

Furthermore, these models can be used to assess the effectiveness of different adaptation strategies. By simulating the potential outcomes of measures such as beach nourishment, dune restoration, or the construction of sea defenses, stakeholders can evaluate the most cost-effective and sustainable approaches to protecting coastal communities.

In summary, climate simulation models are indispensable for predicting coastline evolutions in the context of climate change. They offer a powerful means of visualizing future scenarios, guiding policy and management decisions, and ultimately helping to safeguard coastal regions against the multifaceted impacts of a changing climate.

2. METHODS FOR COASTAL SURVEYS

2.1. Objective

The main objective of coastal surveying is to enhance comprehension of local coastal processes and their interactions with the shoreline but also to help define the extent of risks from coastal flooding and erosion and to provide data to support future reassessment of these risks. While monitoring of costal systems is extremely useful to support coastal managers by supplying relevant information for making sustainable shoreline management decisions.

2.2 Introduction to the remote sensing methods for coastline monitoring

Coastlines are dynamic boundaries between land and sea, that are continuously reshaped by both natural forces and human activities in response to urban development, coastal constructions, tides, waves, sea-level rise, and sediment transport (Vitousek et al., 2023). Monitoring these dynamic changes is crucial for understanding coastal dynamics, managing coastal resources, and mitigating the impacts of coastal hazards such as erosion, flooding, and climate change responses like sea-level rise (Barnard et al., 2021).

Traditional techniques for coastline monitoring like ground-based methods, though valuable, often fall short in spatial and temporal coverage, efficiency, and cost-effectiveness (Provost, 2021). Remote sensing evolution has emerged as a powerful tool to address these limitations for observing and analysing coastlines, providing extensive, accurate, and temporal data over large areas.

In recent years, remote-sensing applications have significantly grown the temporal-spatial domain of coastline-observing endeavours (Apostolopoulos & Nikolakopoulos, 2021). The integration of satellite imagery for earth observation with classifying, detecting, and learning algorithms convert coastal realization from a rogue data range, where facts are spatiotemporally scattered, into an information-dense plateau, where observations are gathered daily from all over the world (Vitousek et al., 2023).

Remote sensing tools combine the observation, collection, and analysis of data from sensors mounted on satellites, aircraft, or drones, which detect and measure electromagnetic radiation reflected or emitted from the Earth's surface (Zhang & Zhu, 2023). These non-disturbing techniques offer a comprehensive way of observing and analysing coastal areas, enabling continuous monitoring and detailed evaluation of coastal dynamics over time. Remote sensing applications can be broadly classified based on the kind of utilized sensor, involving Optical, Radar, and LiDAR (Light Detection and Ranging) technologies (Joshi et al., 2016).

Optical remote sensing uses sensors that capture data in the visible, near infrared, and short-wave infrared spectrums. High-resolution optical imagery is particularly effective for mapping coastline positions, identifying coastal landforms, and monitoring changes in land cover and vegetation (Lira & Taborda, 2014). Multispectral and hyperspectral sensors can provide detailed information on the spectral properties of coastal environments, allowing for the dynamic observation of coastline conditions (Klemas, 2011). Advances in optical remote sensing technologies, such as developing high-resolution satellites like Landsat, and Sentinel-2, have significantly improved the ability to monitor fine-scale coastal features and changes with temporal frequencies ranging from daily to monthly.

Radar remote sensing, especially Synthetic Aperture Radar (SAR), offers the unique advantage of being able to acquire data irrespective of weather conditions and daylight (Lin et al., 2019). This is particularly important for coastline monitoring in regions with frequent cloud cover or during periods of darkness. SAR sensors emit microwave signals that penetrate through atmospheric obstacles and reflect from the Earth's surface, providing high-resolution imagery (Tsokas et al., 2022). SAR can be used to monitor shoreline changes, detect coastal erosion and sediment transport, and assess coastal infrastructure and built environments. Notable SAR missions, such as Sentinel-1, provide frequent and reliable data critical for understanding coastal dynamics.

LiDAR technology involves emitting laser pulses toward the Earth's surface and measuring the time taken for the pulses to return to the sensor. This allows for the creation of highly accurate topographic and bathymetric maps (Sakib, 2022). Airborne LiDAR systems are particularly effective in mapping coastal elevation and morphology, and detecting subtle changes in beach profiles, dunes, and intertidal zones. LiDAR data supports a wide range of applications, including coastal erosion studies, flood risk assessment, and the design of coastal defence structures.

Remote sensing methods are indispensable for many coastal applications, providing critical data for effective management and conservation. These methods enable precise monitoring of shoreline positions and dynamic movements, allowing for a better understanding of erosion and accretion patterns (Apostolopoulos & Nikolakopoulos, 2021). They play a crucial role in assessing the impact of climate change actions like storms, sea-level rise, and flooding on coastal areas, facilitating timely hazard assessments and mitigation strategies. Furthermore, remote sensing is essential for mapping and monitoring coastal habitats such as mangroves, supporting conservation efforts and biodiversity preservation (Klemas, 2011). It also aids in managing coastal urbanization and infrastructure development, helping to minimize environmental impact and enhance resilience. Additionally, remote sensing is vital for monitoring coastal resources, including fisheries, aquaculture, and recreational areas, ensuring sustainable use and management.

The integration of data from various remote sensing sources enhances the accuracy, comprehensiveness, and reliability of coastline monitoring. Combining optical, radar, and LiDAR data can provide a multi-dimensional view of coastal environments, capturing both surface and subsurface features under different conditions. Advanced data processing techniques, including artificial intelligence (AI), machine learning algorithms, data fusion methods, and geographic information systems (GIS), are increasingly being employed to extract meaningful insights from large and complex remote sensing datasets (Vitousek et al., 2023). These techniques facilitate the automated detection of coastal changes, prediction of future trends, and support decision-making processes in coastal management.

2.3 Coastline monitoring through in-situ surveys

In situ surveys involve collecting data directly from the field, allowing researchers and coastal managers to assess beach profile changes, sediment dynamics, and erosion rates. Seasonal or monthly surveys help track short-term changes, and are often performed in conjunction with beach restoration works to verify their effectiveness at the end of their execution. Long-term data collection reveals trends and patterns, trying to bypass the effects of intrinsic variations in the morphology of the beach, and in particular of the shoreline.

Beach morphology monitoring includes both the emerged and submerged part of the beach profile, and the survey techniques relating to them differ from each other, although they all rely on GPS technology for the positioning of the surveyed points. Cross-shore sediment transport is normally studied through the tracking, by a human operator equipped with instrumentation connected to the RTK-GNSS network (real-time kinematic global navigation satellite system), of profiles on the backshore and foreshore zone transverse to the shoreline at a fixed distance between them.

The coastline monitoring is instead carried out by walking along the foreshore, detecting with the same instrumentation the points at zero altitude above sea level, corresponding to the momentary position of the shoreline. Alternatively, for greater execution speed, it is preferable to acquire a point above the zero level and one below it, and then interpolating the data obtained in the post-processing phase. For a detailed survey, the long-shore distance of the acquired points depends on the linearity of the shoreline morphology, but should be limited to no more than a few meters in correspondence with cusps, and even in the straightest stretches should not exceed in any case about ten meters.

For direct 3D topography mapping of the beach, and wider areas covered by the surveys, UAVs (unmanned aerial vehicles) equipped with cameras or LIDAR systems, should be used.

The submerged beach morphology can be monitored through different bathymetry surveying systems, such as:

- Single-Beam and Multi-Beam Echo Sounders (SBES and MBES): equipped on boats or remotely piloted vehicles, they emit acoustic beams downward. By measuring the time it takes for the sound pulse to bounce off the seafloor and return, the seafloor depth is determined. Single-beam echo sounders provide point measurements along a survey track in the nearshore zone, whilst MBES systems emit multiple acoustic beams simultaneously, in order to cover a wider swath of the seafloor, providing detailed bathymetric maps. The analysis of MBES data reveals seafloor features, such as channels, sandbanks, and submerged structures.
- Side-Scan Sonar: this sonar system uses acoustic waves to create detailed high-resolution images of the seafloor, showing variations in substrate type, seafloor morphology and submerged objects.
- Sub-Bottom Profilers (SBP): SBPs penetrate the seafloor to image sediment layers and subsurface structures, helping to understand sediment distribution and transport and geological processes.

2.4 Coastline monitoring using satellite data

Satellite technology has been utilized to observe and analyse the dynamic changes of coastlines on a global scale and over time. Satellite-based coastline observation shows great possibilities for understanding coastal movement, erosion patterns, sediment transport, sea-level rise, and the impacts of human activities on coastal ecosystems with high resolution, accuracy scaled to meters level, and sub-daily observation deliveries.

There are two main types of satellite-based coastline observation used:

1. Optical Satellites: These include Landsat, and Sentinel-2, which capture high-resolution images in visible and infrared spectrums. Landsat provides images with a spatial resolution of 30 meters, which is sufficient for detecting large-scale coastal changes. Sentinel-2 offers higher resolution images up to 10 meters, making it suitable for detailed monitoring of smaller coastal features.
2. Radar Satellites: Synthetic Aperture Radar (SAR) satellites like Sentinel-1 can capture data through clouds and during nighttime. SAR is particularly useful in regions with frequent cloud cover or during adverse weather conditions. Sentinel-1 provides high-resolution radar images with a spatial resolution of up to 10 meters, allowing for detailed analysis of coastal changes.

Satellite data acquisition involves obtaining images from historical archives or in near real-time from providers like NASA, the European Space Agency (ESA), or commercial satellite operators and platforms under consideration of temporal consistency for detecting changes over time, spatial resolution suitable for regional assessments and revisit frequency to capture the dynamic nature of the coastlines.

Preprocessing the acquired satellite images and data is essential to enhance the accuracy and usability of the images. One of the critical preprocessing of satellite images is cloud removal by using algorithms to mask out cloud cover in optical images. Techniques such as cloud shadow masking and interpolation are employed to mitigate the impact of clouds on the analysis.

Once the data is pre-processed and clear satellite images were obtained, the next step is image classification and feature extraction. This involves identifying and categorizing distinctive features in the images, such as water bodies, and land. Several techniques are used in image feature classification like applying spectral indices for enhanced feature extraction e.g. Normalized Difference Water Index (NDWI) that enhances water body detection by emphasizing water features' spectral characteristics. Additionally, supervised classification algorithms involve using training data to classify different land cover types like Support Vector Machines (SVM), and Random Forests. Also, unsupervised classification algorithms like k-means clustering identify natural groupings in the data without prior knowledge of the classes.

Once the satellite images are classified and coastline boundaries extracted the dynamic coastline change detection is performed by comparing images over time to identify and present the changes in the coastline. Change detection provides insights into coastal erosion, accretion, or stability, allowing for the assessment of long-term and short-term trends and patterns. The results can be validated using ground truth data, such as field measurements and historical records.

Satellite-based coastline observation has a wide range of applications, including:

1. Erosion and accretion trends definition by monitoring areas of significant erosion or accretion which helps in designing effective mitigation strategies to protect vulnerable coastal areas and maintain the integrity of coastal infrastructure.
2. Climate change impact satellite data provide valuable insights into the long-term impacts of climate change like sea-level rise on coastal areas, helping to inform adaptation and mitigation strategies.

2.5 Coastal Monitoring with Ground-Controlled Aerial Platforms (drones) for surveillance and Data Collection

The utilization of ground-controlled aerial platforms, commonly known as drones, has revolutionized coastal monitoring by providing high-resolution, real-time data collection and surveillance capabilities. Drones are equipped with advanced sensors and cameras, enabling comprehensive observation of coastal areas, which is crucial for assessing coastal changes, erosion, sediment dynamics, and the impact of human activities. This section will focus on how drones are used to monitor coastal morphological changes and their applications in coastal management.

- Advantages of drones over traditional coastal monitoring methods:

Drones offer several advantages over traditional coastal monitoring methods, enhancing the ability to assess and manage coastal environments effectively. These advantages include:

High-Resolution and Precision

Drones can capture high-resolution imagery and generate detailed 3D models, providing precise measurements of coastal features and changes. This high spatial resolution is essential for detecting small-scale changes in morphology that may not be visible with other methods. For instance:

- **Detailed Beach Profiles**: High-resolution data allows for the creation of accurate beach profiles, enabling the identification of subtle changes in beach slope and width that are critical for understanding sediment dynamics and erosion processes.
- **3D Terrain Models:** Advanced photogrammetry techniques employed by drones can produce 3D terrain models with centimetre-level accuracy, crucial for mapping coastal features like dunes, cliffs, and tidal flats.

Rapid and Frequent Data Collection

Drones enable frequent monitoring, providing timely data that is critical for understanding the short-term dynamics of coastal areas. This capability is particularly useful for observing rapid morphological changes following storm events or human activities. Key benefits include:

- **Timely Response to Events**: After extreme weather events, such as storms or hurricanes, drones can be deployed immediately to assess damage and morphological changes, facilitating prompt response and mitigation efforts.
- **Seasonal and Monthly Monitoring:** Regular drone surveys can track seasonal variations in coastal morphology, providing valuable data for long-term trend analysis and management planning.

Accessibility to Remote Areas

Drones can access and survey remote or hazardous coastal regions that are difficult or dangerous to reach by foot or boat. This capability ensures comprehensive coverage of diverse coastal environments, including:

- **Cliffs and Rocky Shores**: Drones can safely survey steep cliffs and rocky shorelines where traditional methods pose significant risks to human safety.
- **Estuaries and Wetlands:** These areas often have challenging terrain and can be inaccessible during certain tidal conditions. Drones provide a practical solution for consistent monitoring of these ecologically important regions.

Cost-Effective

Compared to traditional aerial surveys and satellite imagery, drones are relatively inexpensive. Their deployment does not require extensive infrastructure, making them a cost-effective solution for regular coastal monitoring. Specific cost advantages include:

- **Reduced Operational Costs**: Drones eliminate the need for manned aircraft, reducing operational costs such as fuel, pilot fees, and maintenance.
- **Scalability**: The lower cost of drone operations allows for more frequent surveys, enabling better temporal resolution in monitoring programmes without significantly increasing the budget.

