

FEASIBILITY ASSESSMENT OF USING SATELLITE-DERIVED BATHYMETRY TO ANALYSE COASTAL MORPHODYNAMICS

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RESUMO

A morfodinâmica costeira é determinada por interações complexas entre forças hidrodinâmicas, transporte de sedimentos e influências antropogénicas. A compreensão destes processos é crucial para uma gestão costeira eficaz, particularmente em áreas sujeitas a elevada energia das ondas e a rápidas alterações morfológicas. Esta dissertação investiga a evolução morfodinâmica da praia do Furadouro e da restinga do estuário do Douro, com foco nos impactos das condições marítimas, descargas fluviais e nos padrões do transporte de sedimentos. A investigação explora também a viabilidade da utilização da batimetria derivada de satélite (SDB), especificamente a metodologia S2Shores, como possível ferramenta para obtenção de dados batimétricos complementares para a monitorização da morfodinâmica costeira.

Nesta dissertação foi efetuada uma análise comparativa entre os resultados batimétricos derivados do S2Shores e os levantamentos COSMO (*in-situ*), para avaliar a precisão e a fiabilidade das técnicas de deteção remota na captação das variações batimétricas costeiras. Para o efeito foram usados dois casos de estudo: praia do Furadouro e restinga do estuário do Douro. Os dados gerados revelaram limitações significativas na capacidade do S2Shores para produzir estimativas de profundidade consistentes e fiáveis. Consequentemente, este método, na sua versão atual, não foi considerado adequado para obtenção de batimetrias de alta resolução em zonas costeiras, impedindo a sua aplicação na monitorização mensal das alterações morfológicas dos dois casos de estudo, como inicialmente planeado. Apesar das limitações, a análise dos três levantamentos topo-hidrográficos anuais existentes para cada caso de estudo forneceu informações valiosas sobre o transporte de sedimentos e a evolução da linha de costa. Na praia do Furadouro, foram observados padrões alternados de erosão e acreção, possivelmente influenciados pela atividade das tempestades e pelos períodos de recuperação pós-tempestade. No Estuário do Douro, as interações entre a elevada energia das ondas e o caudal do rio desempenharam um papel fundamental na formação da restinga, com períodos de deposição de sedimentos no canal estuarino seguidos de erosão devido a eventos hidrodinâmicos extremos.

O estudo realizado destaca a importância da monitorização batimétrica frequente para captar melhor as alterações morfológicas de curto prazo e melhorar as estratégias de gestão costeira. A investigação futura deve focar-se no refinamento das metodologias de SDB, na integração de abordagens de modelação numérica e na expansão do uso de tecnologias de deteção remota para melhorar a monitorização e a previsão da morfodinâmica costeira.

PALAVRAS-CHAVE: morfodinâmica costeira, levantamentos batimétricos, imagens de satélite, S2Shores, praia do Furadouro, estuário do Douro.

ABSTRACT

Coastal morphodynamics are determined by complex interactions between hydrodynamic forces, sediment transport and anthropogenic influences. Understanding these processes is crucial for effective coastal management, particularly in areas subject to high wave energy and rapid morphological changes. This dissertation investigates the morphodynamic evolution of Furadouro beach and the Douro estuary sandbank, focusing on the impacts of maritime conditions, river discharges and sediment transport patterns. The research also explores the feasibility of using satellite-derived bathymetry (SDB), specifically the S2Shores methodology, as a possible tool to obtain complementary bathymetric data for monitoring coastal morphodynamics.

This dissertation performed a comparative analysis between the bathymetric results derived from S2Shores and the COSMO surveys (*in-situ*), to evaluate the accuracy and reliability of remote sensing techniques in capturing coastal bathymetric variations. For this purpose, two case studies were used: Furadouro beach and the sandbank of the Douro estuary. The data generated reveals limitations that impair the ability of S2Shores to produce consistent and reliable depth estimates. Consequently, this method, in its current version, was not considered suitable for obtaining high-resolution bathymetry in coastal areas, preventing its application in the monthly monitoring of morphological changes in the two case studies, as initially planned. Despite the limitations, the analysis of the three existing annual topo-hydrographic surveys for each case study provides much valuable information on sediment transport and shoreline evolution. At Furadouro beach, alternating patterns of discharge and increase were observed, possibly influencing storm activity and post-storm recovery periods. In the Douro Estuary, interactions between high wave energy and river flow played a key role in the formation of the sandbar, with periods of sediment deposition in the estuarine channel followed by deposition due to extreme hydrodynamic events.

The study highlights the importance of frequent bathymetric monitoring to better capture short-term morphological changes and improve coastal management strategies. Future research should focus on refining SDB methodologies, integrating numerical modeling approaches, and expanding the use of remote sensing technologies to improve monitoring and prediction of coastal morphodynamics.

KEYWORDS: coastal morphodynamics, bathymetric surveys, satellite images, S2Shores, Furadouro beach, Douro estuary.

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SYMBOLS

c – Wave celerity [m/s]

d – Water depth [m]

g – Gravitational acceleration [m/s²]

h – Water depth [m]

H – Wave height [m]

H_{mo} – Spectral significant wave height [m]

H_s – Significant wave height [m]

k – Wavenumber [m⁻¹]

L – Wavelength [m]

P – Wave power per unit width of wave crest [kW/m]

T – Period [s]

T_e – Wave energy period [s]

T_m – Mean wave period [s]

T_p – Peak period [s]

Δt – Temporal lag [s]

$\Delta\Phi$ – Spectral phase shift [rad]

θ_m – Mean wave direction [°]

ρ – Seawater density [kg/m³]

γ – Wave linearity parameter [-]

ACRONYMS

APA – Agência Portuguesa do Ambiente (Portuguese Environment Agency)

AUV – Autonomous underwater vehicles

CNES – Centre National d'Études Spatiales

COSMO – Coastal Monitoring Programme of Continental Portugal

DDB – Delft Dashboard

DEM – Digital Elevation Models

DFT – Discrete Fast Fourier Transform

DOA – Direction of arrival

ESA – European Space Agency

GNSS/RTK – Global Navigation Satellite System/ Real-time Kinematic positioning

INCCA – Integrated Coastal Climate Change Adaptation for Resilient Communities

LiDAR – Light Detection and Ranging

MBES – Multibeam echo sounder

MSL – Mean Sea Level

MSI – Multi-Spectral Instrument

PDBS – Phase differentiating bathymetric Sidescan sonars

POC-OMG – Programa De Orla Costeira Ovar – Marinha Grande

RT – Radon Transform

S2Shores – Satellite to Shores

SBES – Single-beam echo sounder

SDB – Satellite-derived bathymetry

Shom – Service Hydrographique et Océanographique de la Marine

SNIRH – Sistema Nacional De Informação De Recursos Hídricos

SWAN – Simulating WAVes Nearshore

TOA – Traditional time of arrival

UAV – Unmanned aerial vehicle

WKB – Wave kinematics bathymetry

1

INTRODUCTION

1.1. MOTIVATION

Population worldwide is drawn to coastal areas for their economic opportunities, access to resources, and aesthetic appeal. These regions are home to major industries, such as shipping, tourism, and fishing, which drive economic growth and connect global trade networks. However, the coastal environment, while beneficial, also exposes communities to significant risks (Gomes da Silva *et al.*, 2024). Coastal zones are in a constant state of dynamic change due to wave action, tides, wind, and sediment movement. Natural factors, such as seasonal variations in wave energy, storms, and sea-level rise, drive the continuous reshaping of these coastlines. Additionally, human activities like coastal development, infrastructure construction and resource extraction can intensify erosion, compounding the risks to both human assets and natural habitats located inland. The dynamic nature of the coastline has led to the gradual reshaping of beaches, dunes, and estuaries. Coastal erosion directly threatens cities and human settlements located along the shore, placing properties, infrastructure, and critical assets at risk. Cities near eroding coasts face challenges such as flooding, storm damage, and land loss, which can be highly disruptive to local economies and community life. The impact of coastal erosion is often compounded in densely populated areas where space is limited, and relocation options are few (Gomes da Silva *et al.*, 2024). As shown in Figure 1, a significant percentage of the population resides within 100 km of the coast, where shorelines have been extensively altered.

Coastal erosion is intensifying due to a combination of climate change, human activities, and natural processes. Increased storm surge frequencies, rising sea levels increase the reach of waves and allow them to attack higher elevations along the shoreline, eroding beaches, dunes, and cliffs more aggressively. Human activities exacerbate erosion, with coastal development placing structures in vulnerable areas and the extraction of sand and other resources depleting the materials needed to sustain beaches (Roebeling *et al.*, 2013).

Regular coastal assessments are essential for cities near eroding coastlines in order to understand the current coastal situation and predict future changes. Temporal assessments of risk and vulnerability can reveal trends in erosion (rates of coastal retreat), volumes of sediment deficit, and beach morphology, helping planners make informed decisions on development and coastal defence strategies. These evaluations and the coastal monitoring benefit from accurate and up-to-date topographical and bathymetric information.

Traditional ground-based data collection methods using sonar and LiDAR systems provide high detail, accurate and high-resolution data. However, the use of these systems is limited by accessibility, cost, and operational constraints for collecting topographic and bathymetric data. For the past 50 years, the Satellite-derived bathymetry

(SDB) method has been studied as an alternative to provide cost-effective, temporal, and spatial continuity for bathymetric analyses in shallow coastal waters (Uzakara et al., 2024).



Figure 1 - Coastal population and shoreline degradation (UNEP, 2009).

Remote-sensing methods, encompassing sensor and satellite technology, have been widely used in the past to obtain nearshore bathymetry and topography data. However, on-ground measurement and *in-situ* observation are still fundamental to the knowledge of coastal monitoring (Chen *et al.*, 2024).

The development of satellite-derived bathymetry has advanced significantly since the 1970s, driven by continuous improvements in remote sensing technology. The earliest SDB methods were based on physics-driven models, first introduced by Polcyn *et al.*, (1970). These models established fundamental relationships between seafloor depth and reflectance, incorporating the principles of light propagation and attenuation in water. By quantifying how light interacts with the water column and the seabed, these early approaches laid the foundation for subsequent refinements in SDB techniques.

Over the decades, advancements in sensor capabilities, data processing algorithms, and computational power have further enhanced the accuracy and applicability of SDB, making it an increasingly valuable tool for coastal and marine studies.

These monitoring tools are particularly relevant for a country such as Portugal, which is bordered by the Atlantic Ocean for approximately 987 km (mainland Portugal), with near 75% of its population residing in the coast as well 26% of the buildings associated with urban, tourist and industrial use (APA, Plano de Ação Litoral XXI, 4^o update, 2024)¹. Due to the exposure to high-energy waves from the Atlantic Ocean and the presence of densely populated and economically significant coastal cities, coastal engineering in Portugal needs to be aware of these challenges and protect densely populated coastal areas.

This Dissertation attempts to use a new approach in the SDB field by applying a methodology recently developed by the Centre National d'Études Spatiales (CNES), Institut de recherche pour le développement- Laboratoire d'Études en Géophysique et Océanographie Spatiales (IRD-LEGOS) and Service Hydrographique et Océanographique de la Marine (Shom). The methodology, named Satellite to Shores (S2Shores), is based in wave kinematics and applied in two small nearshore areas in Portugal, which are dynamic coastal sites. The underlying

¹ https://apambiente.pt/sites/default/files/Agua/DLPC/Acao_valorizacao/PAL-XXI_Actualizacao-20240607.pdf accessed in 13/01/2025

goal was to achieve a continuous monthly-scale coastal morphology monitoring of the two case studies after the validation of the methodology using traditional bathymetric surveys.

Two distinct coastal environments along the northwestern coast of Portugal were selected for this study, each presenting unique challenges that require careful monitoring. Furadouro beach was chosen due to its rapid erosion rates, which pose significant risks to the civil community. In contrast, the sandspit at the mouth of Douro Estuary (commonly known as Cabedelo do Rio Douro) was selected for its critical role as a natural coastal defense. These sites represent contrasting dynamics, making them valuable case studies for assessing coastal morphodynamics and the effectiveness of monitoring techniques.

The Furadouro beach belongs to the long 13 km sandy shore of Esmoriz-Cortegaça-Furadouro, well known for its alarming increase in erosion rate and for its many coastal protection works involving in total 8 revetments and 6 groins. Furadouro is a very critical region, between 1998 and 2015, 3 emergency situations have been observed (Veloso Gomes, 2023).

The Douro estuary sandspit is a complex and very dynamic natural defence. The intervention built between 2004 and 2008, involving the construction of two breakwaters, intended to improve navigation safety in the entrance to the estuary, as well as to protect estuarine banks and stabilize the sandspit. The intervention has successfully stabilized most of the sandspit's area and volume only leading significant changes in the morphology of the spit's head and altering previous patterns of erosion and accretion (Bastos *et al.*, 2012).

Both sites are of important monitorization and risk assessment especially in the context of major storm and river flood events, requiring short temporal observations of coastal morphology. The Portuguese Environment Agency (APA) developed the “Coastal Monitoring Programme of Continental Portugal - COSMO” which has carried out annual hydro-topographic surveys in the two study cases from 2018 to 2020, therefore creating an opportunity to use the SDB tool to validate its bathymetry output data.