Versatility in Sensor Payloads

Drones can be equipped with a variety of sensors, allowing for the collection of diverse data types that are essential for comprehensive coastal monitoring. The versatility of sensor payloads includes:

- **RGB Cameras:** Standard RGB cameras provide high-resolution visual imagery, suitable for mapping coastal features and detecting changes in morphology.
- **Multispectral and Hyperspectral Sensors:** These sensors capture data in multiple wavelengths, enabling detailed analysis of vegetation health, sediment composition, and other environmental parameters.
- **LiDAR Systems:** LiDAR (Light Detection and Ranging) systems generate precise elevation data by measuring the time it takes for a laser pulse to return after hitting the ground. This technology is particularly effective for creating high-resolution topographic maps and identifying subtle changes in elevation.
- **Thermal Cameras**: Thermal imaging can be used to monitor temperature variations along the coast, which can indicate groundwater seepage, underwater springs, or other thermal anomalies.

Overcoming Cloud Cover Limitations

In regions like Ireland and other northern countries, frequent cloud cover can significantly hinder the effectiveness of satellite-based coastal monitoring. Drones provide a crucial advantage in such environments:

- **Unobstructed Data Collection**: Unlike satellites, drones can fly below the cloud cover, ensuring continuous and unobstructed data collection. This is particularly important in areas where cloud cover is persistent, and satellite imagery is often obscured.
- **Enhanced Temporal Resolution:** Drones can be deployed on demand, allowing for flexible scheduling of surveys to coincide with clear weather conditions, ensuring that critical data is not missed due to cloud cover.

- Applications of Drones in Monitoring Coastal Morphological Changes

Beach Profile Monitoring: Drones can capture detailed images and generate 3D models of beach profiles through photogrammetry. Regular drone surveys enable the tracking of changes in beach width, slope, and volume, providing critical data for understanding sediment transport and erosion processes. High-resolution 3D models allow researchers to measure beach elevation changes with centimeter accuracy, which is crucial for identifying erosion hotspots and assessing the effectiveness of beach nourishment projects.

Sediment Dynamics and Distribution: By using drones to create high-resolution orthomosaics and digital elevation models (DEMs), researchers can study sediment distribution patterns along the coast. This information helps in identifying areas of sediment accumulation and erosion, which are crucial for coastal management and engineering projects. For example, monitoring the movement of sand dunes and the deposition of sediments in estuaries can inform the design of coastal protection measures.

Erosion and Accretion Analysis: Drones facilitate the detection and quantification of erosion and accretion by comparing successive surveys over time. This temporal analysis helps in understanding the impact of natural events, such as storms and tidal cycles, as well as human interventions like coastal defenses and beach nourishment. By creating time-series data, drones provide insights into long-term erosion trends and help predict future changes, allowing for proactive coastal management.

Dune Dynamics and Vegetation Mapping: Drones equipped with multispectral sensors can monitor coastal dune systems and vegetation cover. This is important for studying the role of vegetation in stabilizing dunes and protecting the coastline from erosion. Vegetation indices derived from drone imagery can be used to assess the health and density of dune vegetation, which is essential for understanding its role in coastal resilience.

Hazard Assessment and Risk Management: High-resolution data from drones can be used to assess coastal hazards, such as landslides and flooding. Accurate elevation models generated from drone surveys support flood risk modelling and the development of mitigation strategies to protect coastal communities and infrastructure. Drones can also be deployed immediately after extreme weather events to assess damage and inform emergency response efforts.

2.6 Video Surveillance for Coastal Monitoring

Currently, video monitoring techniques offer an alternative to traditional methods of coastal monitoring, featuring low installation and management costs. The traditional approaches, such as cross-shore profile surveys and aerial photographs, are inadequate due to infrequent measurements of shoreline position and its temporal variability. In contrast, land-based video platforms using digital image-processing techniques provide an optimal solution for determining the objective shoreline position.

The use of video cameras to monitor the constantly changing coastal conditions eliminates the need to deploy individual instruments, which can take a lot of time and do not provide observations continuously and everywhere. The images and videos captured by the cameras are useful to observe current coastal conditions and to compare the changing conditions along the coast over time. This includes, for example, monitoring the rise in water level during a storm and the potential impact of tides on the coast.

A video, or a sequence of individual images, can also be processed to create various image products, which can be used to measure several coastal processes, including:

- the increase of the wave movement
- statistics on the regular and extreme water level
- time series of the position of the shoreline
- existence and movement of the sand banks
- presence of rip currents
- change of the coastline

Camera images enable the acquisition and sharing of long-term, continuous information, including real-time data, with higher temporal and spatial sampling frequency. A limitation is the substantial data storage requirement, especially for remote sites. Collected images (*snapshots)* are elaborated by specific software to extract quantitative information of the shoreline positions. The resulting products of post-processing analysis are:

- Time exposure images (timex), which are obtained by digitally averaging image intensity over a predefined acquisition time, and are created by processing and superimposing snapshot images of an acquisition cycle. This process eliminates random sea conditions and variability in wave run-up and swash. On timex images, the variation in pixel colour intensity allows for better distinction of beach morphological features. Therefore, timex images are an excellent instrument to highlight submerged sand bar topography.
- Variance images, derived by digitally averaging image intensity over a predefined acquisition time and computing the standard deviation of pixel colour intensity, enhance the contrasts achieved by processing time-exposure images. This enhanced contrast facilitates the identification of submerged foreshore structures that might otherwise be obscured in conventional time-exposure images. Moreover, variance images provide a unique perspective on the temporal dynamics of the scene, enabling the detection and analysis of transient phenomena that unfold during the acquisition window.
- Daily time exposure images (or day-timex) are obtained by averaging all images acquired in the whole day. The process of averaging effectively reduces the impact of transient factors, such as wave patterns, surface reflections, and underwater visibility fluctuations, which can introduce noise and variability in individual images. The resulting day-timex image presents a more stable and reliable depiction of the scene, enhancing the accuracy of subsequent analyses or monitoring efforts.
- Time-stack images are created by extracting a line of pixels along a predefined array in a video frame. The same set of pixels is extracted from images of a selected period and stacked vertically to create an image with time on the vertical axis and cross-shore distance on the horizontal axis. Time-stack images offer a powerful tool for analysing and understanding the intricate dynamics of coastal environments. By condensing the spatial and temporal information from video footage into a single, visually striking representation, these images provide a comprehensive overview of the complex interplay between waves, currents, and sediment transport processes.

The primary application of video monitoring involves shoreline detection using oblique or rectified images, enabling the monitoring of long-term coastline movements and short-term responses to storms. Extracting the shoreline from images requires distinguishing between sea and sand. This necessitates initial image-processing procedures to identify the shoreline contour, which may vary according to the beach's morpho-dynamic environment.

2.7 Coastal Monitoring Data Availability for SCORE Coastal Cities, a summary

2.7.1 Benidorm

The study of the evolution of the shoreline was carried out by vectorizing the shoreline from aerial images since 1956. Satellite images have not been used given the low resolution compared to the orthophotos used for this work. Since not all the images used to study evolution of the shoreline were georeferenced, the first step was the photogrammetric restitution of all those non-georeferenced images (Pagán et al. 2016). The methodology of shoreline vectorization consists of the visual identification of the last wet mark of the tide on the beach profile, namely the wet-dry boundary in the intertidal zone (Ojeda Zújar et al. 2010). On the Mediterranean coasts this criterion is appropriate due to the low variation in tides. This feature eliminates possible variations due to sea state when capturing the aerial image. The 5.3 km of shoreline were vectorized for each of the 21 available years (Table 1).

Table 1. Summary of available aerial images.

Date	Source	Image	Format	Resolution
04/07/1956	American Fly	Orthophoto	ECW	50 cm
02/1977, 03/1989	Cartoteca, IGN	Aerial	ECW	1 m/pixel
07/1981, 07/1986 07/1990, 07/1992 07/1994, 07/1996 22/08/1998	DGC – SPC Alicante	Aerial	ECW	1 m/pixel
08/2000, 29/09/2005, 27/08/2007, 18/08/2009, 24/06/2012, 28/06/2014	PNOA	Orthophoto	ECW	25 cm/pixel– 50 cm/pixel
22/08/2017, 15/06/2018, 17/06/2019, 21/05/2020, 26/06/2021, 29/05/2022, 28/07/2023	IDEV	Orthophoto	ECW	25 cm/pixel

The data on beach morphology were obtained from digital elevation models (DEM) for the following dates: 13/11/2009, 18/08/2016. These data came from LiDAR flights that are part of the National Plan for Aerial Orthophotography (PNOA, in Spanish) government surveys and are publicly available under the CC-BY 4.0 license. All data refer to Datum ETRS89. Given the format in which the data was provided (LAS point clouds), the first step consisted of the creation of a terrain dataset for each date in GIS software. A terrain dataset is a multiresolution TIN-based surface created from measurements stored as features in a geodatabase. The characteristics of the elevation models are shown in Table 2.

Table 2. Characteristics of the sources to obtain the elevation models

Date	Source	Resource type	Point density	Pixel size	RMSE z	Spatial reference
13/11/2009	CNIG	LiDAR	>0.5 pt./m^2	2 m/pixel	<0.40 m	UTM ETRS89 H30N
18/08/2016	CNIG	LiDAR	>0.5 pt./m^2	2 m/pixel	<0.20 m	UTM ETRS89 H30N

The bathymetry of the study area, which dates to 2006, was provided by the General Directorate of Coasts (DGC) based on the Ecocartographies Plan of the Spanish coast. The elevation range includes elevation 0 to elevation -40. The bathymetry was carried out with a Multibeam probe of the submerged coastal platform, at a scale of 1:1,000.

Wave data (significant wave height, period, and direction) were provided by Puertos del Estado, based on the SIMAR series, specifically the database of SIMAR Node 2082102 (0.167° W, 38.500° N) was used, located about 5 km south of the study area. SIMAR dataset is composed of simulations carried out through numerical modelling of the atmosphere and waves that cover the entire Spanish coast. The wave fields have been generated by WAM and WaveWatch models, fed by wind fields of the model provided by the Spanish Meteorological Agency (Puertos del Estado, 2020). In addition, SWAN model is applied to these wave fields to consider the transformations that the waves undergo when approaching the coast. In general, these data are collected during the period 1958-2023 with an hourly frequency and a spatial resolution of less than 3 km.

Sea level data (astronomical tide and storm surge) have been obtained through the Gandía Tide Gauge, from the Puertos del Estado Tide Gauge Network (REMPOR). Located in the Port of Gandía (0° 9’ 5“ W, 38° 59’ 43” N). This data point is the closest to the study area. This is hourly data collected over 16 years, over the period 2007–2023. The Storm Surge, a random variable caused by atmospheric pressure and wind, is estimated as a residual or difference between the starting data (total sea level) and the Astronomical Tide, a deterministic variable resolved by harmonics analysis (Tapia et al., 2016).

In terms of sedimentology, the samples were taken by the University of Alicante in three periods: 2012, 2014 and 2021. Sediment collection was carried out outside the drainage areas to the beach. These samples were dried after their extraction for 24 h in an oven to subsequently proceed to their granulometric test. These tests were carried out following the UNE-EN ISO 17892-4 standard, and in a complementary way the UNE 7050-2 and the UNE 103 100. The value of the second quartile -equivalent to parameter D50- was obtained from these tests. Also available are the seabed granulometry data for 2006, provided by the General Directorate of Coasts.

Finally, some climate projections were obtained through the Viewer for adaptation to coastal climate change (Available: https://geoadaptacostes.gva.es/) developed by the regional government of the Generalitat Valenciana. The proposed methodology contemplates the characterization under the hypotheses of different climate change scenarios that combine projections of average sea level rise and extreme events, the latter treated statistically. The projections are based on the 5th IPCC report and for the Representative Concentration Pathway RCP 4.5 and RCP 8.5 (IPCC, 2015). The change in mean wave height, the change in Mean Seal Level, the shoreline projection and the beach flooding level were obtained for the horizon years 2045 and 2100.

2.7.2 Dublin

The study of coastline changes in the Dublin area, stretching from Dún Laoghaire Harbour to the northern Dublin Bay, aimed primarily to assess the contribution of satellite data processing algorithms within the GEE framework (as described in D3.9) to advancing our understanding of these phenomena. Additionally, the most significant behavior in this area, whose morpho-dynamics appear closely linked to rapidly evolving factors requiring further exploration, leans towards accretion and is notably influenced more by anthropogenic rather than natural factors.

Dublin coastline analysis methodology:

Data acquisition and preprocessing:

Satellite imagery retrieval Landsat (5, 7, 8, 9) and Sentinel-2 imagery through Google Earth Engine's platform. These images are retrieved in multiple spectral bands to facilitate detailed analysis of coastal features and processes.

Image processing enhance clarity and remove clouds interference, ensuring accurate coastline detection

Water/land classification advanced algorithms within classify imagery into water, land, and transitional zones, enhancing the accuracy of shoreline delineation and change detection.

Shoreline patterns analysis:

DSAS application: Shoreline positions extracted from classified imagery are analysed using DSAS. This tool calculates rates of shoreline change, identifies areas of significant erosion or accretion, and generates trend lines to visualize long-term coastal dynamics.

Statistical Analysis: DSAS incorporates statistical methods to validate shoreline change measurements, assess the significance of trends, and quantify uncertainties in erosion rates over time.

Accessibility of used tools: Coastsat, Google Earth Engine, and DSAS are open access platforms and tools with freely accessible to users, and researchers.

Dublin coastline analysis results

Figure 1 shows the spatial distribution for the shoreline movement along the Dublin coastline area. The transects analysis presents the central area with mainly pink and blue the most significant changeable shoreline while the northern and southern sections as yellow and orange showed moderate to minor movement.