1.2. OBJECTIVES

In line with the context above, the primary objective of this research dissertation is to analyse the feasibility of using bathymetric data derived from satellite imagery to assess coastal morphodynamics at a monthly scale. The study focuses on two distinct sites along the north-western coast of Portugal: Furadouro beach and the sandspit at the mouth of the Douro estuary. These locations were selected due to their contrasting characteristics—Furadouro beach is highly vulnerable to erosion, while the Douro estuary sandspit functions as a natural coastal defence and is growing in size and volume over recent years. Conducting monthly assessments allows for a more detailed understanding of their morphodynamic evolution over time. Indeed, short-term coastal monitoring provides the opportunity to relate how morphological and geological changes are influenced by oceanic conditions, such as sea waves, tides, storms, and strong winds.

The Dissertation aims to assess the accuracy of the bathymetric data derived from satellite imagery by comparing it with traditional topo-bathymetric surveys covering the entire active beach domain of the two case study sites. The data used is from the COSMO program, which conducts topo-hydrographic surveys using a multibeam sounder with full coverage, a single beam sounder in the nearshore shallower areas for the bathymetry, and aerial photogrammetry using airborne methods (UAVs) for the topography (Pinto *et al.*, 2021).

The aim of this dissertation is to critically analyse the similarity between the two methods that obtain bathymetric information to analyse if the S2Shores SDB method is a viable technique for the two case studies to later assess the bathymetry from satellite images taken at a monthly scale between 2018 and 2020.

1.3. DISSERTATION STRUCTURE

This dissertation consists of six chapters, with each chapter addressing important aspects of the research in coastal morphodynamics and in bathymetric estimation using a remote sensing method.

This chapter introduces the research topic, states the problem, sets out the objectives, and explains the relevance of the research. It places in context the need to understand coastal morphodynamics and emphasizes Satellite-Derived Bathymetry (SDB) as a complement to traditional survey methods. Section 2 contains a comprehensive literature overview explaining fundamental concepts in coastal morphodynamics, sediment transport processes, and bathymetric survey techniques. Remote sensing applications receive specific focus, with a detailed description of the used SDB method, highlighting its advantages, limitations, and recent developments. Chapter 3 defines the research methodology used in this research and gives a detailed description of data sources and data processing methods. It details the implementation of the S2Shores SDB methodology, including the processing of satellite imagery and the application of S2Shores-derived bathymetry against *in-situ* measurements.

Followed by section 4 which provides an in-depth characterization of the study areas, Furadouro beach and the Douro estuary sandspit, detailing their geomorphological, hydrodynamic, and sedimentary characteristics. It examines the main physical and environmental factors influencing their morphodynamic evolution, including wave exposure, tidal influence, sediment transport patterns, and human interventions. It establishes the contextual framework necessary to understand the processes driving coastal changes in these locations and serves as a foundation for interpreting the results of the study. Chapter 5 summarizes findings obtained from the carried out analysis and provides a detailed discussion. It starts with the validation attempt of S2Shores bathymetry data with the *in-situ* measurements and then continues to assess annual sediment transport processes and morphological changes in both research sites. This is then followed by correlating obtained results with hydrodynamic factors like wave energy and river discharge to enable a better understanding of basic processes controlling morphodynamic changes. Chapter 6 is a synthesis chapter and leads to a conclusion. Evaluates the work relevance and identifies research limitations.

2

COASTAL MORPHODYNAMICS ASSESSMENT

2.1. INTRODUCTION

Wright and Tom (1977) introduced the term ‘coastal morphodynamics’ defining it as ‘the mutual adjustment of topography and fluid dynamics involving sediment transport’. Their approach applied a system perspective to coastal morphology and evolution, conceptualizing the coast as a dynamic geomorphic system with energy and material inputs and outputs, shaped by surrounding environmental conditions. Figure 2 represents the main environmental conditions and properties of coastal morphodynamic systems, where Δt shows the time dependence inherent in coastal morphodynamic evolution.

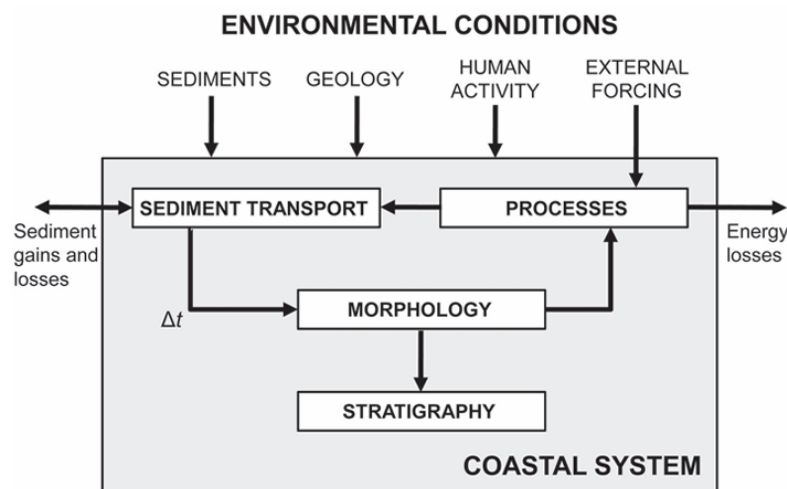


Figure 2 - Schematic representation of primary components involved in coastal morphodynamic (Masselink et al., 2011).

Coastal morphodynamics consists of comprehending the complicated interaction of the physical forces of waves, tides, currents, and sediment transport interacting with morphological changes within the form and structure of landforms along the coast (Boer et. al, 2018). This becomes important for understanding how coastlines change with time, while ways are being sought for managing, protecting, and sustaining these dynamic systems. Due to the continuous challenge of climate change, increased sea levels, and strengthened human activities, monitoring and the assessment of the dynamics have become a pertinent issue in ensuring resiliency in those coastal areas (Hogrefe et. al, 2008; Santos et al., 2015).

The morphodynamic assessments examine the complicated interrelation between wave, tide, and current motions, together with sediment transport, and morphological features; supplying substantial knowledge of how coastal systems function. By means of this interaction, morphodynamic assessments can help anticipating changes and help mitigate coastal hazards such as erosion, flooding, and storm surges (Santos *et al.*, 2015).

These assessments are important and form the very basis for successful practice in coastal engineering and management. Protection strategies, involving seawalls, breakwaters, beach nourishment, and shoreline stabilization projects require an understanding of coastal morphodynamics in their formulation and implementation. Correct assessments ensure that the measures not only shall be successful but also sustainable, catching high-priority problems while at the same time limiting negative long-term environmental impacts (Hogrefe *et al.*, 2008).

Besides their importance to engineering projects, morphodynamic assessments along coasts are quite significant for environmental conservation. Many coasts have a variety of complex and sensitive biomes, such as wetlands, coral reefs, and mangroves, that are experiencing increased threats from erosion, habitat degradation, and other environmental stresses. Assessment of morphological changes allows for the identification of regions most at risk and thus guides these conservation efforts toward protecting these biomes and contributing to long-term sustainability in managing coastal resources (Narra *et al.*, 2017).

One of the priorities of morphodynamic studies is also to ensure safe navigation and maritime safety as the accurate mapping of the bathymetry allows the delimitation of shipping routes, the correct planning and monitoring of dredging, and the assurance of safe maritime transit (Jawak *et al.*, 2015).

This chapter provides a comprehensive overview of the key concepts underlying this study. It begins by framing the main drivers of coastal morphodynamics, offering a general explanation of environmental conditions that form the boundary conditions of the coastal system (Figure 2). Followed by examining the coastal system itself, which properties correspond to the flow of energy and material through the system (Cowell *et al.*, 1995), with a specific focus on their application to the case study sites: a sandy beach and an estuary.

The section 2.3 discusses the primary parameters that are typically observed, measured, and analysed over time in coastal studies. Many of these parameters, including shoreline position and sediment volume, can be derived from bathymetric data. Given its critical role in coastal assessments, bathymetry represents the central focus of this thesis.

Next, the chapter 2.4 presents the two main methods used in this study for generating bathymetric data, followed by section 2.5 which outlines the theoretical framework of the S2Shores tool (Almar *et al.*, 2024; Bergsma *et al.*, 2023) and its recent applications in practical situations. This is followed by a discussion on the application of bathymetry in nearshore coastal studies, emphasizing its relevance to coastal monitoring and management.

Finally, the chapter concludes with a summary comparing the advantages and limitations of traditional bathymetric survey methods and introduces the approach implemented in the S2Shores algorithm, detailing its novel application in selected case studies.

2.2. DRIVERS OF COASTAL MORPHODYNAMICS

Coastal morphodynamics is a key field of study that examines how coastal landforms evolve in response to natural and anthropogenic forces across different temporal and spatial scales. Involving the complex interaction of waves, tides, and currents, influenced by geological, biological, and human activities (Figure 3), which together shape the coastline, determine its stability, and influence its ecological significance (Masselink *et al.*, 2011).

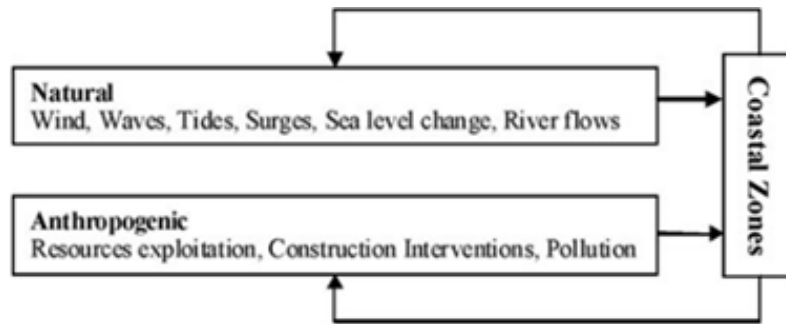


Figure 3 - Forces driving change in coastal zones (Taveira-Pinto et al., 2011).

In this thesis, the analysis of two case studies involving the sandy beaches of Cabedelo do Douro and Furadouro in Portugal necessitates a clear understanding of the concept of spatial and temporal scales in beach change. Beach processes and responses can be categorized into 4 overlapping time scales (Cowell et al., 1995): instantaneous, event, engineering and geological as illustrated in Figure 4.

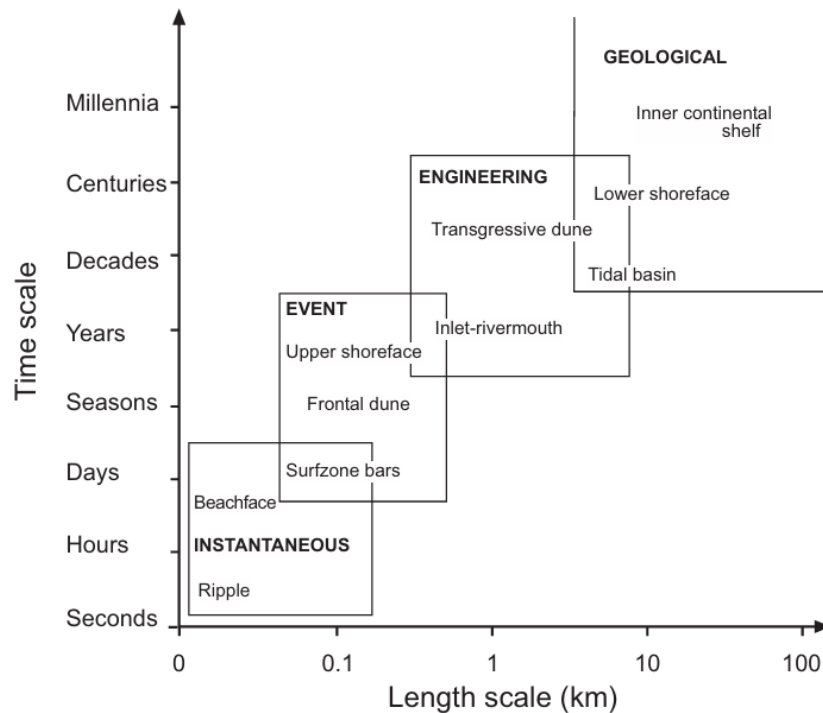


Figure 4 - Spatial and temporal scales for coastal evolution (Cowell et al., 1995).

The hours to years scale, is characterized by variability driven by wave, tide, and surge conditions, as well as seasonal climate variations. These factors lead to fluctuations, quasi-linear trends, and trend changes in beach morphology. Seasonal and inter-seasonal beach variability represents the shortest-term type of variability relevant to coastal management. This type of variability involves periodic fluctuations in the dynamic behaviour of a beach, occurring over time scales ranging from seasons down to single events. A classic example of seasonal variability is the systematic change in beach profiles between summer and winter. During the summer, milder wave conditions typically result in a steeper "swell" profile, while in the winter, higher-energy wave conditions often lead to a flatter "storm" profile. On an event scale, this seasonal variability manifests as rapid shoreline erosion during storms, followed by slower but more continuous accretion of beachfront during periods of milder wave conditions (Stive *et al.*, 2002).

This study focuses on coastal evolution at event scales, examining the system's response to processes occurring over varying time spans—from individual events, such as storms, to seasonal fluctuations in environmental conditions (Cowell *et al.*, 1995).

To comprehensively analyse coastal morphodynamics, this subsection addresses the key driving forces that shape coastal dynamics: hydrodynamic forces (external forcing), geological and biological systems, human activity (the environmental conditions as indicated in Figure 2) and the sediment dynamics in sandy beaches and estuaries. Interaction between these interrelated factors forms a basic platform for explaining complex coastal processes, and in consequence, enabling more informed management and decision-making.