Figure 1: Dublin shoreline movement

Figure 2 shows the yearly shoreline changing rate based on the weighted linear regression (WLR) for long-term coastline analysis. WLR can help in identifying the erosion and accretion trends

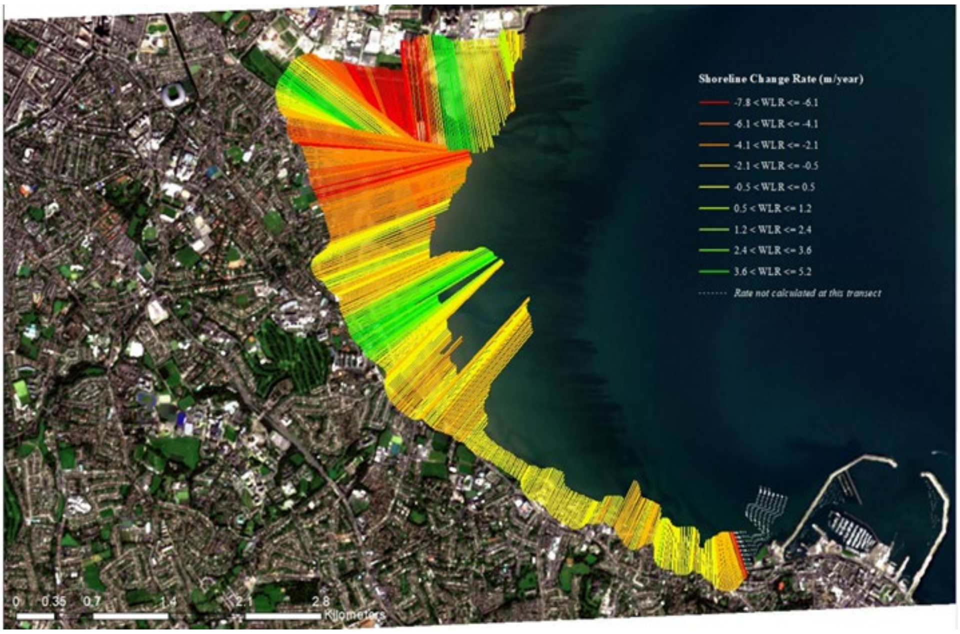


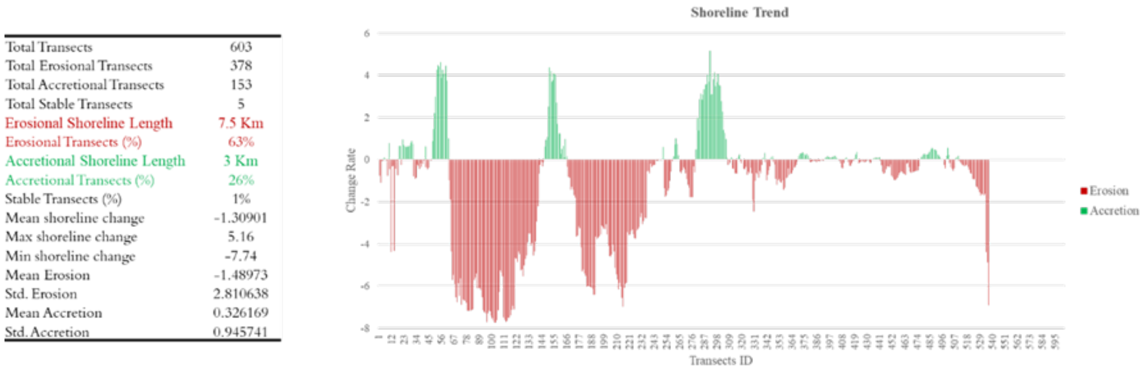
Figure 2: Dublin shoreline yearly changing rate

The transect analysis based on WLR can express the erosional shoreline when the value of WLR<0, while the accretional shoreline are found at WLR>0.

Figure 3 illustrates the erosional and accretional shorelines based on changing rate.

Figure 3: Dublin coastline trends

Figure 4 demonstrates the Dublin coastline analysis to present the erosional and accretional shoreline patterns.



Total Transects	603
Total Erosional Transects	378
Total Accretional Transects	153
Total Stable Transects	5
Erosional Shoreline Length	7.5 Km
Erosional Transects (%)	63%
Accretional Shoreline Length	3 Km
Accretional Transects (%)	26%
Stable Transects (%)	1%
Mean shoreline change	-1.30901
Max shoreline change	5.16
Min shoreline change	-7.74
Mean Erosion	-1.48973
Std. Erosion	2.810638
Mean Accretion	0.326169
Std. Accretion	0.945741

Figure 4: Dublin coastline pattern

As shown in Figure 4 the historical analysis for Dublin coastline presents 63% of transects classified as erosional shoreline while 26% are accretional shoreline, altogether illustrating that the present focused area is suffering from erosion conditions.

2.7.3 Massa

Coastal monitoring data for the Massa territory are relatively abundant, due to the tendency towards erosion of these beaches and the consequent frequency of monitoring and restoration interventions, executed in the last decades by local and regional administrations. In addition to local-scale topographic and bathymetric data from these sources, a wide quantity of information on regional-scale shoreline evolution has been collected over time.

The first data about it were extracted from maps and aerial photos from the 1900s, while the first in situ surveys have been available since the early 2000s. In particular, for the Massa area the shorelines of 1938, 1954, 1967, 1978, 1985 and 2005 are available. The most recent data were obtained from orthophotos with a spatial resolution of 20 cm (for the years 2010, 2013 and 2016) and from Pleiades satellite images with a resolution of 50 cm (acquired every summer from 2017 to 2022).

The choice of the proxy representing the shoreline on the images has been adopted trying to identify the smallest possible deviation the vertical datum zero of the national coordinate system, which is generally chosen as unique indicator for the shoreline (MATTM-Regions, 2018), and which, based on the checks carried out, results almost always between the run-up limit (wet-dry limit) and the last wave breaker in correspondence with the beach-step. So, with optimal wave conditions the midline of this strip should represent the zero isobath with the best accuracy: the results of this method have been compared with coeval dGPS surveys, pointing out that for almost all the checks, the verified error was about 1 meter.

A comparison between the 2005 data and the most recent ones has been performed in order to obtain an overview of the mid-term shoreline evolution; the coast of Marina di Massa boards to the north with the Marina di Carrara port, and beyond it there is the homonymous beach, that results to be in accretion in the investigated period, due to a certain number of restoration works. To the south there are the beaches of the area called Versilia, particularly the ones of Forte dei Marmi, which is in balance, and of Marina di Pietrasanta which is instead advancing (Fig. 5). A beach has been considered in balance when the mean annual rate is less than +/- 0,5 m, whilst an eroding or accreting beach can be defined if this value is higher, in one direction or the other.

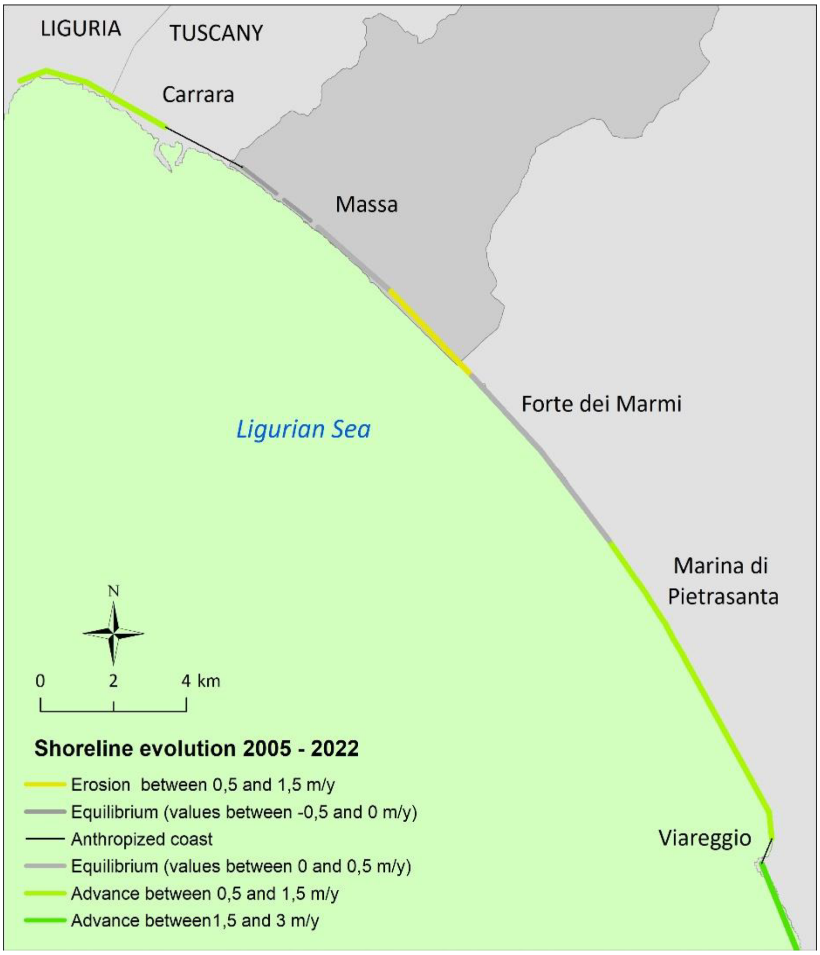


Figure 5: Shoreline evolution in the northern part of Tuscany, including Marina di Massa beaches.

Looking at the Marina di Massa territory, in the northern part the beach is dominated by the presence of breakwaters, and in most of the sector the current shoreline is slightly behind compared to 2005, with a mean shoreline variation of -5,6 m. In the central coastal stretch, there is a strong presence of groynes protecting the beach, causing a prevailing equilibrium, with advance of the shoreline in some transepts. Here, the mean shoreline variation is +2,7 m. “Ronchi” is the name of the southern part of Marina di Massa, where a stretch of beach free from coastal structures follows one instead defended by groynes. There is a prevailing and widespread erosion compared to 2005, with a mean shoreline variation of -11,1 m (Fig.6).

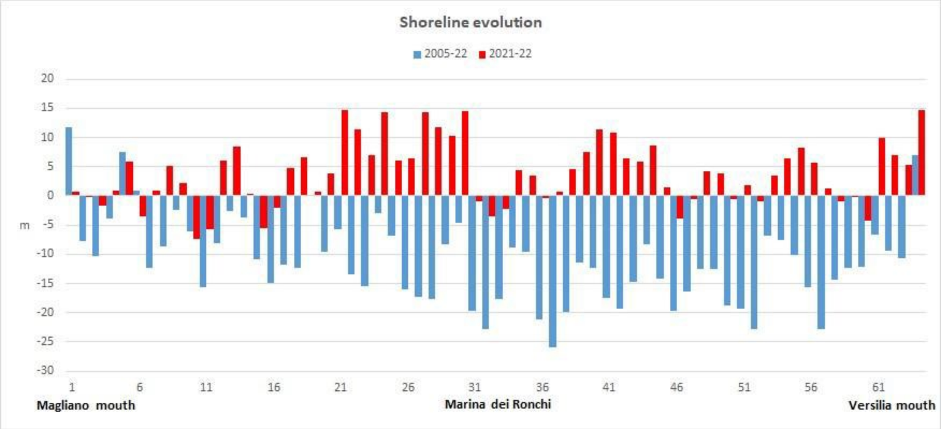


Figure 6: Shoreline evolution at Ronchi, the southernmost of Marina di Massa beaches

Between 2019 and 2022, 4 coastal webcam systems have been installed along the Marina di Massa beaches. They have been mounted on as many existing poles belonging to the local provincial administration, and they are equipped with a camera that controls two divergent lenses; this allows to get images of a stretch of coast of approx. 300 m both north and south of its position (Fig.7).

Figure 7: Cameras view perspective

The system provides a dual image acquisition mode:

1) Acquisition of high temporal resolution images, according to a schedule that acquires 10 minutes at the beginning of each hour from 10 am to 2 pm, with a frequency of 2 Hz. Image acquisition is performed at a resolution of 2 Mpx. This acquisition is aimed at studying wave run-up and producing data useful for coastal modelling activities. In this case, given the number of images acquired, they are stored on an SD card installed in the system, and downloaded remotely only for the days affected by storm events.

2) Acquisition of images with lower temporal resolution, planned to get, in the same time windows, images every 3 seconds approximately, which allows them to be sent live to an FTP server. This type of acquisition is used to study the daily/monthly variability of the shoreline, as well as for other purposes (analysis of bottom structures, identification of rip currents, variations in sea level, etc.)

In the image processing phase, for each day approximately 850 acquired frames are processed (the first 10 min. of each hour from 10 am to 1 pm), to obtain the final average timex image (Fig.8).

Figure 8: Example of timex image

After the image georeferencing, a supervised classification is performed on the obtained timex, identifying areas (training sets) of beach and sea pixels. Then, an edge detection algorithm (image Canny Edge Detector) is applied to the classified image to identify the shoreline.

Examples of uses of the data obtained from coastal webcams are the determination of time series of shoreline oscillation on different scales and the identification of the generation conditions of rip currents, as well as the analysis of run-up during intense events.

3. MODELS FOR COASTAL EVOLUTION

Several models are utilized in coastal modeling to represent the complex two-dimensional and three-dimensional processes of coastal dynamics. Overall, one-line models offer simplicity and efficiency for long-term simulations and large-scale shoreline changes but are limited in detail and accuracy compared to more complex models, often requiring extensive calibration with observed data for reliable results (Dean and Dalrymple, 2002).

These models include, among others, GENESIS (Hanson and Kraus, 1989), LITPACK, part of the MIKE software suite (DHI, 2017).

The COSMOS-COAST (Coastal One-line Assimilated Simulation Tool) model integrates satellite-derived shoreline observations for improved accuracy and is open-specification, making it adaptable for various research needs. We have chosen the COSMOS-COAST model due to its flexibility of use and, most importantly, because it estimates model parameters based on observed trends rather than relying on complex and arbitrary calibrations. This is achieved through the assimilation of previous years' coastline data using a Kalman filter, making it an ideal model for climate-scale simulations. Moreover, COSMOS-COAST effectively utilizes marine data (such as waves and sea level) produced by the project, enhancing its applicability and accuracy in long-term coastal evolution studies.

There are also very complex models for coastal erosion that can represent processes on different spatial and temporal scales. However, we will focus on describing the choices made for the SCORE project and their application to the case studies of interest for SCORE.

3.1. Long-term coastline evolution models

Coastal processes show a variety of spatial/temporal scales processes that shape coastal morphology. In figure 9 short-term (days-to-weeks), medium-term (months-to-decades), and long-term (>decades) categories are described. On wave-dominated coastlines, cross-shore and longshore gradients in sediment fluxes, wave set-up, and changing water levels are some of the principal processes driving coastal change at short-to-medium timescales whereas, over longer timescales (multi-decadal/centurial), eustatic and isostatic sea level change may have a more significant influence on shoreline change. Eustatic sea level change refers to a global change in sea level, while isostatic (or ‘relative’) sea level change refers to localized changes in land height, relative to sea level (Rovere et al., 2016).