2.2.1 HYDRODYNAMICS FORCES

Large-scale hydrodynamic mechanisms basically initiate the formation and modification of the coastal terrains. Among these, ocean waves, tides, currents, and winds act as major agents of sediment movement, erosion, and deposition that shape diverse coastal typologies.

Wind is a primary driver for generating waves, and in turn, waves are a major agent of coastline change. Waves are among the most powerful of all the causes of coastline adjustments. They carry substantial energy to erode cliffs and beaches, to transport sediments, and to shape beaches in different forms. Wave characteristics are a function of several factors: wave height (H), period (T), and direction vary with wind speed, storm duration, water depth, and fetch length (distance the wind blows over the water). On the open ocean, unrestricted by fetch and water depth, waves can reach their maximum size and are known as a fully developed sea. The size of the waves, along with the direction, controls the rate and direction of sediment movement and hence the vigour of erosion and deposition on coastlines (Masselink *et al.*, 2011).

Waves locally generated by wind are termed "sea" and often propagate in the same direction as the wind. They are defined by an irregular pattern, with variations in height and period. As these waves propagate away from their generating area, they start to acquire a more regular pattern, longer periods and reduced heights. This regular pattern is called "swell". In fact, wave dynamics properties change dramatically as a function of relative value of water depth (d) and wavelength (L). In deep water (i.e., for values of the ratio d/L greater than about 0.5) the waves can travel free and independently of the bottom. In shallow waters, however, waves tend to be affected by the seabed and hence experience different wave transformation processes (Figure 5).

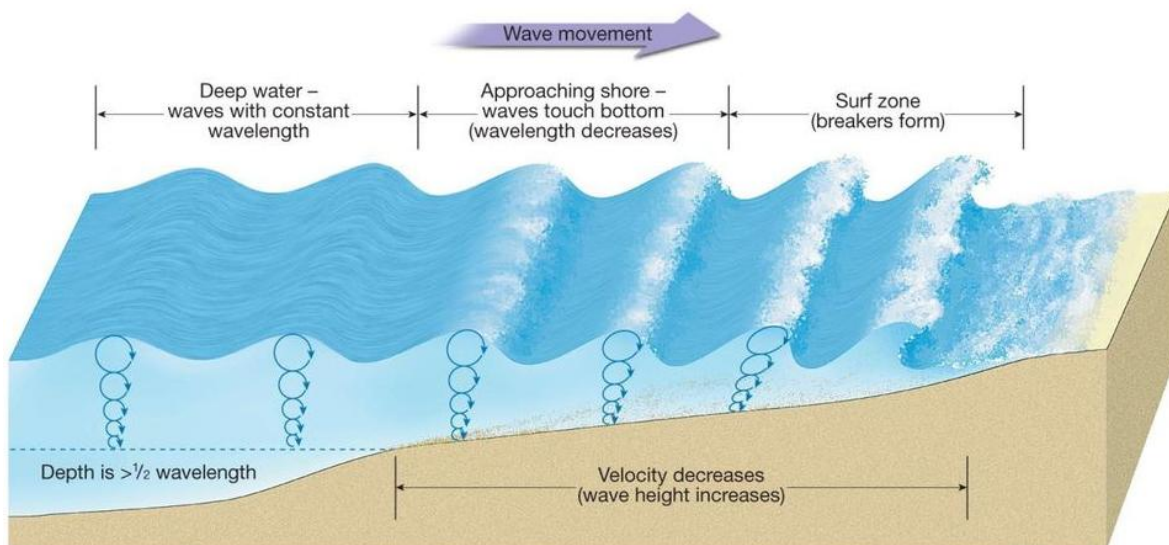


Figure 5 - Deep water and shallow water waves.

As waves enter shallower water their speed and wavelength decrease while their height increases. This shoaling process concentrates wave energy near the coast. When waves approach the shore at an angle, their crests' bend or refract owing to the change in water depth. This process – refraction – focuses wave energy on headlands and disperses wave energy in bays. The refraction phenomenon also helps to develop some patterns of erosion and accretion (Figure 6).

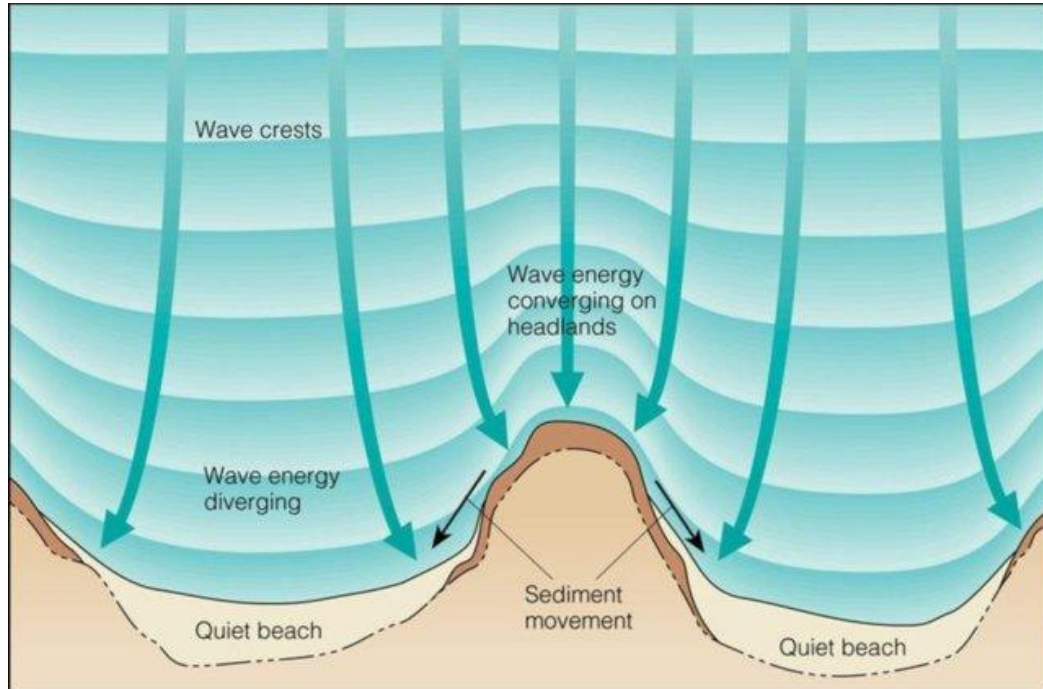


Figure 6 - Wave refraction and diffraction (Garrison, 2005).

Furthermore, when waves encounter obstacles such as breakwaters or headlands they bend or diffract around such structures, spreading wave energy into sheltered areas. In the nearshore, due to the continuous shoaling, refraction and water depth reduction, waves with increasing height become unstable and break, releasing most of their energy. The way waves break (spilling, plunging, or surging) depends upon factors such as wave steepness and beach slope, which in turn influence sediment transport and beach profile.

Tides are periodic sea level changes that result from the gravitational pull of both the moon and the sun combined with the centrifugal force generated by the rotation of the earth. The differences between tidal amplitudes depend on the continuous changing spatial relationships between Earth, the moon, and the sun. When the sun, moon, and Earth are in a linear alignment, the combined gravitational pull creates spring tides characterized by the highest high tides and the lowest low tides thus a greater tidal range. By contrast, when the Sun and Moon are at right angles with respect to Earth their pulls partially cancel out, producing the neap tide having lower high tides, higher low tides, and a smaller tidal range. Meteorological tides add to the astronomical component therefore also contributing to the changes of the sea level.

Tides can significantly influence coastal morphodynamics through various mechanisms. For instances, the tidal currents, generated by the rising and falling tides, can erode coastlines, transport sediments, and therefore alter coastal features.

Their strength and direction vary with the change in tidal phases. In estuarine conditions, where freshwater from rivers reach the ocean, the action of tides produces a complex circulating movements with implications for the salinity gradients and sediment movements. Besides tidal currents, other types of currents also play a role in coastal morphodynamics (Figure 7): alongshore currents, running parallel to the shore, arise from waves reaching the coast in an oblique direction and contribute to sediment transportation along the shores and beaches, which is

an integral part in morphology regarding coastal manifestations of sandspits and barrier islands. On the other hand, the rip currents, i.e., the ones running seaward through openings in the sandbars, transport sediment away from the shore and may also be dangerous for people swimming near shorelines (Kamphuis, 2000).

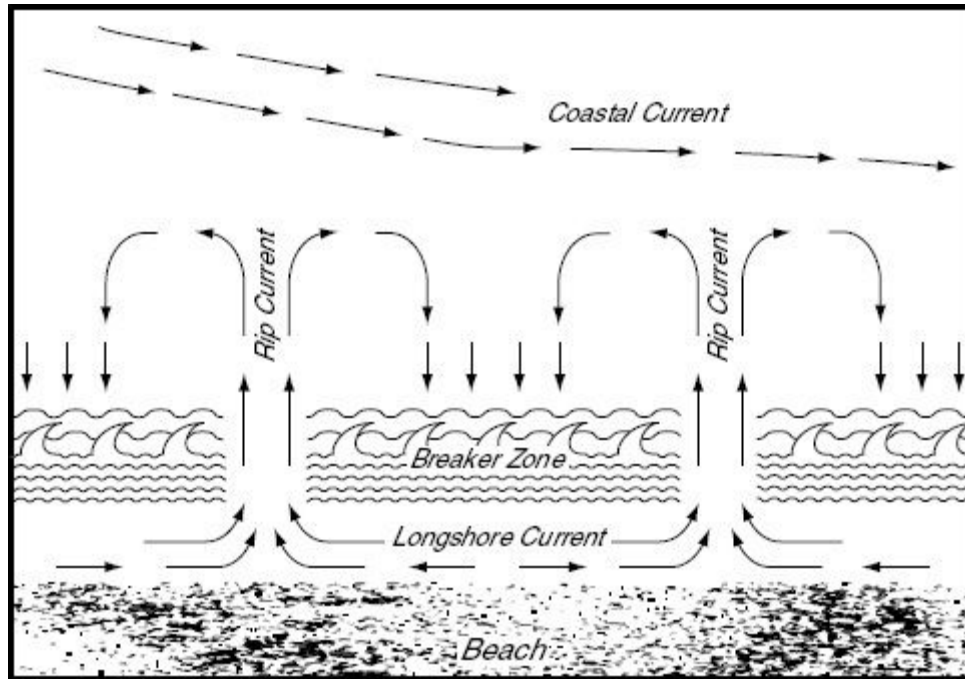


Figure 7 - Nearshore currents (Sigismondi, 2008).

2.2.2 GEOLOGICAL AND BIOLOGICAL FACTORS

Geological and biological features impact coastal transformation and have been extensively studied in the past. Several textbooks on coastal processes and geomorphology englobe a detailed and broad overview of the coastal systems and processes and outline the fundamental concepts (e.g., Davidson-Arnott et al., (2019); Masselink et al., (2011)).

The geological factors form the framework, with physical processes (such as tidal and wave activity) providing room for transformation, and biological factors contributing significantly to developing or/and eroding coastal structures. All these factors combine themselves to form the very diverse and dynamic environments that make coastlines worldwide unique.

Geological characteristics play a fundamental role in terms of coastal morphodynamics, as the type of material that constitutes a coastline influences its susceptibility to erosion and its pace of geologic transformation. For instance, strong and resistant rocks such as granite suffer little erosion, and in most cases, develop steep, rock coastlines with platforms, notches, and sea stacks. In contrast, the presence of susceptible materials, such as unconsolidated sediments or erodible rocks, develop sandy coastlines, dunes, and cliffs. Regional tectonic background, yet another variable, plays an important role, with coastal areas located at plate margin convergences developing such features as narrow coastal shelves, narrow coastal platforms, and nearby deep ocean basins; tectonic uplift and subsidence can alter relative sea level according to its geographical location, creating marine platforms and river valley submergence. Isostatic adjustments such as glacial rebound and water loading fluctuations have a significant impact in controlling coastal development through sediment deposition patterns and landform distribution. Regional geologic background and stratigraphy, including rock types and its structural

weaknesses, contribute a significant role in defining coastal forms, such as sea stacks, arches, and terraced coastlines, amongst many others.

Biological factors, at times overlooked, also play an important role in coastal morphology development. For instance, the vegetative cover is a key feature for coastal ecosystem stabilization and shaping landforms. In coastal environments with dunes, shrubs and grasses enable windblown sand deposition, subsequently creating dunes and preventing erosion. For dune development, the vegetative cover density and composition have a considerable impact according to its susceptibility to waves and wind. Salt marshes and mangroves, too, stabilize coastlines through widespread root structures, holding sediments in position and reducing erosion. These ecosystems also attenuate wave energy, promoting sediment deposition and the formation of intertidal flats and marsh platforms. Apart from contributing to sedimentation, these habitats act as protective barriers, protecting coastal and inland areas against storm surges and erosion, besides providing critical habitats for a wide range of species (Alongi, 2008; Gedan *et al.*, 2011). In addition, living coral reefs are also key parts of coastal environments, and act as powerful bio-magnets with regard to responsible biological factors for them. As natural breakwaters, such reefs dissipate waves, ease impacts, and protect coastlines against erosion. Besides providing habitat for marine species, coral reefs promote marine diversity and productivity in aquatic environments. In a similar manner, oyster reefs stabilize coastlines and promote ecologic function through habitat creation and water purification. Not only do such biogenic structures shape coastal form, but through such continuous processes they build coastal ecosystem resilience.