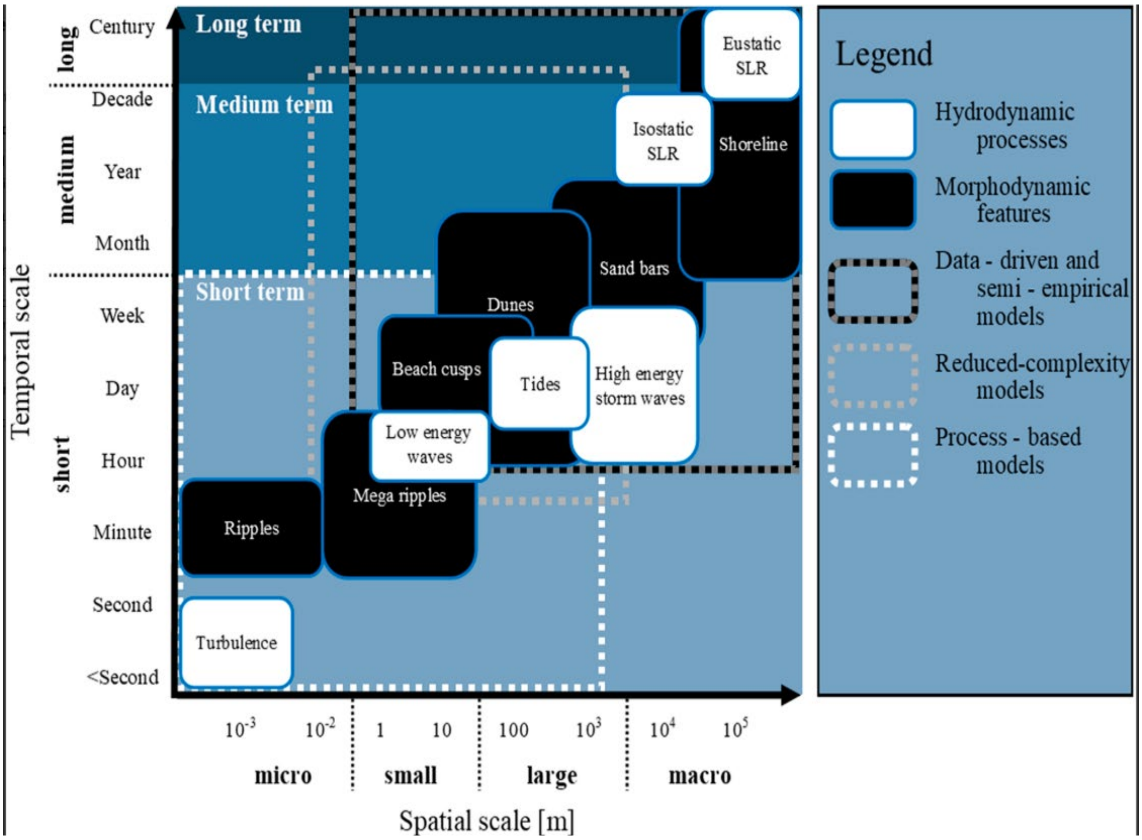


Figure 9: Processes of coastal erosion and their temporal versus spatial resolution impacts

A classification of coastal morpho-dynamic models can be performed according to their spatial and temporal scales, or to the number of dimensions (e.g. profile, depth-averaged coastal area, 3D models).

In a bottom-up representation of models' complexity, the most inclusive ones are located at the base. Models become more and more simple and stable going upward but the need for calibration data and the difficulty of dealing with complex structures and processes are also growing.

3.2. Hybrid modelling approach

Hybrid shoreline evolution models are increasingly being used to inform the management of sandy coastal systems. These models generally apply a two-dimensional physics-driven approach to calculate littoral drift and use the one-line theory to update the shoreline morphology.

Indeed, two-dimensional or three-dimensional models like XBeach, although much more sophisticated in describing complex nonlinear and multidimensional processes (wave-current interaction, sediment transport, and morphological evolution), still have limitations because: 1) they suffer from significant uncertainties due to the complexity and nonlinearity of the systems of equations they solve; 2) they have limitations in some representations of the physics of phenomena; and finally, 3) they require extensive computational resources.

For example, a major limitation of many storm impact models, such as XBeach, is that they do not allow for the description of the post-storm gravitational adjustment process, which occurs on longer time scales. This makes XBeach unsuitable, for example, for running long-term morphological evolution simulations.

In the hybrid approach, the balances that govern the morphological evolution of the shoreline are described by reduced-physics models. This approach allows more efficient computation while maintaining an adequate level of accuracy. Hybrid models can integrate the detailed, short-term predictions of sophisticated models with the broader, long-term trends captured by simplified models. This integration enables more effective and sustainable coastal management strategies.

The hybrid approach will be developed and tested, especially during the testing phase, and thus as part of Task 3.6. This phase will involve calibrating the models against observed data and validating their predictive capabilities. The ultimate goal is to provide coastal managers with reliable tools that can predict shoreline changes over various time scales, enhancing their ability to make informed decisions regarding coastal protection and development.

3.3. The COSMOS-Coast model

Modeling coastal morpho-dynamic evolution over extended time scales presents significant challenges. Let’s break down the key points:

- Drivers of Change:
    - Coastal morpho-dynamics involve sediment transport and shoreline alterations.
    - These changes result from hydrodynamic processes (like tides, waves, and currents) and geologic factors (such as cliff erosion, sediment supply, and fluvial inputs).
- Numerical Modeling Challenges:
    - Achieving accurate simulations while managing computational effort is crucial.
    - Increasing model resolution (more grid points) enhances accuracy but demands more computational resources.
    - However, higher resolution also reduces the allowable time step for stability.
- Human Impact:
    - Anthropogenic activities significantly affect coastal evolution.
    - Land reclamation, dam construction, and altered sediment supply impact ecosystems and morpho-dynamics.

Balancing accuracy and computational efficiency remain a central challenge in modeling coastal changes over long-time spans. Researchers must consider both natural processes and human activities to improve predictions and ecosystem protection.

A nonlinear, implicit one-line model to simulate long-term (decadal and longer) shoreline evolution is represented by the COSMOS-Coast model. By allowing large time increments without compromising model stability in comparison to explicit alternatives, the implicit numerical method introduced here aims to increase computational efficiency. The coastline location, or solution to the governing equations, is computed by the model using a Jacobian-free Newton-Krylov solver. An analytical solution for alongshore shoreline diffusion is used to validate the model.

The CoSMoS-COAST model was initially developed as the long-term shoreline change component of the USGS Coastal Storm Modeling System (CoSMoS; Barnard et al., 2014), which was developed to make detailed predictions of storm-induced coastal flooding, erosion, and cliff failures over large geographic scales.

In summary, the notable and novel aspects of the latest version (2021) of the model include:

- Accounts for longshore and cross-shore sand transport and local trends
- Assimilation of historical shoreline observations to calibrate and validate the model
- Typically applied to project shoreline change on decadal to centennial time scales
- Run in an ensemble to better characterize uncertainty

Model output is optionally .kml files, easily readable in Google Earth.

3.4. X-Beach model for seastorm (short-term) time-scale

Extreme oceanographic events brought on by extratropical or tropical storms have the potential to drastically change coastal morphology, which will affect how vulnerable communities and infrastructure are to flooding. They can also have a significant impact on the short-term sediment dynamics in coastal areas (Santos et al., 2019). According to Roelvink et al. (2009), XBeach is thought to be among the most sophisticated methods for forecasting how sandy beaches would morphologically react to severe storms. This numerical model, which is process-based and two-dimensional, can simulate the morpho-dynamic behavior of coastal areas in different storm impact scenarios.

In order to model a seastorm using XBeach on its time scale, one must first choose a storm event and take into consideration the oceanographic variables' time-dependent evolution. With wave and bathymetry data serving as boundary conditions, XBeach is able to forecast the storm event's morphological response characteristics. The XBeach model's structure is shown in Figure 10.

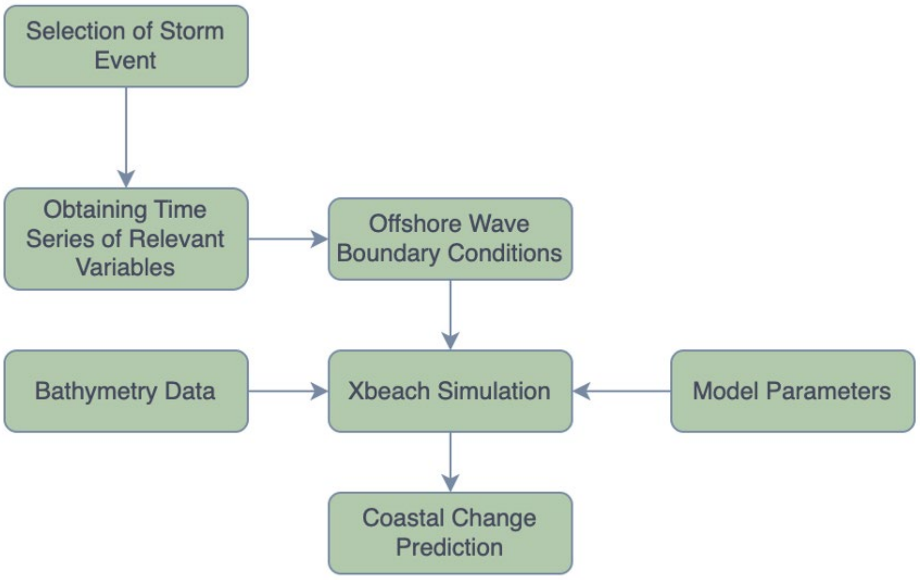


Figure 10: XBeach model structure flowchart.

The dynamics of nearshore waves and currents, sediment transport, morphological changes, and the nonlinear interactions between these processes throughout the course of a storm are all simulated by the process-based XBeach model (Roelvink et al., 2009).

Precise hydrodynamic and morphological conditions are necessary for an accurate simulation of nearshore morphology. First, as shown in Table 3, parameters pertaining to hydrodynamic conditions need to be ascertained. Model parameters not specified in Table 3 can be inferred in the event that data is insufficient by using the numerical model's suggested values.

Table 3: Hydrodynamic parameters to apply the Xbeach Model

Parameter	**Definition**
instat	seaward boundary condition
bcfile	wave boundary conditions
eps	water depth threshold, beyond which water is deemed wet
zs0	starting water level
tideloc	The quantity of corner points that are designated for a tide time series
bedfriccoef	coefficient of bed friction
nuhv	longshore enhancement factor for viscosity
morfac	morphological acceleration factor

Wave boundary conditions can be defined as stationary or instationary using the 'instat' parameter. For each storm, the parameters Hm0 (significant wave height), Tp (peak wave period), θ (main angle in degrees), s (spreading parameter), and duration must be included in a file called "bcfile".

The morphological acceleration factor, or "morfac" parameter in XBeach, resets the hydrodynamic and morphological time scales. It is employed when the morphological reaction is shorter than the hydrodynamic time scale. The morphology gets accelerated by the given factor in order to shorten the simulation period (Demirci, 2016).

Table 4 provides an explanation of morphology characteristics, which include bed update systems and sediment movement.

Table 4: Morphology parameters to apply the Xbeach Model

Parameter	**Definition**
D50	size of the median grain
form	equilibrium sediment transport formulation
wetslp	critical wet slope for the wet area
dryslp	critical dry slope for the dry area
struct	option for the non-erodible structure

Model output is optionally available as .nc (NetCDF) files, which are easy to visualize and manipulate with programming languages such as Python, Matlab, and NCL.

4. NUMERICAL MODEL BUILDING: INPUT AND OUTPUT DATA

4.1 Model configuration and implementation

Different model configurations include the assimilation of the different types of data, for example, GPS versus satellite-derived shorelines versus both types. The wave-forcing time series are split into “Hindcast (Calibration)” and “Hindcast (Validation)” periods, where shoreline data assimilation is turned on and off, respectively. The goal of this test is to better understand the accuracy of the calibrated model when using several years of high precision but lower temporal frequency data (e.g., monthly GPS observations) versus using several years of lower precision but higher temporal frequency data (e.g., satellite-derived data). With this comparison, we seek to determine if (for the purposes of model calibration) satellite-derived shorelines can be used in lieu of in situ observations, which exist only at a handful of well-monitored beaches and are generally unavailable for perhaps over 99% of other beaches worldwide.

4.2 Input data

Inputs needed to run the model include:

- Transects:
  - The *transect file* is perhaps the most important data structure for running the model. The transects data structure contains the spatial information and historical shoreline observations used in the code.
  - The variable ‘transects’ is actually a ‘struct array’, with each element of the array corresponding to an individual transect and its accompanying data.
- Data sources:
  - *Shoreline observations:* derived from existing surveys or remote mapping.
  - *Wave hindcast and forecast data*: Wave height, period, and direction data come from the downscaling activities of the project (as reported in D3.3 and D3.4).
  - No *bathymetric data* are required directly in the model, but a foreshore slope for each transect must be derived from existing bathymetric datasets of the study area.

4.3 Output data

The model's output data primarily consist of shoreline projections considering: 1) recent past evolution, 2) climate wave evolution scenarios, and 3) SLR. Shorelines are generated by the model in georeferenced formats, easily visualized in Google Earth (*.kml files), enhancing usability for relevant CCLLs.

Coastline projections can be provided at arbitrary frequencies, potentially accompanied by uncertainty estimates, necessitating multiple model realizations. Ancillary data may include sediment transport flows (long-shore and cross-shore), crucial for sediment balance assessments

4.4 Model calibration

Model calibration is performed over the "Hindcast (Calibration)" period and can be adjusted based on the availability of historical or recent shoreline datasets. Unlike some other models that rely on user-driven trial and error processes, COSMOS-COAST utilizes a Kalman filter for parameter calibration. The parameters estimated by the Kalman filter, as shown in the results of Fig. 19, correspond to longshore and cross-shore transport parameters, and unresolved processes, as described by the terms ϵ and v_{lt} of the folloqing equation

$$\frac{\partial Y}{\partial t} = -\frac{1}{d_c}\frac{\partial Q}{\partial X} - \frac{c}{\tan\beta}\frac{\partial S}{\partial t} + \nu_{lt} + \frac{1}{\tau}(Yeq - Y) + \varepsilon$$

It is important to note that the calibration is conducted on a different set of shorelines than those used for validation, ensuring the robustness and reliability of the model.

4.5 Model validation

Model validation is performed over the "Hindcast (Validation)" period and is tailored to the shoreline datasets available during both the calibration and validation periods, as well as the forecast period to be performed. Skill metrics, specifically for the Benidorm case study, are reported in Fig. 17. The validation is conducted on a different set of shorelines than those used for calibration. Additionally, it is important to note that wave forcing data were separately calibrated for all coastal cities based on the adopted WWIII model. All of this will be further documented in the final project deliverables related to task 3.6 (testing).

4.6 Use cases

4.6.1 Benidorm

Benidorm, located on Spain's eastern shore of the Iberian Peninsula, is home to Poniente Beach and Levante Beach, the two main beaches in this case study. These beaches are popular tourist destinations, attracting visitors from the Valencian Community as well as other parts of Spain. Their appeal is due in part to their morphology—their extensive length and width—and the fine sediment that forms them. Levante Beach stretches 2.3 km, while Poniente Beach extends 3 km. Both beaches are part of a headland embayment within a closed littoral system. They face south, with Levante Beach being well-protected by the Sierra Helada massif from the easterly waves that are most common in this region. Poniente Beach, however, is slightly more exposed to waves from the southwest. Benidorm beaches have this special natural protection that results in less storm damage compared to other eastern regions of Spain. Additionally, Benidorm Island to the east and Sierra Helada to the west significantly influence the wave regime in the area.

Figure 11: Benidorm study case

In 1991, a breakwater was constructed and 710,847 m^3 of sand was artificially supplied through dredging on the east side of Poniente Beach to address the ongoing coastal erosion in the study area. This intervention resulted in a 70-meter increase in the beach's width.

Furthermore, the position of *Posidonia oceanica* within the beach's cross-shore profile was significantly impacted by the nourishment project, causing it to recede more than 100 meters offshore and dropping three to five meters below the original depth where nourishment was applied. This occurred due to the excessive discharge of sand, which buried a portion of the *Posidonia oceanica* meadow, leading to its degradation. As a result, the backshore surface disappeared, and the beach profile became less steep. The study area is located in a microtidal zone, where air pressure oscillations have a greater influence than the actual tides. Meteorological tides can reach levels of up to 0.45 m, while astronomical tides have a maximum value of 0.3 m.

MODEL IMPLEMENTATION

In the Benidorm area, two different models were tested, one for each beach. For Poniente Beach, 128 transects spaced approximately 20 meters apart were used, while 96 transects were used for Levante Beach. Since both beaches can be treated as closed systems, the first and last transects of each beach were considered as "cross-shore only" transects, to avoid accounting for longshore transport to or from areas outside the beach. All other transects were treated as "full model" transects, allowing for the evaluation of both cross-shore and longshore transport.

A baseline is set (“no-erodible” line) at the internal limit of the backshore, which can be set as a fixed line (shoreline can’t cross it).

Figure 12: Poniente (left) and Levante (right) beach transects

For each beach, a set of 11 shorelines derived from aerial images have been used (table 5).

Table 5: Aerial images available

Date	Source/Image/Format/Resolution/Spatial reference
27/08/2007	PNOA Orthophoto ECW 25 cm/pixel–50 cm/pixel UTM ETRS89 H30N
18/08/2009	
24/06/2012	
28/06/2014	
22/08/2017	IDEV Orthophoto ECW 25 cm/pixel UTM ETRS89 H30N
15/06/2018	
17/06/2019	
21/05/2020	
26/06/2021	
29/05/2022	
28/07/2023	

Shoreline used spans from 2007 to 2023 and are derived from different aerial surveys (tab. 6)

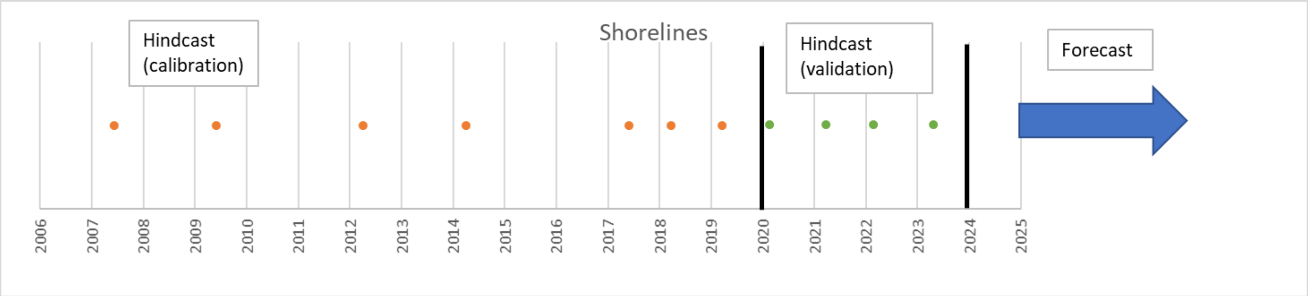


Figure 13: Shorelines used for validation

The shorelines from 2006 to 2020 were used to calibrate the model through the Kalman filtering procedure, and shorelines from 2020 to 2024 were used for validation (fig.13).

Wave height, period, and direction data were obtained from the Downscaling Wave Climate Activity using wave prediction models driven by a Global Circulation Model (see Task 3.2), employing an unstructured grid modeling approach based on the WW3 model. High-resolution modeling (up to 500 m) was specifically applied to the areas surrounding the Benidorm coastal site. Within the unstructured grid, two points located just outside the beaches were selected to assign wave data to the transects (see Fig. 14).

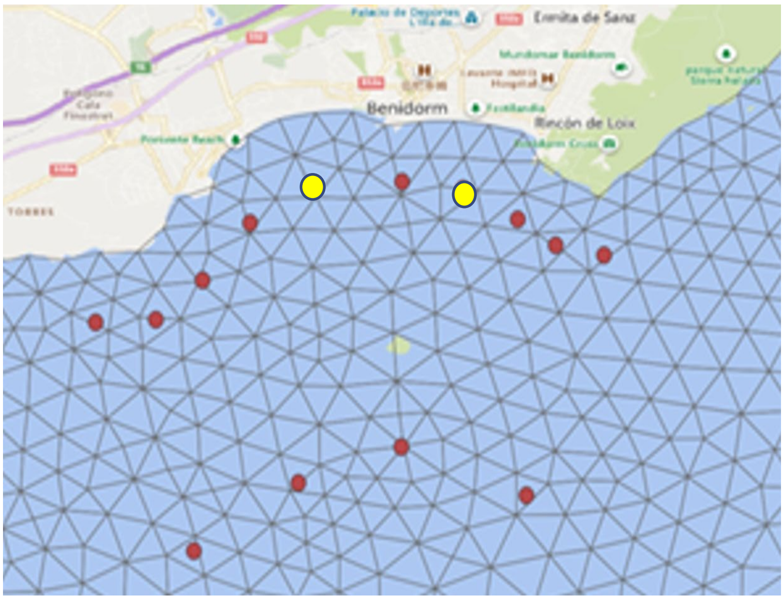


Figure 14: Unstructured grid of downscaling model. Wave climate data were extracted from the yellow nodes.

The bathymetry and Digital Elevation Model of the area were used to determine the slope of the foreshore along each transect line. The yellow areas in Fig. 15 represent the foreshore where the slope has been evaluated.

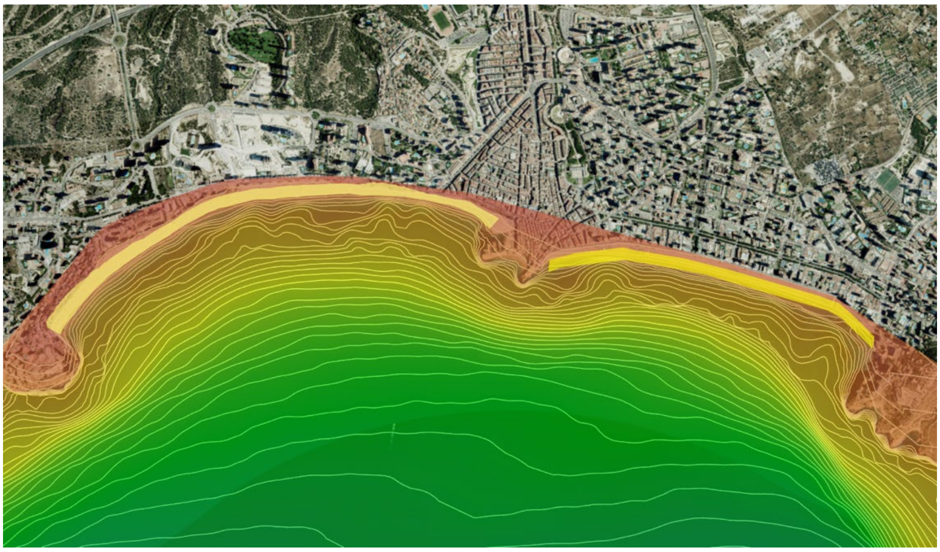


Figure 15: Coastal topo-bathymetry model of Benidorm Poniente and Levante beaches. Yellow areas include the shorefaces where the beach slope was evaluated, along each transect.

RESULTS

Simulations of specific scenarios can be performed using the wave climate data computed in Task 3.2. In this case, the RCP8.5 climate projection scenario for the period 2006-2100 was simulated. The COSMOS Coast model was driven by wave data corresponding to the RCP8.5 scenario, with the total Sea Level Rise (SLR) set to 1.00 m over this period.

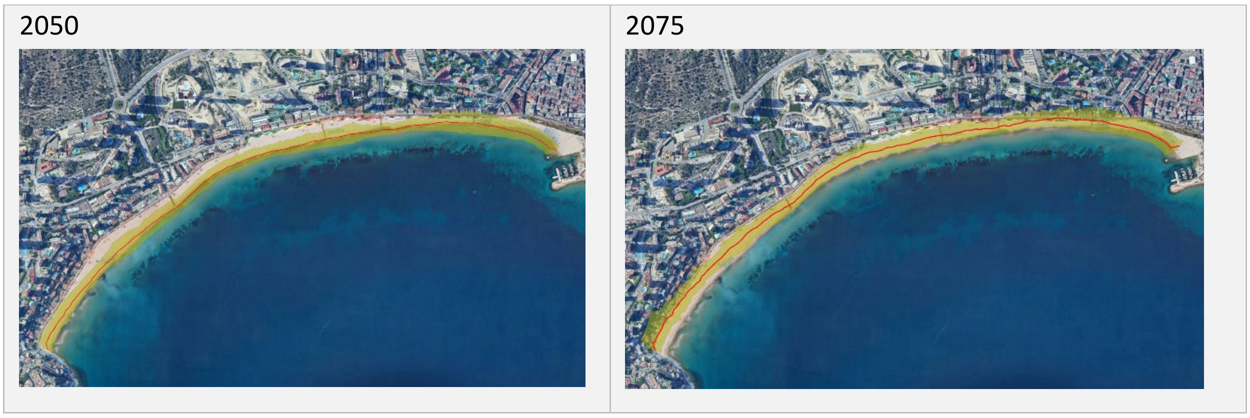
Preliminary results, visualized on Google Earth, show the progressive retreat of the shoreline under this scenario. The green line represents the projected shoreline position in 2050 with an SLR of 33 cm, the yellow line represents the projection for 2075 with an SLR of 62 cm, and the red line indicates the projection for 2100 with an SLR of 1 m (Fig. 16).

Poniente beach with forecasted shorelines

Zoom of the yellow area in the left image

Figure 16: Results of coastal shoreline erosion projections for Poniente beach

The results also include the uncertainty area maps of the shoreline projections of fig. 17.



2050

2075

2100 	

Figure 17 Maps of the uncertainty areas for Poniente beach with each shoreline projection (in yellow).

Model produced Kml of simulated future shorelines for specific dates defined by the user, each with uncertainty areas and winter erosion produced by different return period (i.e. in our run 1 yr storm, 20 yr storm and 100 yr storm), through a GEV analysis performed inside the model .

The RMSE of the modelled shorelines w.r.t. the observed ones was also computed. For the Poniente Beach, the mean RMSE for shoreline predictions in 128 transects is 5.1 m, with a std of 2.02 m (fig.18).

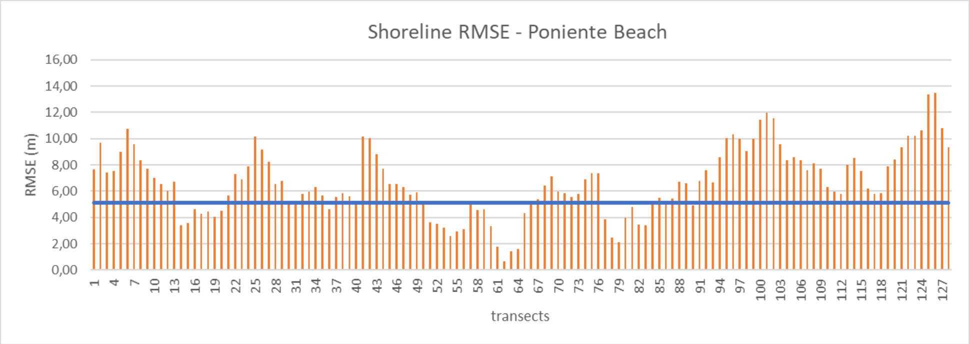


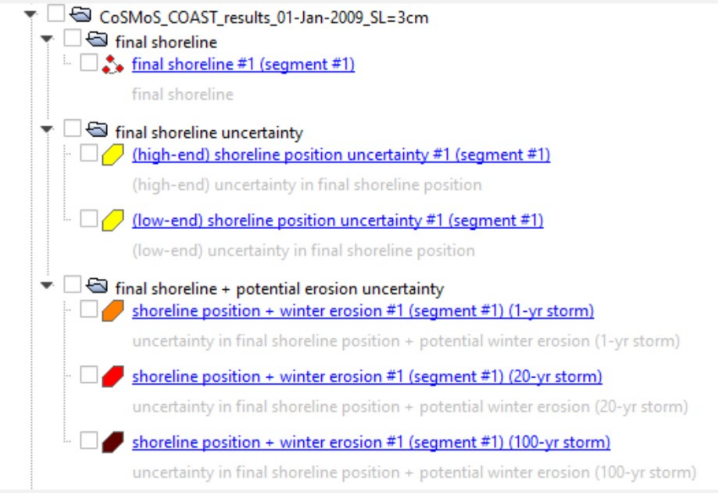
Figure 18: RMSE evaluated per each transect of Poniente beach. In blue the mean RMSE (5.1m).

All the datasets were produced both in kml and (optionally) in shapefiles. Also, xls files with statistics and rates for each transect were saved (fig. 19).