Nevertheless, biological processes do not necessarily produce beneficial consequences in all cases. Some marine animals, such as rock-eating mollusks and crustaceans, practice bioerosion by penetrating and digesting rock substrates. This bioerosion then reduces rock structures' integrity, making them susceptible to erosive powers of waves and current over long times, ultimately producing characteristic coastal forms such as notches, potholes, and caves, and changing coastal rock landscapes' morphology in the process (Grabowski *et al.*, 2012).

Bioerosion, a naturally occurring mechanism, can actually be accelerated by environmental factors (e.g. increased temperatures in seawater and/or increased pollution) and, in turn, influence coastal processes. Coastal dynamics' complexity arises through an intertwined complex of geologic, physico-mechanical, and biologic processes. For instance, flora proliferation can cause the expansion of dunes and, in its wake, modify wind regimes and sedimentation processes, respectively. Likewise, reefs can modulate waves and sedimentation processes in nearby regions and, in turn, modify coastal development, such as in producing coastal forms such as a beach and a variety of coastal forms, respectively.

The long-term sea level fluctuations, at both a global (eustatic) and a localized (isostatic) level, likewise remodel regions under the impact of waves and sediment transport into new forms. For instance, during a transgression in the early part of the current geologic period (Holocene period), flooding of submerged coastlines produced fjords and rias, whereas ongoing sea level rise jeopardizes low-elevation coastal regions through increased flooding and increased coastal erosion, respectively.

Coastal ecosystems serve an important function in providing habitats and supporting ecosystem processes. In particular, coastal wetland and estuary environments act as nurseries for many species of fish and habitats for shellfish, amongst many others. Biological productivity in these areas promotes species diversity and overall coastal ecosystem wellbeing. In addition, these processes serve as key functions in cycling nutrients in coastal environments. For instance, filtering out pollutants and water purification is facilitated through the presence of marsh vegetation, and decomposition releases nutrients supporting microorganisms and flora (Barbier *et al.*, 2011). Waves and current processes, too, contribute to shaping the environment through species dispersal and increased survival of sedentary habitat dwelling species such as shellfish in coastal environments.

However, these environments have significant vulnerability to changing environments, in part particularly those derived through anthropogenically generated processes. Anthropogenically derived processes such as infilling, pollution, dredging, and wetland loss can perturb ecological processes and modify coastal morphodynamics. For

instance, salt marsh and mangrove degradation through coastal development reduces sediment stability and increases vulnerability to coastal storm waves and coastal erosion. Likewise, overfishing, degradation through pollution, and degradation through changing climate processes in coral reefs erode its protective role for coastlines and reduce biodiversity in coastal environments. Climate change and sea level rise, in addition, present additional danger, possibly contributing to the loss of important coastal habitats such as salt marsh and reefs, with significant consequences for coastal morphodynamics.

In summary, the coastal morphology configuration is determined through a complex interrelationship between geological, physical, and biological factors. Geological processes form the basis, and physical processes allow for transformation, with both processes contributing towards coastal landform development and coastal erosion processes, respectively. By appreciating these interrelationships and key role played by geological and biological processes in coastal development, proactive conservation and protective interventions can then be initiated to safeguard and rehabilitate coastal environments, with a view to maintaining long-term coastal sustainability and future viability for future generations (Davidson-Arnott et al., 2019; Masselink et al., 2011).

2.2.3 ANTHROPOGENIC FACTORS

Anthropogenic factors are highly involved in coastal morphodynamics, often magnifying natural processes and accelerating coastal changes. Various human activities such as coastal developments, extraction of resources, pollution, and even climate change all combine in complex ways to disturb coastal ecosystems and modify the ways that sediments are transported along the coast. The following discussion on coastal morphodynamics, human interventions, and their consequences is primarily based on the works of Davidson-Arnott et al. (2019) and Masselink et al. (2011).

Most coastal development and urbanization impact the morphodynamic variability of coasts, which is driven by ever-increasing population aggregation and infrastructural growth. This often results in coastal squeeze, which is described as a process where natural features like beaches, dunes, and wetlands are squeezed between the advancing sea and human-made structures. In such cases, when their retreat space becomes minimum, the loss of such features triggers habitat degradation and increased erosion. Another factor brought forth by urbanization is alteration in sediment transport due to seawalls, breakwaters, groins, and other forms of coastal protection impeding natural processes (Figure 8).

management issue	engineered solution(s)	types	description	problems	illustration
cliff erosion	seawalls	revetment	a sloping rectilinear armoured structure constructed with less reflective material, such as interlocking blocks (tetrapods), rock-filled gabions, and asphalt	the slope and loose material ensure maximum dissipation of wave energy	armoured blocks
tidal inlet management	jetties		walls built to line the banks of tidal inlets or river outlets in order to stabilise the waterway for navigation	the jetties protrude into the sea and promote sediment deposition on the updrift side, but also sediment starvation and erosion on the downdrift side	sand, inlet, jetty, erosion, land, longshore drift
beach stabilization	groynes		shore-normal walls of mainly wood, built across beaches to trap drifting sediment	starve downdrift beaches of sediment	longshore drift, sand, groynes
	beach nourishment		adding sediment to a beach to maintain beach levels and dimensions	sediment is often rapidly removed through erosion and needs regular replenishing; often sourced by dredging coastal waters	

Figure 8 - Summary of coastal protection works involved in the case studies (Masselink et al., 2011).

Seawalls, for instance, prevent coastal flooding but may induce erosion at the toe and beach narrowing. Groins trap sediments on the updrift side, while the down-drift areas are starved of sediments and eroded. Fresh water pollution and contamination through urban runoff, industrial waste, and wastewater lead to the degradation of water quality and furthermore affect the coastal ecosystem and sediment dynamics.

Different resource uses, such as sand mining and dredging, have direct effects on coastal morphology through system losses of sediment. Sand mining involves removing sediment from beaches and dunes for construction and leads to a significant decrease in their potential for coastal protection against erosion and storm surges. Correspondingly, dredging for navigational channels or resource extraction alters the water depth, flow, and sediment transport, often causing unexpected erosion or deposition of sediment elsewhere. Climate change accelerates the natural processes along coastlines, particularly through anthropogenic warming, which plays a vital role in accelerating those processes. Rising sea levels due to glacial melt and thermal growth cause the shoreward retreat of coastlines, enhanced erosion, and saltwater intrusion into coastal aquifers. Among those, other important consequences, which are emphasized, refer to the changes in intensity and frequency of storms: higher and more frequent storms generate higher waves and higher storm surges, meaning more damage and erosion to coasts and infrastructures. The acceleration of these changes enhances the anthropogenic impact on coastal morphodynamics.

In addition, land-use changes, such as deforestation and urbanization, further affect coastal morphology, providing additional runoff, changing drainage patterns, and adding to the sediment loadings in the coastal waters. These changes in land use will affect sediment transport, water quality, and habitat stability. For example, deforestation reduces the stabilizing effect of vegetation on the coastal system due to its susceptibility to erosion and habitat loss.

Anthropogenic pollution seriously influences sediment dynamics in coastal ecosystems due to industrial effluents, agricultural runoff, and urban wastewater, causing deterioration in water quality and sediment characteristics. Too much nutrient loading creates algal blooms that, in the process of decomposition, deplete the oxygen levels and disturb the marine ecosystem, thereby indirectly influencing sediment transport (Davidson-Arnott et al., 2019; Masselink et al., 2011).

Complicated interactions among these anthropogenic factors reflect the complexity of coastal morphodynamics. Human activities (e.g., development of defence structures, or extraction of resources) realize a specific solution for a given problem but often provide impulse for a set of cascading effects that alter coastal ecosystems. Natural processes, coupled with human impact, must be taken into consideration in the integrated management of the coastline if the use and conservation of the coast are to be sustainable. Acknowledging the complex equilibrium between developmental initiatives and conservation efforts is crucial for alleviating the enduring effects of human activities on coastal morphology.

2.2.4 SEDIMENT TRANSPORT – SANDY BEACH AND WAVE-DOMINATED ESTUARY

Sediment transport is a fundamental process in coastal systems, as it represents the movement of material within the system. In coastal environments, sediment transport occurs through erosion, transport, and deposition, driven by the interaction between moving fluids and unconsolidated sediments. This interaction generates shear stresses that can lead to sediment entrainment and subsequent transport, shaping coastal morphology over time (Masselink et al., 2011).

The dimensions and categorization of sedimentary particles (e.g., sand, gravel, silt, and clay) are key factors in determining the shapes of coastal landforms. Sediment size controls the gradient of the beach, how sediments are transported and, eventually, what landforms will result. Coarser sediments, such as gravel, tend to produce steeper beach slopes due to their higher resistance to movement, whereas finer sediments, such as silt and clay, are easily mobilized by the flow and usually deposited in protected areas where the wave energy is at minimum. Whereas

sediment supply allows the formation of beaches, its preservation enables their existence. A decline in the supply of sediments, whether due to natural processes or through anthropogenic interference, leads to erosion or retreat of the shoreline, hence accentuating the importance of sediments in maintaining these dynamic ecosystems along the coasts (Kamphuis, 2000).

One of the most important factors is the angle at which the waves contact the shoreline (effective wave angle), which influences the two dominant types of coastal sediment transport: the alongshore and cross-shore patterns. If waves reach the coast at an angle, a longshore current or a continuous water flow is produced, moving parallel to the coast – alongshore transport. It transports material along the coast, which shapes beaches and influences erosion and accretion. Cross-shore transport refers to the motion of sediment at right angles to the shore, driven by the energy supplied both from incoming and receding waves (Kamphuis, 2000).

For example, the imbalance of this sediment input and output through cross-shore and alongshore movement is the main reason for the erosion observed on sandy beaches in northern Portugal (Taveira-Pinto *et al.*, 2022). A deficit in sediment supply along the shoreline and the action of currents and winds eroding beach sands, lead to the recession of the coastline. Consequently, this erosion causes the coastline to shift toward a new equilibrium state characterized by a reduced volume of sediment being transported in leeward direction (Pereira *et al.*, 2013). This process progressively propagates the erosive effects further south along the coast (Figure 9).

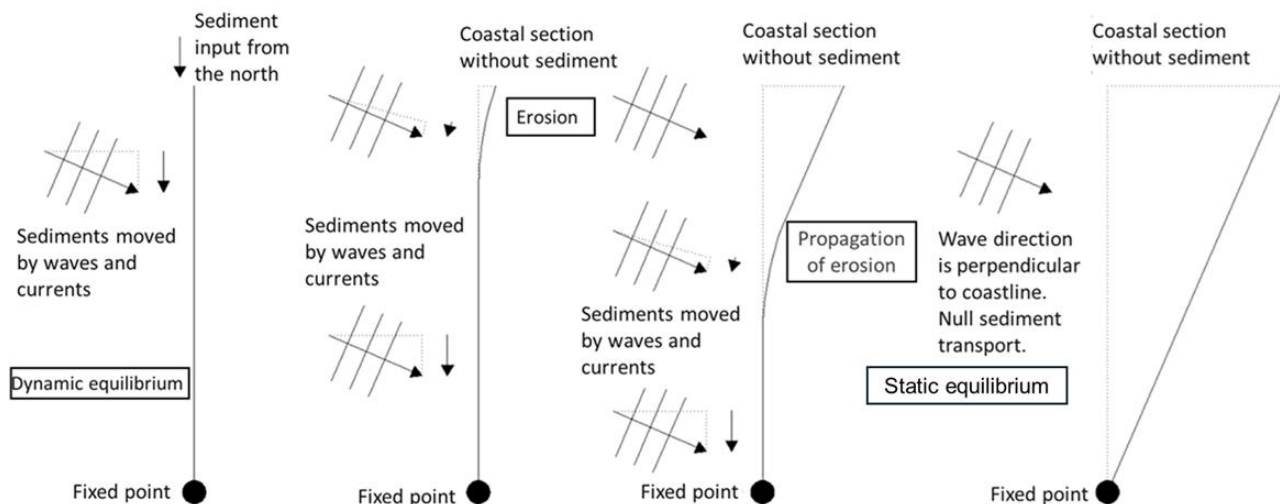


Figure 9 - Generalized sediment deficit effects on erosion propagation and shoreline evolution, from a dynamic equilibrium to a static equilibrium situation (adapted from Pereira *et al.*, 2013).

During storms, high energy waves move sediment offshore, forming bars, while low energy waves carry sediment back onshore, building beaches. The beach profile (the cross-sectional form of the beach) is of dynamic nature due to the changing wave conditions. In periods of calm, there is berm build-up because of sedimentation on the upper parts of the beach, while during storm events there is erosion and sediment transported offshore, forming bars (Figure 10). This is a continuous adjustment in relation to the correlation between wave energy and the morphology of beaches (Short, 1999).

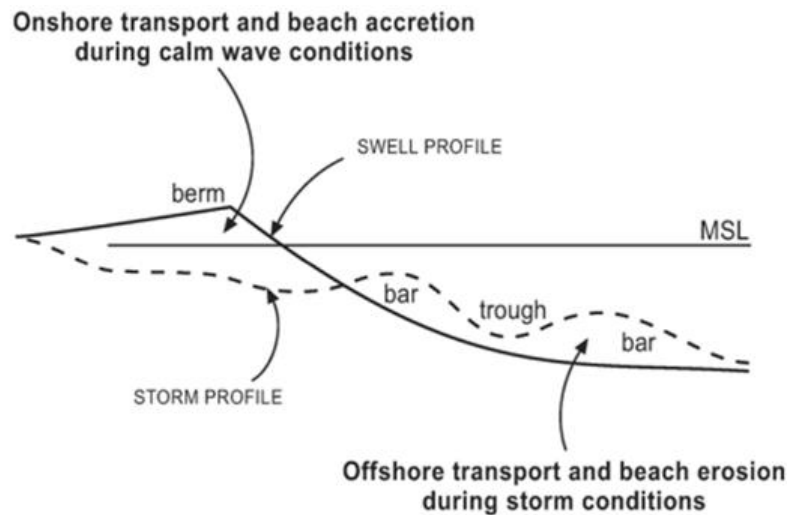


Figure 10 - Idealised barred and non-barred beach profiles due to storm and calm wave conditions (Masselink et al., 2011).

An estuary is a type of tidal basin where seawater is measurably diluted by freshwater inflows. The classification of an estuary as wave- or tide-dominated depends on the relative influence of waves and tidal energy in its outer zone. In the context of this work, wave-dominated estuaries will be described in more detail as one of the selected case studies involves such a system (also features a sandspit).

Wave-dominated estuaries typically exhibit a barrier system in their outer zone, which can be breached or overtopped during storm events, leading to sediment over wash and deposition inland. These estuaries also contain a tidal inlet, facilitating bidirectional sediment exchange between the estuary and the open sea. They receive sediments from both fluvial and marine sources and contain areas influenced by tides, waves, and fluvial processes (Figure 11). From a sediment budget perspective, estuaries often function as net sediment sinks—zones where sediment accumulates rather than being transported further. Negative sediment budget cells, such as estuarine regions undergoing sediment deposition, are often characterized by shoreline transgression and erosion. In some cases, however, estuarine evolution may become arrested, where sediment accumulation leads to the stabilization of the system, forming an armoured estuary resistant to further morphological change.

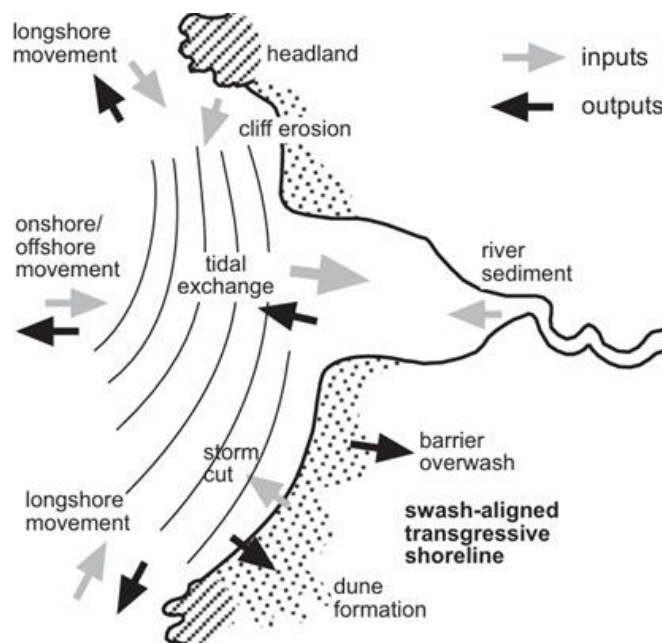


Figure 11 - Sediment fluxes in estuarine coast adapted from (Masselink et al., 2011).

Wave-dominated estuaries exhibit distinct energy gradients (Dalrymple et al., 1992), with a high-energy outer and inner zone and a comparatively low-energy central basin (Figure 12a). Wave processes are most influential in the outer zone, but their impact diminishes rapidly with distance from the coast due to wave breaking over barriers and tidal deltas. The influence of waves is largely confined to the seaward margin of the outer zone, while the inner and outer zones remain the most dynamic, serving as primary areas of sediment transport. Sedimentation patterns within these estuaries are largely controlled by hydrodynamic forces. Coarser sediments, such as sand, tend to accumulate in the high-energy inner and outer zones, where sediment transport is more active. In contrast, finer sediments, including silt and clay, settle in the central basin, where reduced energy conditions favour deposition (Figure 12). This sediment distribution plays a fundamental role in shaping estuarine morphology and influencing long-term coastal evolution.

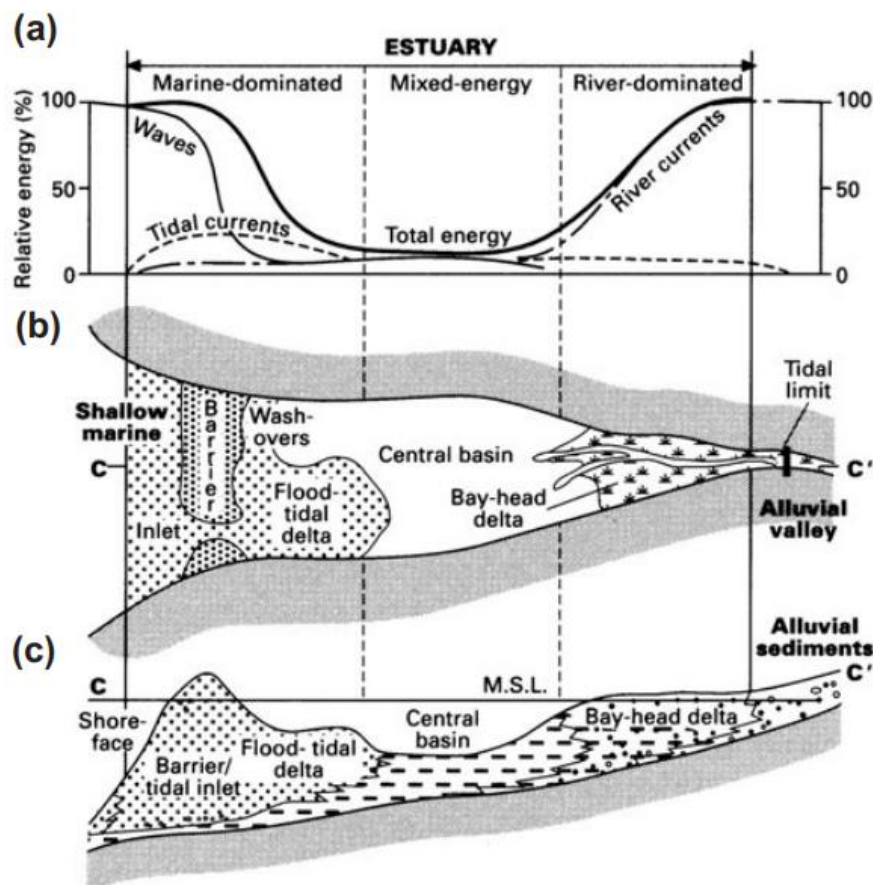


Figure 12 - Idealized wave-dominated estuary distribution of: (a) energy range; (b) morphological components in plan view; (c) sedimentary facies in longitudinal profile (Dalrymple et al., 1992).

Estuarine entrances may be partially constricted due to the development of spits, shoals, or barrier formations driven by persistent wave action and longshore sediment transport.

Sand spits are elongated accumulations of sand or gravel that extend from the mainland into the sea, with one end attached to the coast and the other projecting offshore (Figure 13). They are classified as drift-aligned coastal features formed and maintained by the continuous transport of sediment through longshore drift. The stability and persistence of a sand spit depend on a sufficient sediment supply from updrift sources, making them highly dynamic landforms that respond to variations in wave climate, sediment availability, and sea-level changes.

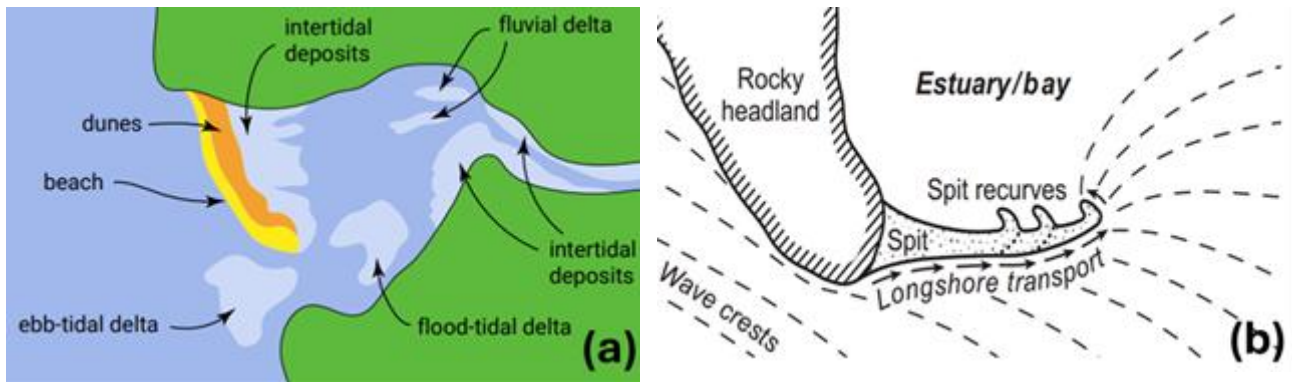


Figure 13 - Idealized sand spit barrier: (a) morphological components (Bosboom et al., 2023); (b) sediment transport (Masselink et al., 2011).

The morphology of sand spits varies depending on hydrodynamic forces and sediment supply. In many cases, the distal end of the spit curves landward due to wave refraction and tidal currents, forming a recurved spit (Figure 13-b). In more complex systems, compound recurved spits develop, characterized by a narrow proximal section and a broader distal end. This distal region often consists of multiple older dune or beach ridges, reflecting a history of seaward shoreline migration. The growth of a spit occurs in the direction of the prevailing littoral drift, with new sediment deposits gradually extending its length over time (Masselink et al., 2011).

The evolution of a sand spit is largely controlled by its sediment budget, which determines whether the feature will grow, stabilize, or erode. A positive sediment budget, where sediment input exceeds losses, supports spit expansion, whereas a negative budget can lead to erosion and retreat. The sediment supply to a spit can be influenced by several factors, including updrift changes in sediment availability, storm events, wave climate fluctuations, sea-level rise, and human interventions. Severe storms, for example, can cause overwash events, leading to a redistribution of sediment across the spit or the formation of new tidal inlets. Similarly, modifications to the coastal system, such as jetty construction, dredging, or river damming, can disrupt natural sediment transport, affecting spit stability and growth (Davidson-Arnott et al., 2019).

Over time, sand spits may become unstable and prone to breaching, particularly when their proximal section narrows due to erosion. This thinning increases susceptibility to overwash and storm-induced breaches, which can sever the spit and interrupt sediment transport to its downdrift portion. In some cases, breaching may lead to the formation of barrier islands, while in others, it can result in the complete disappearance of the spit. Additionally, when a spit is connected to an eroding shoreline, its long-term stability is further compromised, increasing the likelihood of detachment and landward migration (Davidson-Arnott et al., 2019; Masselink et al., 2011).

In conclusion, the sand spits are very dynamic morphological elements created by sediment transport processes alongshore, influenced by climatic, hydrodynamic, and human interventions. Their development and possible instability emphasize the need for continued observation and successful management strategies.

2.3. KEY PARAMETERS

The study of coastal morphodynamics relies on a variety of parameters used to monitor and analyse changes in shoreline position, beach morphology, and sediment dynamics. Recognizing these parameters is crucial for an effective coastal management, erosion control, and the design of sustainable coastal protection interventions. Sandy beaches, being highly dynamic environments, are particularly sensitive to these processes.

As the two case studies of this dissertation correspond to sandy beaches, and as highlighted in recent literature and in the ESA-funded project ‘Space for Shore’², the more relevant indicators for coastal morphodynamic studies are the following: waterline position, upper and lower swash limits, dune foot position, beach width, vegetation limit, bathymetry and sandbar position.

The waterline, defined as the boundary between the marine and terrestrial parts of the coastal system, is a commonly used parameter for assessing shoreline changes. Monitoring the position of the waterline is particularly useful for comparing shoreline conditions before and after storm events, especially in microtidal environments with low wave activity. However, the waterline is less suitable for quantifying seasonal or long-term changes, as it can vary significantly with daily tidal fluctuations and short-term wave dynamics.

The upper and lower swash limits are more appropriate for evaluating seasonal and annual shoreline changes. These limits represent the highest and lowest positions reached by the water on the beach over a selected period. By tracking these positions, researchers can identify patterns of shoreline movement and sediment redistribution over time. However, this parameter is not well-suited for pre- and post-storm monitoring or for macro-tidal dune environments, where the swash zone may be less distinct or more variable.

In coastal areas with developed dune systems, the dune foot position is a valuable parameter for monitoring changes in the coastal profile. The foredune toe is identified by the change in slope at the base of the seaward side of the dune, and its position can provide insights into the multi-metric dynamics of the dune system. However, this parameter is less effective for old, stable, or poorly developed dune systems, where the dune foot may be indistinct or less responsive to changes in coastal processes.

The beach width, measured as the distance between a reference line (e.g., the dune foot, cliff, or a coastal defence structure) and the waterline, is another important parameter for assessing coastal dynamics. This measurement can be taken at low tide, high tide, or using a time-averaged waterline, depending on the specific objectives of the study. Beach width is particularly suitable for wide beaches, where dynamics at both the top and bottom of the beach are significant. However, it is less effective for narrow beaches, where the resolution of available imagery may limit the accuracy of measurements.

The vegetation limit, defined as the seaward boundary of vegetation, is a useful parameter for monitoring long-term trends in coastal evolution or the impacts of exceptional storm events. This parameter is most effective in areas with mature vegetation fringes, where the boundary is clearly defined. However, it is less suitable for areas with young or scattered vegetation, or for analysing seasonal or shorter-term dynamics, as the vegetation limit may not be directly connected to changes in coastal processes.