Kml folders of forecasted shorelines in Levante beach

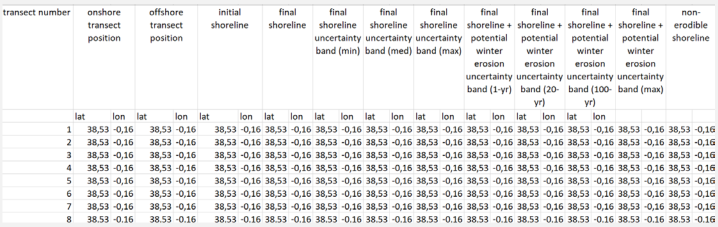
CoSMoS_COAST_Benidorm_100cm_SLR_by_2100_c4_levante_rcp85
- initial conditions
- CoSMoS_COAST_results_11-Jan-2006_SL=2cm
- CoSMoS_COAST_results_01-Jan-2007_SL=2cm
- CoSMoS_COAST_results_01-Jan-2008_SL=3cm
- CoSMoS_COAST_results_01-Jan-2009_SL=3cm
- CoSMoS_COAST_results_01-Jan-2010_SL=4cm
- CoSMoS_COAST_results_01-Jan-2011_SL=4cm
- CoSMoS_COAST_results_01-Jan-2012_SL=5cm
- CoSMoS_COAST_results_01-Jan-2013_SL=5cm
- CoSMoS_COAST_results_01-Jan-2014_SL=6cm
- CoSMoS_COAST_results_01-Jan-2015_SL=6cm
- CoSMoS_COAST_results_01-Jan-2016_SL=7cm
- CoSMoS_COAST_results_01-Jan-2017_SL=7cm
- CoSMoS_COAST_results_01-Jan-2018_SL=8cm
- CoSMoS_COAST_results_01-Jan-2019_SL=8cm
- CoSMoS_COAST_results_01-Jan-2020_SL=9cm
- CoSMoS_COAST_results_01-Jan-2025_SL=12cm
- CoSMoS_COAST_results_01-Jan-2030_SL=15cm
- CoSMoS_COAST_results_01-Jan-2035_SL=19cm
- CoSMoS_COAST_results_01-Jan-2040_SL=23cm
- CoSMoS_COAST_results_22-Jan-2042_SL=25cm
- CoSMoS_COAST_results_01-Jan-2044_SL=27cm
- CoSMoS_COAST_results_01-Jan-2045_SL=28cm
- CoSMoS_COAST_results_01-Jan-2050_SL=33cm
- CoSMoS_COAST_results_01-Jan-2055_SL=38cm
- CoSMoS_COAST_results_01-Jan-2060_SL=43cm
- CoSMoS_COAST_results_01-Jan-2065_SL=49cm
- CoSMoS_COAST_results_05-Oct-2065 06:00:00_SL=50cm
- CoSMoS_COAST_results_01-Jan-2069_SL=54cm
- CoSMoS_COAST_results_01-Jan-2070_SL=55cm
- CoSMoS_COAST_results_01-Jan-2075_SL=62cm
- CoSMoS_COAST_results_01-Jan-2080_SL=69cm
- CoSMoS_COAST_results_11-Apr-2084_SL=75cm
- CoSMoS_COAST_results_01-Jan-2085_SL=76cm
- CoSMoS_COAST_results_01-Jan-2089_SL=82cm
- CoSMoS_COAST_results_01-Jan-2090_SL=84cm
- CoSMoS_COAST_results_01-Jan-2095_SL=92cm
- CoSMoS_COAST_results_01-Jan-2100_SL=100cm
- CoSMoS_COAST_results_31-Dec-2100_SL=102cm

Kml layers produced for each forecasted year



CoSMoS_COAST_results_01-Jan-2009_SL=3cm
- final shoreline
  - final shoreline #1 (segment #1)
    final shoreline
- final shoreline uncertainty
  - (high-end) shoreline position uncertainty #1 (segment #1)
    (high-end) uncertainty in final shoreline position
  - (low-end) shoreline position uncertainty #1 (segment #1)
    (low-end) uncertainty in final shoreline position
- final shoreline + potential erosion uncertainty
  - shoreline position + winter erosion #1 (segment #1) (1-yr storm)
    uncertainty in final shoreline position + potential winter erosion (1-yr storm)
  - shoreline position + winter erosion #1 (segment #1) (20-yr storm)
    uncertainty in final shoreline position + potential winter erosion (20-yr storm)
  - shoreline position + winter erosion #1 (segment #1) (100-yr storm)
    uncertainty in final shoreline position + potential winter erosion (100-yr storm)

Part of xls report of shoreline forecasts showing the statistics and the rates per each transect.



transect number	onshore transect position		offshore transect position		initial shoreline		final shoreline		final shoreline uncertainty band (min)		final shoreline uncertainty band (med)		final shoreline uncertainty band (max)		final shoreline + potential winter erosion uncertainty band (1-yr)		final shoreline + potential winter erosion uncertainty band (20-yr)		final shoreline + potential winter erosion uncertainty band (100-yr)		final shoreline + potential winter erosion uncertainty band (max)		non-erodible shoreline	
	lat	lon	lat	lon	lat	lon	lat	lon	lat	lon	lat	lon	lat	lon	lat	lon	lat	lon	lat	lon				
1	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16
2	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16
3	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16
4	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16
5	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16
6	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16
7	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16
8	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16	38,53	-0,16

Figure 19: Examples of outputs of COSMOS Coast model. Left, Kml folder with all forecasted shorelines. Right top, Detail of a forecasted year (shoreline, uncertainty and potential winter erosion).

For each transect several plots were produced (fig.20):

1. The time series of wave heights and the future shoreline position predicted ed by the model, with the evaluation of RMSE and the CI for the single transect considered (in this example transect 47).
2. The alongshore component parameters used to calibrate the model (vertical red line indicate the position of transect 47).
3. The time series of model components (longterm and short-term) with and without assimilation. Vertical black dotted lines indicate the start of validation period (left) and the start of forecasted period (right).
4. The time series model parameters. Vertical black dotted lines indicate the start of validation period (left) and the start of forecasted period (right)

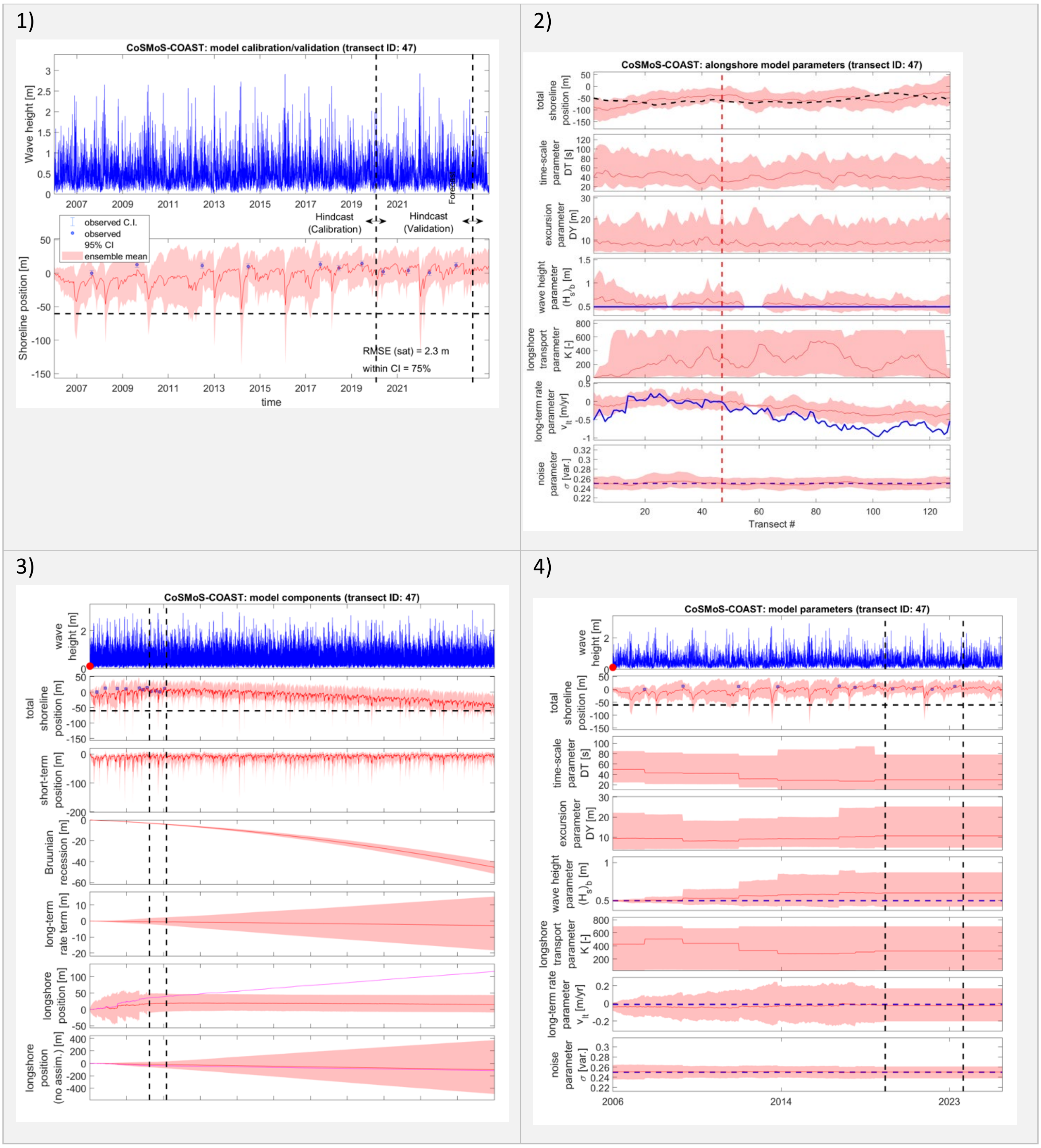
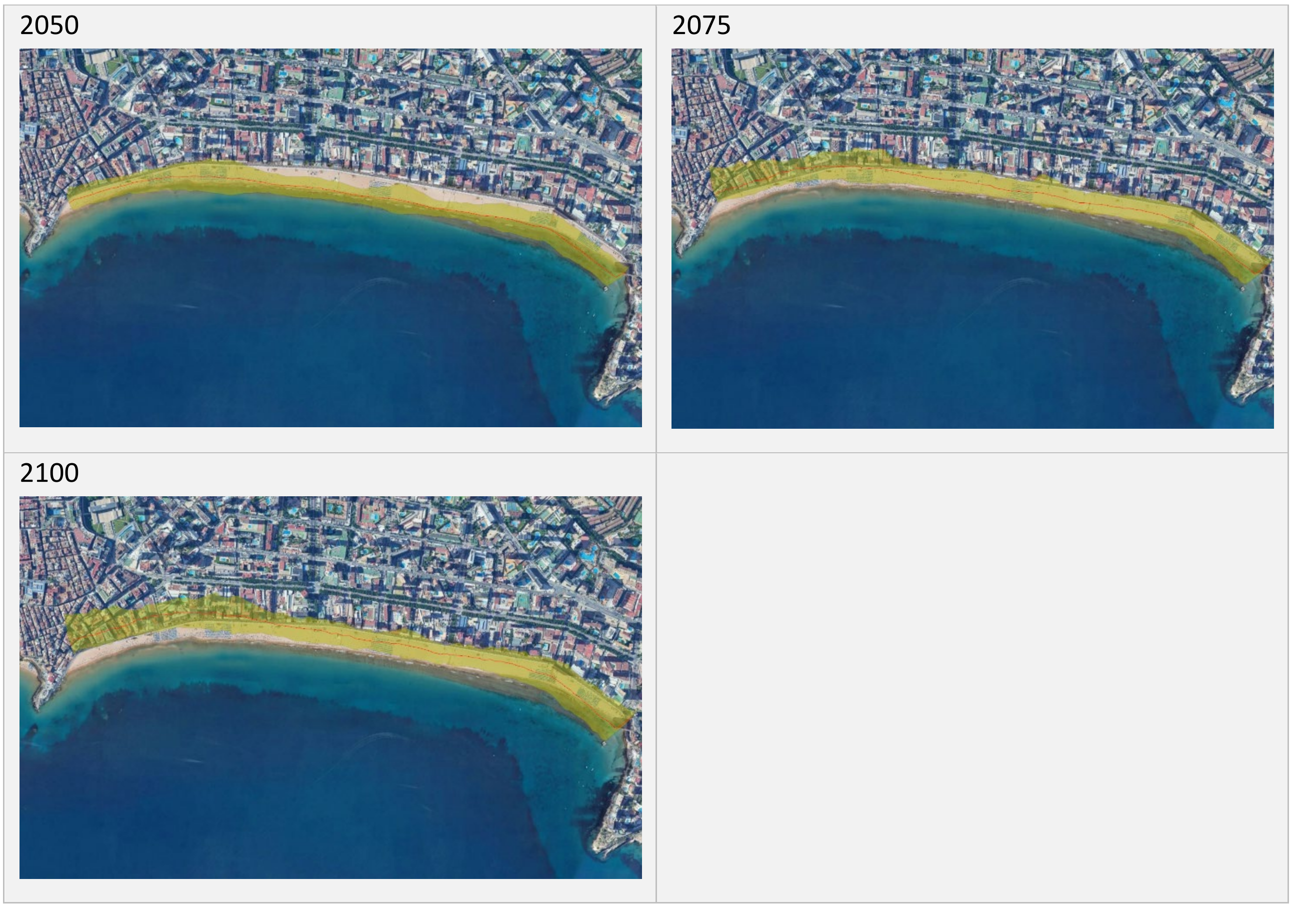


Figure 20: Transect results for Benidorm Poniente beach model (see text)

On Poniente Beach, the western part appears to be the area most affected by future erosion. However, potential effects of diffraction at the ends of the beach, which have not yet been considered in this phase, may influence these results. Conversely, the eastern part shows a trend of accretion, but this could also be influenced by diffraction effects, warranting further investigation.

For Levante Beach, the maximum expected shoreline retreat in the coming years is also projected on the western side (Fig. 21).

Despite these considerations, the results align well with the wave climate, as waves in this area are expected more frequently to come from the east.


2050

2075

2100

Figure 21: Maps of the uncertainty areas for Levante beach with each shoreline projection (in yellow).

4.6.2 Massa

At Marina di Massa, there are no dune belts to protect the area behind the beach. Instead, the area is often characterized by beach establishments situated close to the coastal road, at an elevation near sea level. This configuration increases the risk of flooding during exceptional marine weather events, leading to extensive damage to beach facilities and other coastal infrastructure. The absence of natural protective features is especially concerning in areas where the beach is not wide enough to absorb the most significant storm surges. Additionally, the area suffers from a systematic lack of sediment supply. The prevailing potential sediment transport, directed towards the south (i.e., towards Viareggio), is largely hindered by the presence of the port of Carrara, which blocks sediments coming from the Magra River and, more generally, from all the basins located further north. Furthermore, numerous coastal defense structures, primarily groynes but also barriers, effectively prevent the sediment flow from nourishing the beaches further south.

Figure 22: Massa Beach area

In recent years, extensive coastal engineering works, including groynes and breakwaters (both submerged and exposed), have been implemented to intercept local sediments and mitigate beach erosion (fig. 23). Additionally, most of the coastal inlets are equipped with jetties for navigation purposes. Furthermore, an ongoing and costly beach nourishment program has been carried out annually since 2017, involving the addition of more than 400,000 cubic meters of sediment each year. These sediments are sourced from nearby quarries or from the open sea.

Figure 23 Coastal defenses in Massa Beach area.

Due to its typical exposure, major weather events associated with the most intense sea storms in this area often originate from southwest winds (Libeccio), frequently combined with cyclonic circulation conditions. These conditions can vary, being either associated with local low-pressure systems over the Ligurian Sea or cyclonic circulations coming from the Atlantic. However, in recent decades, there has been an observed increase in events originating from the south and south-southeast, likely due to the effects of climate change. Tidal conditions in Massa, similar to most Mediterranean coastal areas, including Benidorm, are characterized by a micro-tidal range, with a maximum tidal amplitude around 30 cm. In extreme cases, meteorological sea level excursions can be much stronger than those caused by astronomical tides.

The area has always been prone to flooding, including significant events such as the 2014 flooding of the Carrione River and, more recently, the combined river and coastal floods of November 2023. This well-known coastal vulnerability is largely due to the area's specific characteristics. The high Apuane mountains, located just a few kilometers from the coast, play a key role in intensifying local storms, contributing to more extreme weather events. Additionally, in recent decades, late autumn conditions have been marked by a significant increase in sea surface temperatures (SST), which can create conditions conducive to intense orographic precipitation events.

Nevertheless, this area has been chosen to test the long-term risk of beach erosion using the SCORE modeling approach, as it presents a situation quite different from that of Benidorm. While both areas hold significant economic value due to coastal tourism, they are characterized by different exposures to weather events and have employed distinct coastal protection strategies.

MODEL IMPLEMENTATION

In the Massa area, two different implementations of the model were tested: one (a) focused on the southern coastal area with fewer coastal defenses, and the other (b) included the area with groins and breakwaters. Since the individual beach cells between two groins can be treated as closed systems, the first and last transects of each cell were considered as "cross-shore only" transects, to avoid accounting for longshore transport to or from adjacent cells. All other transects were treated as "full model" transects, allowing for the evaluation of both cross-shore and longshore transport.

In addition to the points mentioned above, it is important to note that, at this stage, the model was not configured to account for the longitudinal variation in wave energy flux caused by wave diffraction. This is a significant factor that will need to be considered in future developments of this work, particularly in areas heavily influenced by man-made coastal protection structures.

Regarding our morphodynamic model, a baseline is set at the internal limit of the backshore, which, in the case of Massa, corresponds to the limit of the beach facilities. This baseline serves as the reference for the model to evaluate shoreline movements, both landward (retreat) and seaward (advance).

For the (a) model, which is limited to the area without coastal defenses, 73 transects spaced approximately 20 meters apart were used, while the larger (b) model utilized 156 transects. Since each cell between two groins can be treated as a closed system, the first and last transects of each cell were designated as "cross-shore only" transects to avoid accounting for longshore transport to or from adjacent cells. All other transects were treated as "full model" transects, allowing for the evaluation of both cross-shore and longshore transport.

A baseline, referred to as the "no-erodible" line, is established at the internal limit of the backshore, which can be set as a fixed boundary that the shoreline cannot cross.

Figure 24: Implementation a (left – southern part only, without defenses) and b (right – whole beach) of the model in the Massa area.

For the Massa area a set of 9 shoreline observations have been used. Shorelines span from 2010 to 2023 and are derived from different aerial and satellite images (tab. 6).

Table 6: Shoreline observations

16/07/2010	Orthophoto GEOTIFF 25 cm/pixel
01/07/2013	
01/07/2016	
01/06/2017	VHR Pleiades satellite images - 50 cm/pixel
05/10/2019	
27/06/2020	
12/09/2021	
11/08/2022	

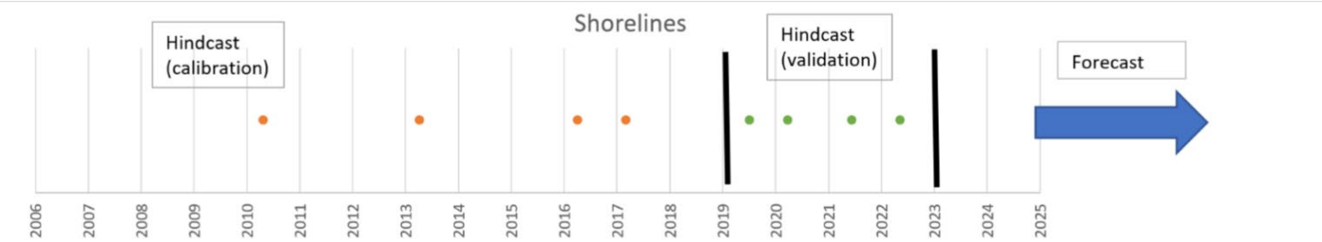


Figure 25: Dates of images used for shoreline detection; in red shorelines used for calibration and in green shorelines used for validation.

The shorelines from 2006 to 2018 were used to calibrate the model, while the data from 2019 to 2023 were used for validation (Fig. 25). For the Massa implementation, four points from the WW3 unstructured grid model were selected to assign wave data to the transects (Fig. 26).

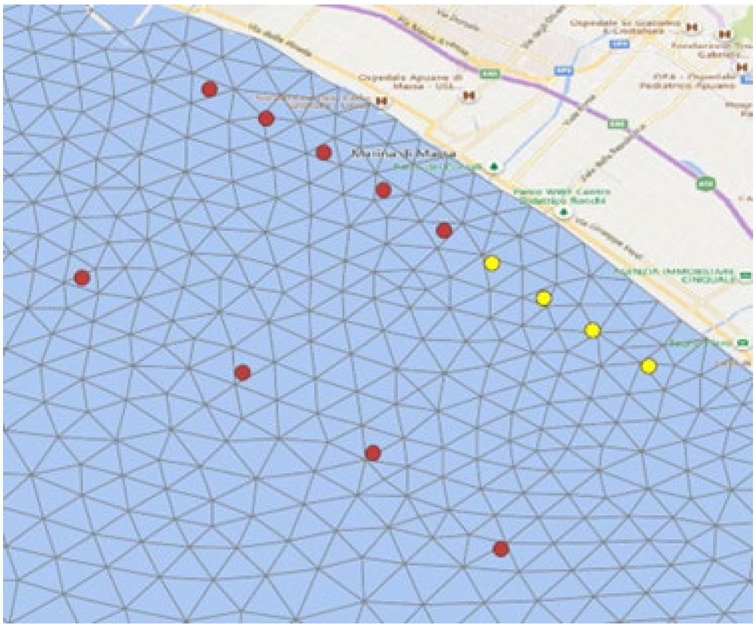


Figure 26: Detail of WW3 unstructured grid used for wave downscaling. Wave climate data were extracted from the yellow nodes.

The bathymetry and the Digital Elevation Model of the area were used to determine the slope of the foreshore along each transect-line

RESULTS

In the current status of the model implementation, which will be updated in the future as scenarios are refined, the COSMOS Coast model was driven by wave data from the RCP8.5 scenario for the period 2006-2100. The total Sea Level Rise (SLR) was set at 1.00 m over this timeframe.

Preliminary results, visualized on Google Earth, illustrate the progressive retreat of the shoreline. The green line represents the projected shoreline position in 2050 with an SLR of 33 cm, the yellow line shows the projection for 2070 with an SLR of 62 cm, and the red line indicates the projection for 2100 with an SLR of 1 m (Fig. 27).

The RMSE of the modelled shorelines w.r.t. the observed ones was also computed for the Massa case study. It is possible to evaluate the RMSE of the correlation between observed and modelled shorelines. For the southern part of the beach (without defenses), mean RMSE for shoreline forecasts in 73 transects is 10.7 m, with a std of 1.8 m (fig.28).

Massa beach with forecasted shorelines

Zoom of the yellow areas

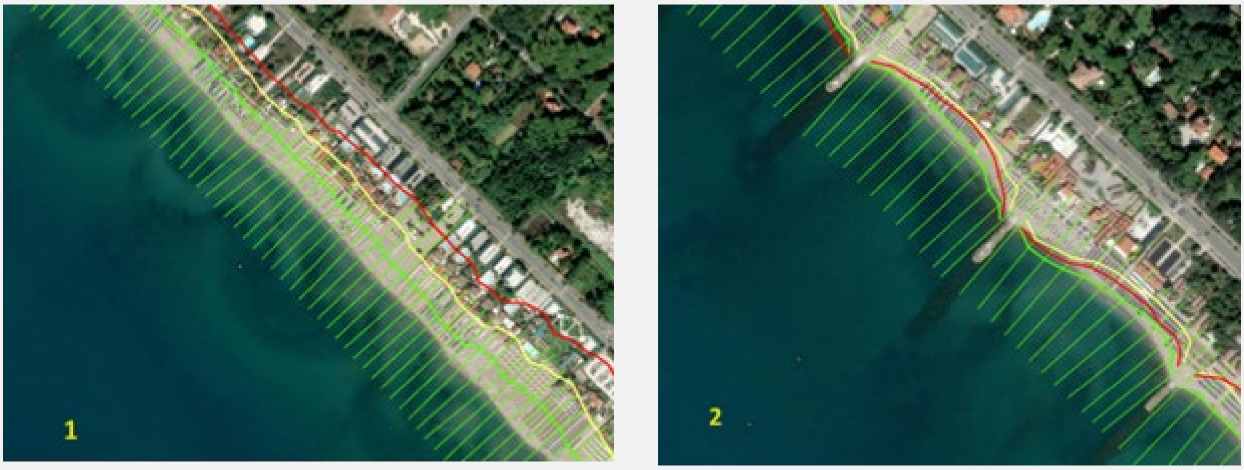


Figure 27: Results of coastal shoreline erosion projections for Massa beach

Figure 28: RMSE evaluated per each transect of the southern part of Massa beach. In blue the mean RMSE (10.7 m)

For the entire beach, encompassing both the southern and northern areas, the mean RMSE for shoreline forecasts across 156 transects is 11.7 m, with a standard deviation of 4.4 m (Fig. 29). The model's primary uncertainty is concentrated in the (b) area which includes the additional 60 transects, where groins and other coastal defenses are located. The higher mean RMSE, and particularly the elevated standard deviation, highlight the significant differences in the model uncertainty between the northern and southern parts of the area.

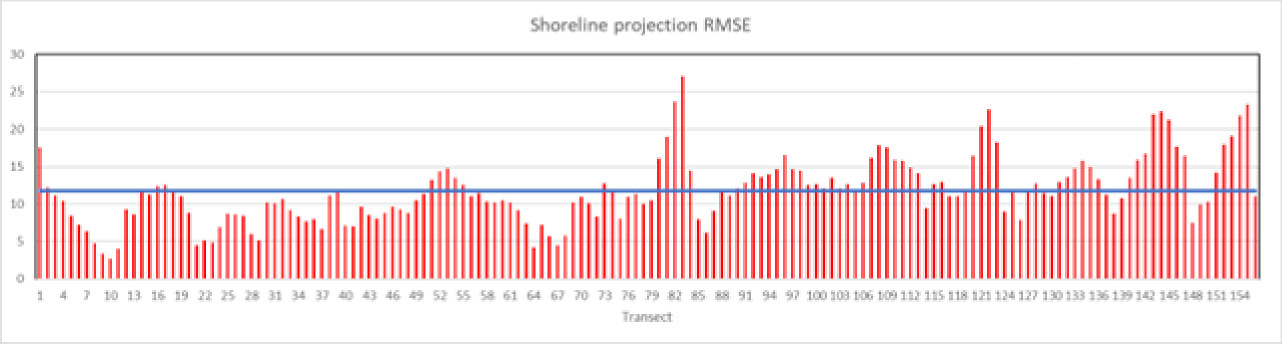


Figure 29 RMSE evaluated per each transect of the whole Massa beach. In blue the mean RMSE (11.7 m).

The same model parameter plots shown for the Benidorm case are presented here as well.

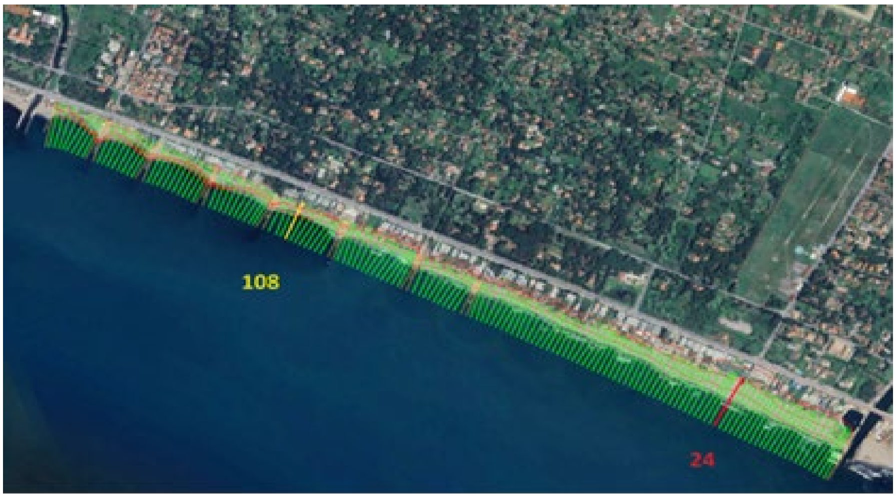
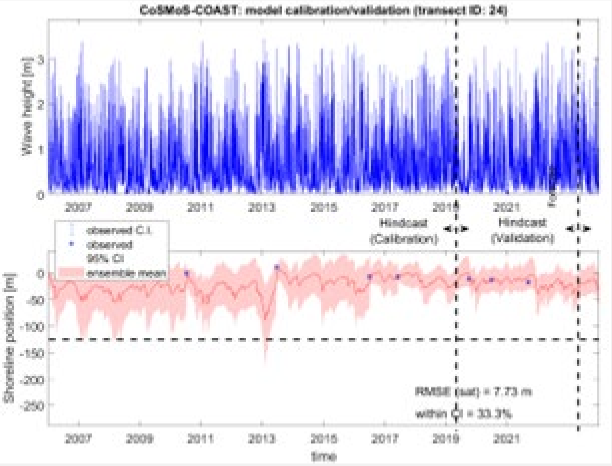


Figure 30: Transect related to the plots in fig.29 and 30

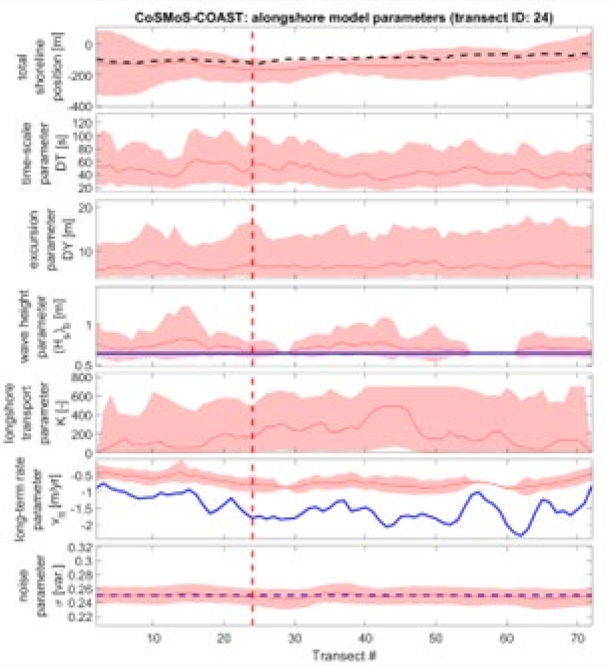
As representative examples, the plots related to the model parameters for transects 24 (southern area) and 108 (northern part) are shown (Fig. 30). Despite some uncertainty, it is evident that the parameters associated with the transect in the area with man-made coastal defenses (Fig. 32) exhibit a more stable evolution compared to others. This stability is due to the reduced morphodynamic changes within the "cells" (areas between two groins). The long-term erosion rate is approximately 0.2-0.3 m/year for transect 108, which is located within a cell (see Fig. 32 - 4), and around 1-1.2 m/year for transect 24, which lies outside the cell (Fig. 31 - 4).