Bathymetry, which involves the use of Digital Elevation Models (DEMs) to map underwater depths, is a critical tool for evaluating sediment balance over seasonal to longer-term timescales. By comparing bathymetric data from different dates, researchers can assess vertical changes in the seabed and identify patterns of sediment deposition or erosion.

Finally, the sandbar position is a key parameter for understanding the dynamics of sedimentary stocks in front of sandy beaches. Sandbars are identified by the spectral signal associated with their crests or the position of wave breaking, and their migration is monitored by measuring the distance from the coastline to the sandbar along perpendicular transects. While this parameter provides valuable insights into sandbar dynamics, it should be coupled with data on coastline dynamics to fully interpret sediment budgets and understand the broader context of coastal change.

In conclusion, each of these parameters offers unique insights into different aspects of coastal morphodynamics, but their suitability depends on the specific characteristics of the coastal environment and the temporal and spatial

² <http://spaceforshore.eu/index.php/indicators-of-coastline-dynamics/> accessed in 13/01/2025

scales of interest. By carefully combining these parameters, it is possible to calculate other diagnostic indicators, for example, sediment volume variation, calculate specific areas, lengths and shoreline evolution rates.

To achieve an unbiased assessment of coastal evolution, measurements must be as independent as possible from high-frequency water level fluctuations and the seasonal morphological changes of the beach. Coastline indicators can include physical features such as the cliff top, the landward edge of shore protection structures, the foredune toe, and the seaward vegetation line. The two case studies analysed are low-lying sandy coasts with dune systems, therefore the foredune toe is usually selected as coastline indicator. This feature is less influenced by short-term tidal variations and medium-term seasonal changes, making it a reliable marker for tracking coastal evolution (Lira et al., 2016).

In Portugal, the environmental agency APA categorizes the indicators for diagnosing the state of a coastal stretch as its presented in Table 1.

Table 1 - Classification of sections according to the evolution of the state of the coastal strip (adapted from APA³).

Section Classification	Evolution Rates
Extreme Erosion	More than -5 m/year
Severe Erosion	Between -3 to -5 m/year
Intense Erosion	Between -1 to -3 m/year
Erosion	Between -0.5 to -1 m/year
Stable	Between -0.5 to +0.5 m/year
Accretion	More than +0.5 m/year

The integration of the previously described parameters plus the background information of the tide fluctuations, hydrodynamic regime and underlying geological formations, collectively, provide a wide framework for a coastal morphodynamics assessment.

In this context it is relevant to mention that this dissertation aims to analyse the feasibility of performing an extensive inter-month analysis of morphodynamic processes observed over coastlines mainly via bathymetric surveys and satellite derived data, specifically focusing on seafloor changes, sediment transport processes, and the subsequent implications for nearshore and coastal morphology. The study involves two very distinct coastland environments (a low sandy beach and an estuary) in an attempt to analyse morphological changes and sedimentary processes in two distinct contexts.

2.4. BATHYMETRY SURVEYS – METHODS

Bathymetry surveying, *i.e.*, the underwater depth and seafloor topography, has advanced significantly with the development of remote sensing technologies. Today, seafloor morphology can be mapped at scales ranging from kilometres to centimetres using a variety of techniques, including multibeam sonar, optical remote sensing, and satellite radar altimetry. Data acquisition platforms are equally diverse, encompassing submersible vehicles, surface vessels, aircraft, and satellites, each suited to specific hydrographic applications (Dierssen et al., 2020).

Different remote sensing methods estimate seafloor depth using distinct physical principles. Acoustic techniques measure depth through the water column, optical methods rely on visible light transmission through both air and

³ <https://apambiente.pt/destaque2/apa-atualiza-diagnostico-do-estado-da-faixa-costeira> accessed in 03/01/2025

water, and radar altimetry estimates depth through measurements taken in the air medium (Ferreira *et al.*, 2022). Among these, acoustic methods remain the most widely used for validating and calibrating optical and radar-derived bathymetric data, owing to their high-resolution depth measurements, which serve as a benchmark for alternative approaches (Cesbron *et al.*, 2021).

Modern bathymetric techniques, particularly for shallow-water environments, include Global Navigation Satellite System (GNSS) receivers, bathymetric Light Detection and Ranging (LiDAR) sensors, and satellite-derived bathymetry (SDB). Each method presents distinct advantages and limitations in terms of spatial resolution, accuracy, and operational depth, requiring careful selection based on environmental conditions and the survey objectives.

This section focuses on acoustic and optical remote sensing techniques, as these are the primary methods applied in the case studies. Specifically, it presents the reference bathymetric survey approach using acoustic sounding, followed by an overview of optical remote sensing techniques and the SDB based on wave kinematics. By examining these methodologies, this review aims to provide a comprehensive understanding of their applications, accuracy, limitations, and suitability for different hydrographic conditions.

2.4.1 ACOUSTIC SENSING TECHNIQUES

The primary disadvantage of surveys with acoustic systems lies in the high costs associated with vessels and crew. In shallow waters, a higher level of detail is always required which reflects a greater number of probed lines. In deep waters, on the other hand, the problem becomes the high costs involved with crew and large ships. Even when autonomous vehicles are used, such as autonomous underwater vehicles (AUVs), there is the need for vessels to, for example, provide control of the uncrewed platform and acoustic positioning (Ferreira *et al.*, 2022).

The single-beam echo sounder (SBES) measures water depth by emitting a sonar pulse directly downward and recording the time taken for the echo to return to the sensor. The depth is then estimated by multiplying this time by the speed of sound in water. SBES provides a single depth measurement directly beneath the vessel, requiring multiple survey lines to create a complete bathymetric map. This method is particularly useful for very shallow waters (less than 5–10 m of depth) due to its simplicity and cost-effectiveness. However, SBES is limited in its ability to cover large areas efficiently, as it only collects depth data along a single line (Figure 14), leaving gaps between survey tracks (Cesbron *et al.*, 2021).

In contrast, the multibeam echo sounder (MBES) emits multiple sonar pulses measuring both the travel time and angle of each reflected beam. Therefore, the MBES can generate detailed three-dimensional maps of the seafloor. This system scans a wider area with each pass, with swath angles typically ranging from 120° to 170°, resulting in a seafloor coverage that is 3.5 to 25 times the water depth (Lekkerkerk, 2020).

MBES systems achieve depth measurements through electronic beamforming, although some advanced models use interferometry. The interferometric sonars, also known as phase differentiating bathymetric Sidescan sonars (PDBS), employ multiple receivers and a projector to determine the direction of arrival (DOA) of the return signal instead of the traditional time of arrival (TOA) (Ferreira *et al.*, 2022).

The modern MBES systems offer high resolution, being able of mapping bathymetry at a horizontal resolution of approximately 0.5 m (Cesbron *et al.*, 2021). Advanced MBES units can operate at multiple frequencies, enabling sediment discrimination and enhanced characterization of the seafloor. Recent advancements have integrated MBES technology with AUVs, significantly reducing costs and improving access to remote or hazardous regions (Cesbron *et al.*, 2021).

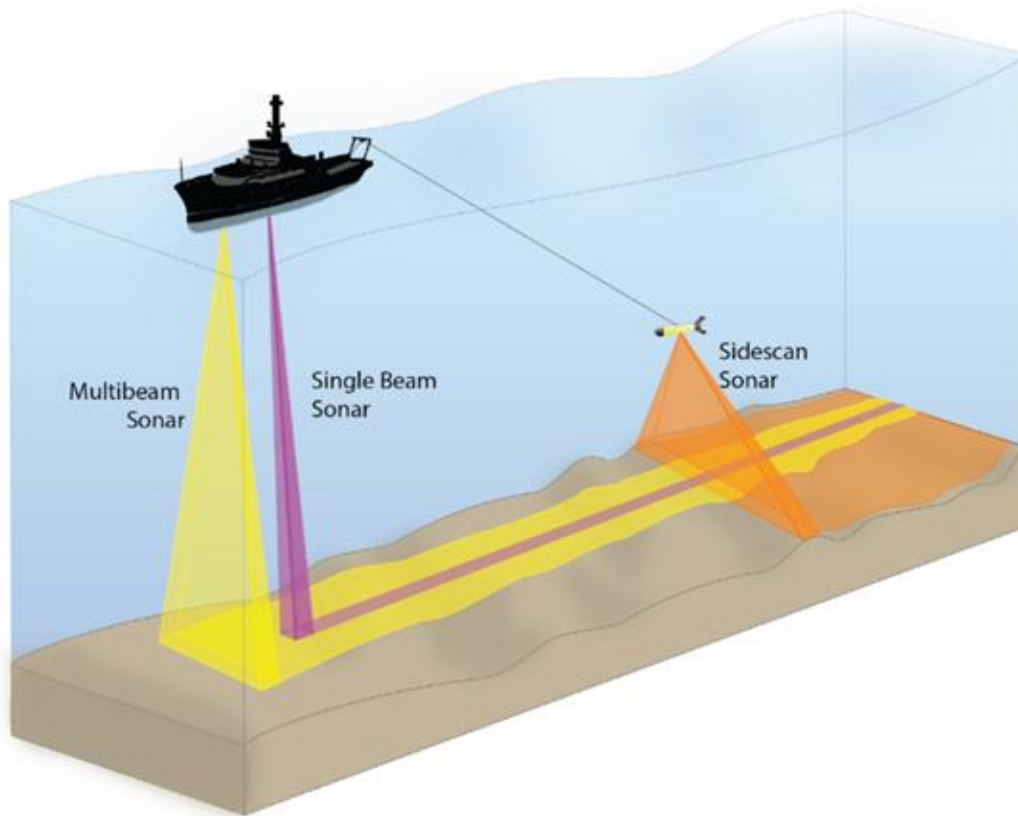


Figure 14 - Acoustic methods for assessing bathymetry (illustration by Vicki Gazzola⁴).

2.4.2 OPTICAL SENSING TECHNIQUES

Optical remote sensing methods provide a cost-effective and significantly faster method for the mapping of coastal and near-shore shallow-water bathymetry. There is a great demand for the direct measurement of depth via Earth Observation remote sensing methods to produce large datasets relevant to regional and global bathymetric scales (Daly *et al.*, 2022; Salameh *et al.*, 2019). Notably, in many parts of the world, satellite remote sensing acts as a main source of information, making up for the deficiency of *in-situ* measurement instrumentation required for the mapping, monitoring, and evaluation of aquatic and terrestrial ecosystems. It is also beneficial, the enormous archive of freely accessible, regularly collected, and readily available imagery of great significance, having recorded information about coastlines worldwide for many decades (C-55 IHO, 2025).

The use of optical remote sensing in the field of bathymetry is based on the use of electromagnetic radiation, notably sunlight, for observing changes in water depth. Two main methods have been utilized: passive sensors, which measure reflected solar radiation, and active sensors, which transmit radiation to a target and then measure the energy reflected back (B-13 IHO, 2024). In both cases, these methods greatly augment bathymetric research by allowing the effective and extensive gathering of data over a wide range of marine environments. Figure 15 presents the main methods of optical remote sensing used for bathymetry surveying (IHO B-13, 2024; Cesbron *et al.*, 2021; Ferreira *et al.*, 2022; Turner *et al.*, 2021).

⁴ <https://ecce.esri.ca/tag/cartography/> accessed in 05/02/2025

Optical Remote Sensing for Bathymetry	
Passive Sensor	Active Sensors
Empirical methods	LiDAR
Spectral response bathymetry	SAR
Wave based	Satellite radar altimetry
Photogrammetric	
The Radiative Transfer Equation (RTE) inversion method	

Figure 15 - Optical remote sensing methods for bathymetry extraction according to sensors.

The passive sensors detect electromagnetic energy, such as visible and infrared light, which can be captured by satellite sensors and utilized for Satellite-Derived Bathymetry (SDB) studies. Figure 16 describes the main optical remote sensing methods that utilize passive sensors for Satellite-Derived Bathymetry (SDB) (B-13 IHO, 2024; Ferreira et al., 2022).

Spectral response bathymetry	uses natural light reflected on the submerged bottom. Sensors embedded in aircraft or satellites detect radiation to measure depth and create bathymetric maps. This method relies on the principle that the intensity of radiant energy reflected by a water column and received by the sensor is a function of the water's depth.
Photogrammetric bathymetry	science that extracts 3D information from data acquired from a satellite stereo pair containing a different viewing geometry exhibiting parallax. This approach combines two images to create a 3D model, allowing the determination of XYZ coordinates of features in the imagery.
Empirical methods	describe mathematical models which are trained on local bathymetric information. A common method of the empirical SDB approach is referred to as the 'ratio approach', a non-linear solution using a band ratio calculation.
Wave-based Inversion	uses wave kinematics to estimate bathymetry from optical images. This method uses the linear wave dispersion relation.
Radiative Transfer Equation (RTE) inversion method	describes the complete sunlight pathway based on the physical behaviour of the light. This requires an accurate, algorithmic physical description of all the environmental variables that influence the light signal pathway, including the atmosphere, sea surface, water column and seafloor optical properties.

Figure 16 - Brief description of the primary SDB via passive sensors.

Space-borne wave observations can be used to derive both local wave characteristics and bathymetry, provided that distinct wave signatures are visible in the optical satellite imagery. The fundamental principle behind this method is that wave celerity (speed) is directly related to the water depth, with waves traveling more slowly in shallower areas. By analysing wave patterns and measuring their propagation speed, depth can be estimated with a reasonable accuracy. The technique relies on a sequence of satellite images captured in rapid succession to track the movement of surface waves. Key parameters such as wave celerity, wave number, wave frequency, wavelength, and wave period are extracted to infer depth. This method can be applied to both radar and optical

satellite imagery and is particularly useful for estimating depths from the nearshore to intermediate water depths (Bergsma *et al.*, 2023).

One of the primary challenges of using space-borne optical imagery for wave-based bathymetry is the reduced visibility due to cloud cover and the absence of distinct wave patterns in some conditions. However, wave-based methods are gaining popularity as they allow depth estimation in conditions where colour-based approaches fail, particularly in turbid waters. Recent advancements in these techniques exploit the small-time delay between different spectral bands of satellite imagery to enhance wave property detection and thus improve bathymetric estimates (Bergsma *et al.*, 2023).

An algorithm that generates bathymetric data based on depth inversion from wave kinematics is presented in the following section, developed in the framework of a cooperation between CNES, IRD-LEGOS and Shom.

2.5. SATELLITE TO SHORE (S2SHORES)

S2Shores (satellite to shores) is a cutting-edge tool, with its development and applications occurring only very recently in the context of remote sensing technology. This tool is a packaged python library that contains the core codes that detect and extract the local wave parameters (geometry and kinematics) to derive coastal bathymetry. It is designed to be agile and can be applied to various sensors, such as optical, radar, shore-based video camera systems and UAVs (Bergsma *et al.*, 2023). It combines the Radon Transform (RT) and Discrete Fast Fourier Transform (DFT) to extract wave characteristics, subsequently applying the linear wave dispersion relation to estimate the local water depth (Daly *et al.*, 2022).

In this work, the method leverages multi-spectral data from the Sentinel-2 satellite, capitalizing on its unique multi-band imaging capabilities and global coverage. Next, the main theoretical framework and operational workflow of this approach is briefly explained.

The S2Shores methodology operates through a four-stage analytical pipeline, integrating signal processing techniques with hydrodynamic principles:

1. Wave Pattern Extraction

The process initiates with the acquisition of Sentinel-2 optical imagery, where surface wave patterns can be visible due to variations in sunlight reflectance (Bergsma *et al.*, 2019). It exploits the small-time delay between different colour bands of Sentinel-2 to track the movement of surface waves. To enhance the detectability of linear wave features – particularly in scenarios complicated by image noise or suboptimal illumination – the Radon Transform (RT) is applied to sub-sections of the satellite image. The RT projects the image into a sinogram, where linear structures are represented by their angular orientation and spatial offset (Bergsma *et al.*, 2019a).

2. Wave Direction and Spectral Analysis

Following RT application, the dominant wave direction is determined by identifying the angle within the sinogram that exhibits maximum variance, corresponding to the primary orientation of wave propagation (Daly *et al.*, 2022). Subsequently, a Discrete Fast Fourier Transform (DFT) is applied along this dominant directional axis to decompose the wave field into its spectral components. This yields a wavenumber spectrum, which quantifies the spatial frequency distribution of the waves and provides critical phase information necessary for calculating wave kinematics (Bergsma *et al.*, 2019a).

3. Wave Celerity Calculation

A distinctive advantage of Sentinel-2 lies in its multi-spectral imaging system, which acquires data across multiple spectral bands with slight temporal offsets (Daly *et al.*, 2022). By analysing the phase shift ($\Delta\Phi$) observed in the wave spectra between two temporally displaced bands, the wave celerity (c)—the speed at

which waves propagate—can be computed. The relationship between phase shift, wavenumber (k), and temporal lag (Δt) is expressed as (Bergsma *et al.*, 2021; Daly *et al.*, 2022):

$$c = \frac{\Delta\Phi}{2\pi k \Delta t} \quad (1)$$

This step harnesses the satellite's multi-band acquisition strategy to resolve wave dynamics without requiring external time-series data.

4. Depth Inversion via Linear Dispersion Theory

The wave celerity, c , can be estimated using the linear wave dispersion relation:

$$c^2 = \frac{g \tanh(kh)}{k} \Leftrightarrow h = \frac{\tanh^{-1}\left(\frac{c^2 k}{g}\right)}{k} \quad (2)$$

where g denotes gravitational acceleration, k the wavenumber and h the local water depth. This equation links the wave kinematics to water depth, enabling the inversion of bathymetric values across the imaged coastal domain (Bergsma *et al.*, 2021; Daly *et al.*, 2022). Iterative numerical methods are employed to solve for h , producing a spatially continuous depth map with resolution constrained by the satellite's native pixel size (10–60 m for Sentinel-2) (Bergsma *et al.*, 2021).

Although a recent tool, S2Shores has been already successfully utilized for coastal bathymetric mapping in a wide range of contexts, namely:

- **Capbreton, France:** S2Shores was tested using Sentinel-2 imagery with a 10 m resolution, extracting wave patterns via a localized Radon transform. It was shown that the 10 m resolution was sufficient to estimate bathymetry for wave periods of 6.5 s or greater. The method was able to achieve an RMS error of 2.58 m and a correlation coefficient of 0.82 when compared to a survey for depths up to 30 m. It was also demonstrated that the Radon transform could augment the 20 m resolution imagery to 10 m, increasing the number of suitable bands for depth inversion (Bergsma *et al.*, 2019a).
- **Gironde Estuary, France:** A spatial correlation method was applied within the S2Shores framework to the Gironde estuary using Sentinel-2 data. The method uses the time delay between different colour bands of Sentinel-2 to approximate wave properties and calculate depth using linear dispersion theory. The results showed that the method was optimal in intermediate waters between 20 and 40 m. The S2Shores estimates captured the main channels in the complex bathymetry, and the Cordouan tidal bank (Almar *et al.*, 2024).
- **West Africa:** S2Shores was used to generate a regional bathymetry atlas along the West African coast, spanning 4000 km. Wave numbers and celerity were extracted from Sentinel-2 imagery, and inverted depths were output at 200 m resolution. The resulting bathymetry mosaic demonstrated good results ($r^2 = 0.76$, RMSE = 4.9 m) when compared with bathymetry surveys along the Senegalese coast. The method was able to detect depths up to 35 m depending on incident wave conditions and cloud cover. Underwater features such as flow channels in Guinea and the St. Ann's Shoal in Sierra Leone were well-reproduced. S2Shores shown to be capable of estimating bathymetry in turbid waters and relatively deep waters, making it a good complement to traditional colour-based methods. It was shown that powerful swell waves with low directional spreading produce the best results (Daly *et al.*, 2022).

Overall, S2Shores tends to overestimate depth in very shallow waters. This can be due to shoreline perturbations, varied pixel intensity around breaking waves, and limitations of the 10m pixel resolution. Furthermore, in deep waters, S2Shores can underestimate the true depth, due to the modulation transfer function between pixel intensity and surface elevation (Almar *et al.*, 2024).

Based on this literature review, it is important to highlight certain limitations related to the S2Shores tool (Almar *et al.*, 2024):

- the cloud cover can lead to unreliable depth estimates as opaque clouds block the view of the sea surface;
- wave non-linearity in shallow waters can impact the accuracy of depth estimation according to the limits of the linear dispersion relation;
- wave conditions, as the method is dependent on the presence of waves and performs best with long swell waves.

Despite previous studies suggesting the applicability of the tool to large coastal areas, there is a lack of knowledge in applying it to smaller, localized nearshore settings. In this context, the current thesis presents a unique chance to explore the use of S2Shores to extract bathymetric data in such particular cases, specifically in the chosen case studies.

2.6. APPLICATIONS

Bathymetric surveys are fundamental for understanding and managing coastal zones, which are recognized as strategic environments with significant socioeconomic and ecological value (Chowdhury *et al.*, 2023; Viaña-Borja *et al.*, 2025). These surveys provide critical data that support a wide range of applications, from coastal engineering and sediment transport studies to climate change assessments and marine resource management (Caballero *et al.*, 2023; Viaña-Borja *et al.*, 2025).

Bathymetric surveys are therefore critical for:

- **Coastal Engineering and Management:** Bathymetric data is essential for analysing coastal dynamics, enabling effective planning and management strategies. Coastal engineers, policymakers, and researchers rely on these data to develop numerical models that predict hydrodynamic processes and assess shoreline stability (Viaña-Borja *et al.*, 2025).
- **Erosion and Sediment Transport Studies:** By estimating sediment transport rates, bathymetric surveys help identify coastal areas undergoing erosion or accretion. These data contribute to monitoring shoreline changes and understanding the evolution of coastal morphodynamics (Chowdhury *et al.*, 2023).
- **Habitat Mapping and Monitoring:** Bathymetric surveys provide insights into seafloor morphology and benthic habitats, aiding in marine conservation efforts and ecological assessments (Boer *et al.*, 2018).
- **Climate Change and Hazard Assessment:** Understanding the impacts of sea-level rise, storm-induced erosion, and changing coastal conditions is a critical application of bathymetric data, helping to inform climate adaptation strategies (Caballero *et al.*, 2023; Viaña-Borja *et al.*, 2025).
- **Navigation and Coastal Safety:** Accurate bathymetric data are crucial for navigational safety, ensuring the reliability of maritime routes and port operations.
- **Coastal Monitoring:** Advanced bathymetric methodologies serve as operational tools for continuous coastal monitoring, improving the assessment of long-term shoreline changes.
- **Marine Resource Management:** Bathymetric data are integral to marine spatial planning and integrated resource management, supporting sustainable use of coastal and marine ecosystems.
- **Assessing Morphological Impacts:** These surveys enable the evaluation of morphological changes caused by extreme weather events, such as storms and hurricanes, providing insights into coastal resilience (Santos *et al.*, 2015).

Locations such as those of the selected study cases (*i.e.*, Furadouro beach and Douro estuary) can benefit from implementing frequent bathymetric monitoring, considering that these measurements may provide high-temporal

resolution datasets that can detect rapid coastal changes (*e.g.* after a large storm) and improve coastal management measures.

At Furadouro beach, which is especially susceptible to coastal erosion, shoreline retreat and overtopping, monthly bathymetric monitoring can facilitate the observation of short-term sediment fluctuations, identify areas that are subject to intense erosion, and assess the success of coastal defence measures at a low price. In addition, the ongoing acquisition of data also makes it possible to set up early warning systems, hence allowing preventive measures to mitigate impacts of extreme weather events to be implemented.

Along the Douro estuary, where the sediment dynamics control water depth (and hence the security conditions) along the Douro navigational channel as well as the sandspit stability, systematic acquisition of bathymetric data can provide valuable information on tidal sediment conveyance, deposition trends, and changes in morphological features of Douro River. In addition, ongoing acquisition of bathymetric data can help tracking underwater changes in the positioning of the sandspit that naturally protects the coastal area and the existing natural reserve from wave and tidal forcing and flooding.

By overcoming the typical temporal issues of bathymetric data acquired with an annual frequency (or even less), the satellite-derived bathymetry may be a cost-saving and effective mean of continuously monitoring dynamic coastal areas, as in the aforementioned case studies. This thesis will attempt to evaluate the feasibility of applying the S2Shores tool for such purposes on the Portuguese coast.

2.7. SUMMARY AND KNOWLEDGE GAPS

Coastal morphodynamics refers to the dynamic processes that shape and alter the morphology of coastal environments over time. These processes are driven by a variety of factors, including tidal forces, wave action, storm events, and human activities such as dredging and construction. The assessment of coastal morphodynamics is critical for understanding shoreline changes, sediment transport, and the long-term sustainability of coastal ecosystems. Among the many tools used to assess these changes, bathymetry plays a fundamental role. Bathymetric surveys provide essential data on underwater topography, allowing for the accurate mapping of seafloor features and the evaluation of coastal processes that shape the morphology of coastal regions.

Traditional methods for measuring bathymetry often involve using acoustic techniques, such as single-beam or multibeam echo sounders (Ferreira *et al.*, 2022; Jawak *et al.*, 2015). These systems are typically mounted on ships and measure the time it takes for sound waves to travel to the seafloor and back (Li *et al.*, 2023). Acoustic methods are capable of generating accurate point measurements or depth profiles (Jawak *et al.*, 2015). They are considered the most widely used technique for depth measurement and can be coupled with Global Navigation Satellite Systems (GNSS) and other sensors to improve data accuracy (Ferreira *et al.*, 2022). However, traditional acoustic surveys are constrained by inefficiency, high logistical costs, and inaccessibility, particularly in shallow waters and remote areas (Jawak *et al.*, 2015). They are also time-consuming and can be dangerous to operate in shallow-water areas (He *et al.*, 2024). Furthermore, these methods often struggle in nearshore waters due to environmental conditions and technical limitations (Jawak *et al.*, 2015). Traditional surveys can be limited in coverage, with many areas, especially in coastal regions, remaining unsurveyed or having outdated bathymetric information (Cesbron *et al.*, 2021). Hydrographic services often survey a small percentage of their continental shelf each year, meaning surveys are repeated over many years (Almar *et al.*, 2024).

Satellite-Derived Bathymetry (SDB) offers a valuable alternative to traditional methods, providing a more cost-effective and efficient means of mapping bathymetry over large and remote areas (Kras *et al.*, 2023; Viaña-Borja *et al.*, 2025). SDB uses remote sensing technologies to estimate water depths from satellite imagery (Jawak *et al.*, 2015), its techniques can be broadly categorised into active and passive methods. Passive methods use sensors that measure reflected sunlight, while active methods use sensors that emit radiation, such as LiDAR (IHO B-13, 2024).