The erosion trend observed for transect 24 is characteristic of this coastal area, which is known for experiencing significant erosion. This region is one of the 2-3 most severely eroded areas in Tuscany, where erosion is not primarily driven by sediment deficits from nearby river mouths. The long-term model indicates that this erosion trend will likely continue into the future, influenced by the projected wave climate under the RCP8.5 scenario and the hypothesized Sea Level Rise (SLR).

1)



2)



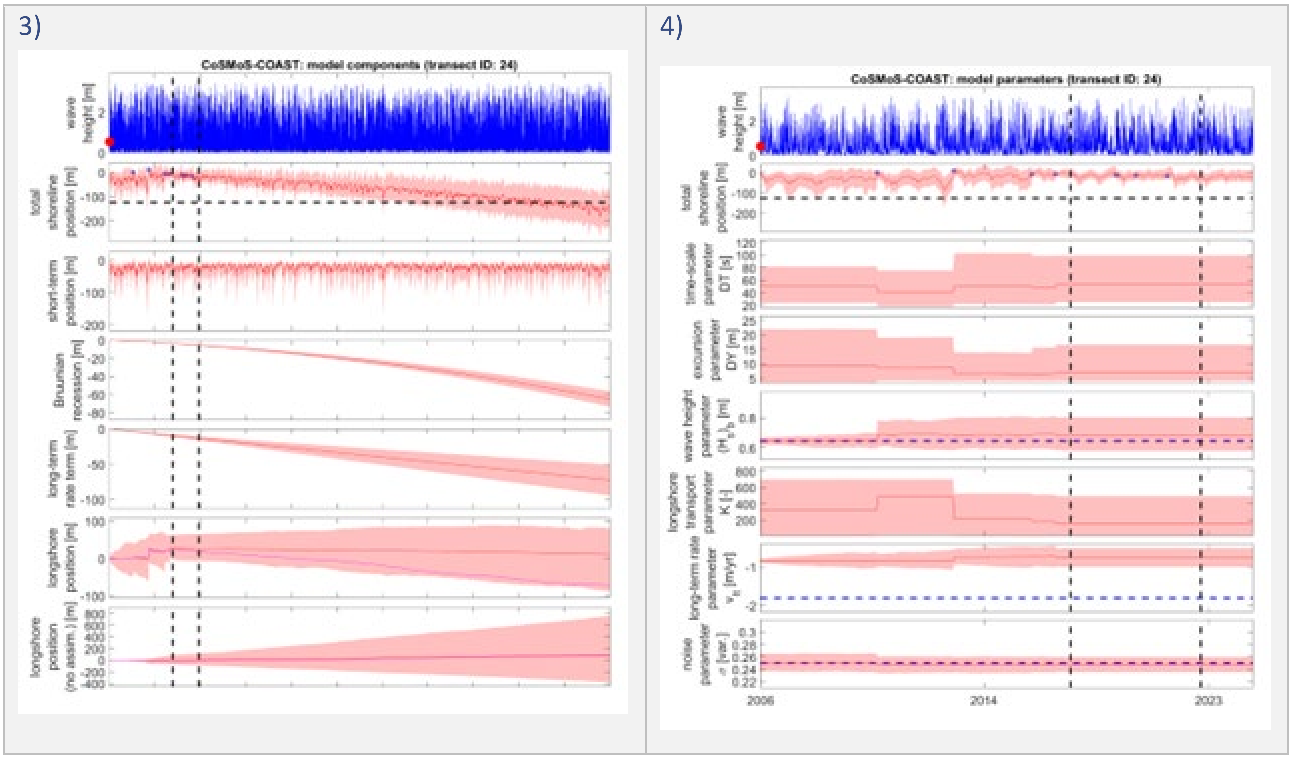
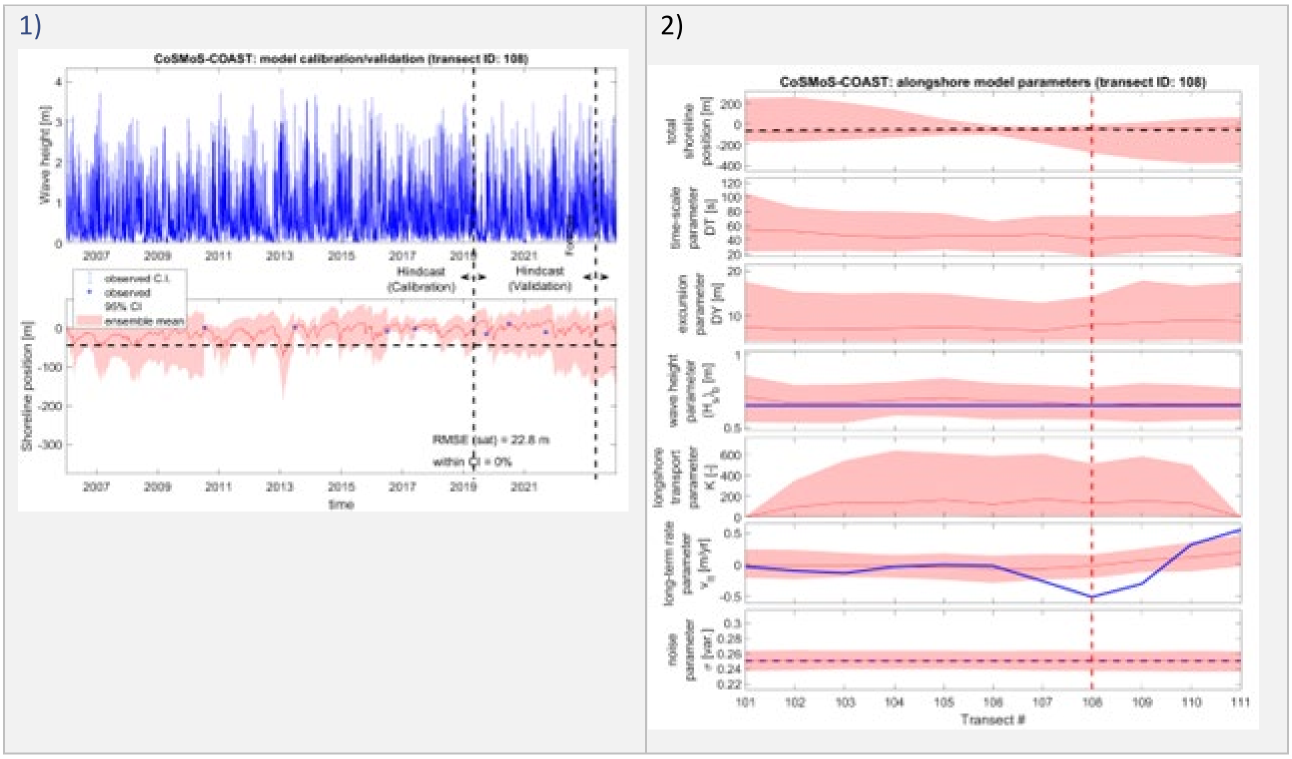


Figure 31: Parameters plot for transect 24 in the for southern side of Massa beach (see text)



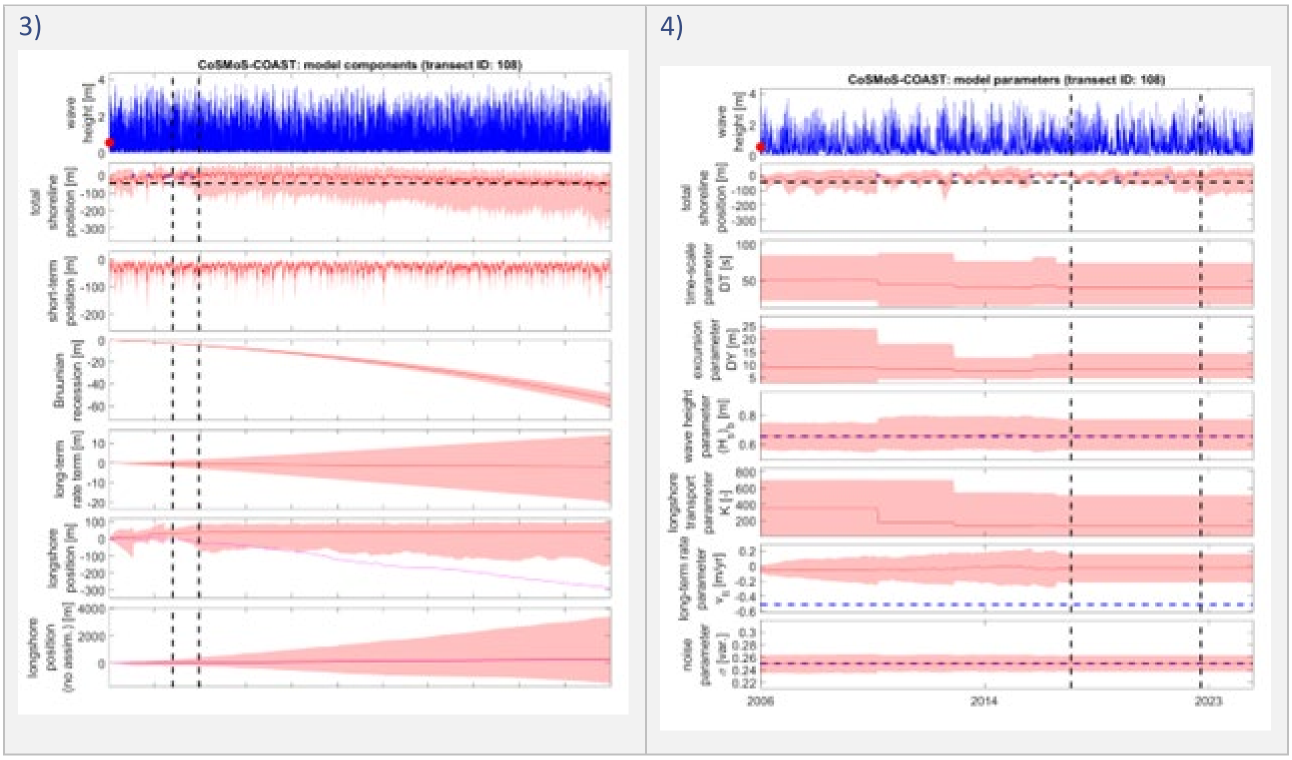


Figure 32: Parameters plot for transect 108 in northern side of Massa beach (see text)

As mentioned, the southeastern part of the Massa beaches is the area most affected by erosion. Annual nourishment activities have been conducted in recent years to address the seasonal demand for a larger beach to better accommodate tourism. However, this effort has been insufficient to counteract the long-term erosion in this area, which is exacerbated by nearby coastal defenses that prevent sediments from reaching this part of the coastline. The northwestern area, in particular, is characterized by a dense concentration of groins (spaced 250-300 m apart) and breakwaters further north, with almost no gap extending from the Carrara harbor. These defenses intercept much of the sediment transported from the Magra River, the Frigido River, and smaller streams in the area.

5. DISCUSSION AND CONCLUSIONS

The availability of both in-situ and satellite data, combined with climate projection models, enables the effective use of coastline evolution models to meet the objectives of the SCORE project. These objectives focus on advancing our understanding and modeling of long-term coastline evolution within the context of climate change and its impacts on European coastal cities.

This document serves as a user manual, guiding readers in the application of satellite data analysis methods and simulation models outlined in D3.9. These methods and models are intended to be used within the limitations described in the previous deliverable.

While the modeling approach employed is simplified in terms of physics, the analysis still requires careful consideration of the various factors influencing shoreline changes. The case studies of Benidorm, Dublin, and Massa emphasize the importance of localized studies in understanding the unique morpho-dynamic behaviors driven by both natural processes and human activities.

The use of separate datasets for model calibration and validation enhances the reliability of the models, ensuring that forecasts are based on robust and unbiased data. The application of the Kalman filter in model calibration has proven to be an effective method for parameter estimation, reducing the reliance on user-driven trial and error. The estimated parameters reflect longshore and cross-shore transport processes, as well as other unresolved factors, though some intrinsic uncertainty remains. Nevertheless, the validation results, particularly for Benidorm, demonstrate the effectiveness of the COSMOS-Coast model in simulating shoreline changes.

Importantly, these models can play a critical role in guiding discussions within the CCLLs (Coastal City Living Labs), steering the debate towards raising awareness and fostering co-creation and co-design of solutions that can enhance the resilience of coastal cities to the effects of climate change. By engaging stakeholders in these processes, the models support the development of informed and collaborative strategies to address the complex challenges posed by coastal erosion and sea-level rise.

The study also underscores the necessity for continuous monitoring and updating of coastal models to incorporate the latest data, thereby improving predictive capabilities. This dynamic approach is crucial for adapting to the rapidly changing coastal environments influenced by climate change.

The findings and methodologies presented in this report will be further detailed in the final project deliverables related to Task 3.6 (testing). These deliverables will provide valuable resources for coastal managers, policymakers, and within the CCLLs, to enhance climate resilience in European coastal cities.

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