S2Shores is a relatively new approach of SDB that estimates bathymetry from wave kinematics derived from satellite optical imagery (Bergsma *et al.*, 2023; Daly *et al.*, 2022). It uses the small-time delay between different color bands of Sentinel-2 imagery to approximate wave properties and then calculates depth using wave linear dispersion theory (Almar *et al.*, 2024). This approach can be used in turbid waters and relatively deep waters and is an important complement to traditional optical bathymetric methods (Bergsma *et al.*, 2023; Daly *et al.*, 2022). S2Shores is a python library that detects and extracts local wave parameters (geometry and kinematics) to derive coastal bathymetry (Bergsma *et al.*, 2023).

While SDB methods, such as S2Shores, do not yet achieve the same resolution and accuracy as traditional *in-situ* hydrographic surveys, their ability to provide frequent updates on coastal bathymetry presents a significant advantage for the continuous monitoring of dynamic coastal environments. The ongoing development and application of the S2Shores methodology are expanding the potential for coastal monitoring and research, particularly in areas where conventional surveys may be logistically challenging or cost prohibitive.

This dissertation explores the application of the S2Shores method in a more localized coastal setting, focusing on nearshore areas with depths of less than 20 meters. Unlike previous studies that have primarily analysed large-scale regions, this research aims to assess the feasibility of obtaining bathymetric data at a 10-meter resolution in smaller, targeted areas closer to the shoreline. The derived bathymetric data will be systematically compared with reference datasets obtained from traditional hydrographic surveys to evaluate its accuracy and reliability.

If validated, the integration of SDB-derived bathymetric data will enable the practical implementation of its key advantage—high-frequency monitoring. In this case, monthly bathymetric updates will complement the existing annual COSMO surveys, enhancing the temporal resolution of coastal bathymetric assessments and supporting improved management of nearshore morphological changes.

3

METHODOLOGY

3.1 OVERVIEW

The aim of this dissertation is to assess the feasibility of analysing coastal morphodynamics through bathymetry surveys in a monthly frequency (or less) in two different coastal sites from the Portuguese coast. These monthly assessments can be achieved combining traditional surveys with bathymetry generated from satellite images using an algorithm based in wave kinematics.

The satellite images utilized in this study stem from the European Space Agency's (ESA) Sentinel-2 satellite, an openly accessible data source with a revisit time of at least five days, yielding approximately six images per month for any given location, with records available since June 2015. The bathymetric data are extracted from these images using the S2Shores algorithm, developed within the framework of a collaboration between CNES (Centre National d'Études Spatiales), IRD-LEGOS (Institut de Recherche pour le Développement - Laboratoire d'Études en Géophysique et Océanographie Spatiales), and Shom (Service Hydrographique et Océanographique de la Marine). Table 2 presents the key specifications for the Satellite Sentinel-2.

Table 2 - Satellite Sentinel-2 key specifications (IHO B-13, 2024).

Satellite name	Satellite owner	Spatial Resolution	Multispectral resolution	Temporal resolution	Bit depth	Recording period	Geo. location accuracy
Sentinel 2	European Space Agency	10m/20m/60m	Coastal: 433-453 nm Blue: 458-523 nm Green: 543-578 nm Red: 650-680 nm Red-Edge 1: 698-713 nm Red-Edge 2: 733-748 nm NIR: 785-900 nm NIRn: 855-875 nm Water Vapor: 935-955 nm Cirrus: 1360-1390 nm SWIR1: 1565-1655 nm SWIR2: 2100-2280 nm	3-5 days	12 bit	23 June 2015-ongoing	10m RMSE

The Sentinel-2 mission (ESA) carries the Multi-Spectral Instrument (MSI), which captures surface reflectance data with a 1.005-second interval between its 10-meter resolution bands. The Satellite to Shores (S2Shores) method exploits this time difference between the blue (Band 2) and red (Band 4) bands to track surface wave

movement. Using a localized Radon Transform combined with a Discrete Fast Fourier Transform (DFT), the algorithm determines wave direction, wavelength, and celerity, allowing for water depth estimation through the linear wave dispersion relationship (Daly *et al.*, 2022).

The initial phase of this research work involves validating the bathymetric data generated by the S2Shores tool against *in-situ* bathymetric surveys conducted in the scope of COSMO project. The COSMO surveys employ both multibeam and single beam echosounders, complemented by topographic data obtained through aerial photogrammetry using UAVs combined with GNSS/RTK. The integration of these datasets results in a freely accessible Digital Elevation Model (DEM), providing a 30 cm high-resolution coastal topography and bathymetry (Pinto *et al.*, 2021).

The two locations selected to work as case studies were: Cabedelo do Douro sandspit and Furadouro beach. At these sites, DEMs of the coastline are available for three different dates between 2018 and 2020, with surveys conducted at approximately 11-month intervals, Table 3.

Table 3 - Date of survey.

Case study	COSMO time of survey		
Cabedelo Sandspit	2018/09	2019/08	2020/07
Furadouro beach	2018/09	2019/07	2020/07

The selection of the satellite images is done according to the cloud cover percentage (0%) in the areas of study and their prominent wave patterns (long swell) to facilitate the S2Shores run.

Following the selection of satellite images, the next step involves processing them using the S2Shores algorithm to derive the bathymetric data. For this process, a few specific configuration adjustments are needed within the S2Shores framework to produce stable and smooth depth estimates, Figure 17.

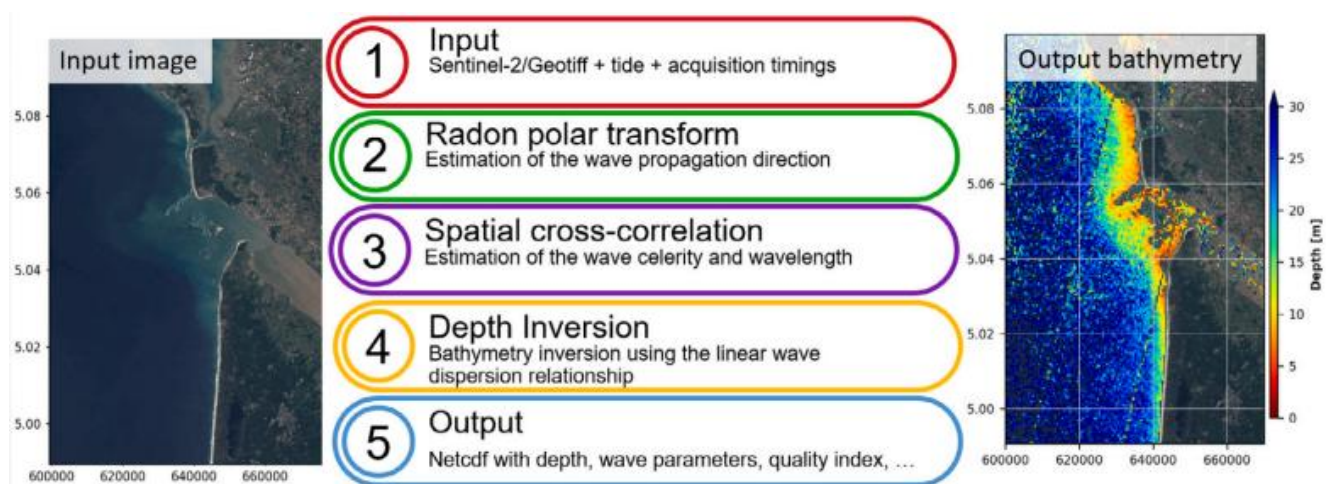


Figure 17 - S2Shores schematic framework, illustrating the process from initial satellite imagery to the final derived bathymetry (Almar *et al.*, 2024).

Once the bathymetric output is generated, a vertical correction is applied based on tidal conditions. Subsequently, depth profiles obtained from the satellite-derived bathymetry are compared with those available from the COSMO surveys. If the comparison yields similar depth values, the validity of the SDB methodology can be established, Figure 18.

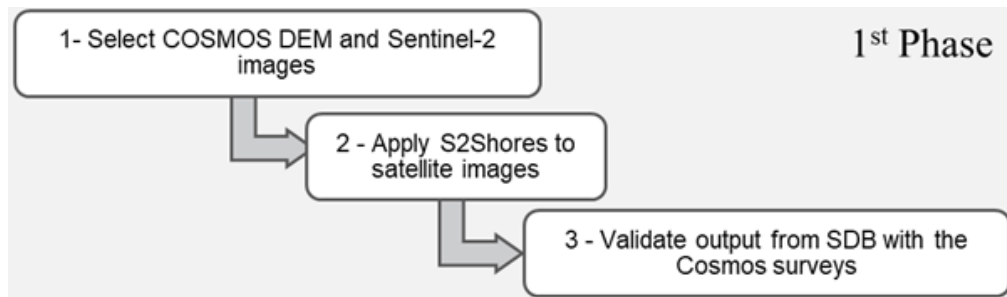


Figure 18 - Methodology of the 1st phase regarding the S2shores output validation.

Upon confirming the reliability of the S2Shores-derived bathymetry from Sentinel-2 images, the study proceeds to its second phase. This phase involves applying the algorithm to a series of monthly images acquired throughout the two-year period. The goal is to analyse coastal morphodynamics by leveraging the chronological history of bathymetric variations, thus providing valuable insights into sediment dynamics and shoreline evolution over time, Figure 19.

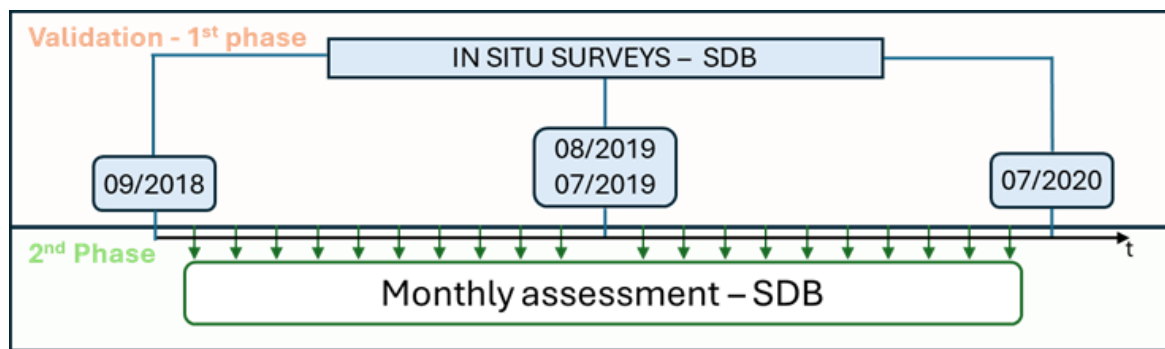


Figure 19 - Schematic representation of the overall methodology.

3.1 PRE-SELECTION OF IMAGES

The applied methodology starts with the selection of the satellite images to be used in the analysis based on the following criteria:

- Captured during the same month as close as possible to the date of COSMO bathymetric survey to ensure temporal consistency.
- A 0% cloud cover over the study area.
- Presence of visible swell patterns, allowing for effective wave-based bathymetric analysis.

Each selected image corresponds to the T29TNF tile ($109.8 \times 109.8 \text{ km}^2$), encompassing both study sites, and are accessible via the GEODES Portal maintained by CNES. Table 4 presents the satellite images files pre-selected according to location and date, as well as the criteria previously mentioned.

Table 4 - Satellite images files pre-selected according to location and date.

Furadouro Beach	2020/07	SENTINEL2B_20200706-113958-404_L2A_T29TNF_D
		SENTINEL2A_20200711-114000-536_L2A_T29TNF_D
		SENTINEL2B_20200716-113957-527_L2A_T29TNF_D
		SENTINEL2A_20200731-114002-138_L2A_T29TNF_D_V2-2
	2019/07	SENTINEL2X_20190715-000000-000_L3A_T29TNF_D_V2-1
		SENTINEL2A_20190717-114001-515_L2A_T29TNF_C_V2-2
		SENTINEL2B_20190729-113008-377_L2A_T29TNF_C_V2-2
	2018/09	SENTINEL2B_20180902-112716-061_L2A_T29TNF_D_V1-8
		SENTINEL2B_20180925-113312-456_L2A_T29TNF_D_V1-9
Douro Estuary	2020/07	SENTINEL2B_20200703-113002-478_L2A_T29TNF_D_V2-2
		SENTINEL2A_20200711-114000-536_L2A_T29TNF_D
		SENTINEL2B_20200716-113957-527_L2A_T29TNF_D
		SENTINEL2A_20200731-114002-138_L2A_T29TNF_D_V2-2
	2019/08	SENTINEL2X_20190815-000000-000_L3A_T29TNF_D_V2-0
		SENTINEL2A_20190816-113959-429_L2A_T29TNF_C_V2-2
		SENTINEL2B_20190821-114001-722_L2A_T29TNF_C_V2-2
		SENTINEL2A_20190826-113957-891_L2A_T29TNF_C_V2-2
	2018/09	SENTINEL2B_20180902-112716-061_L2A_T29TNF_D_V1-8
		SENTINEL2B_20180925-113312-456_L2A_T29TNF_D_V1-9

Using QGIS software, Bands 2 (blue) and 4 (red) with a 1.005-second time lapse are overlaid, allowing for the tracking of surface wave movement. For instance, satellite images of the Douro estuary from two different dates in July 2020 exhibit distinct wave patterns, as clearly illustrated in Figure 20.

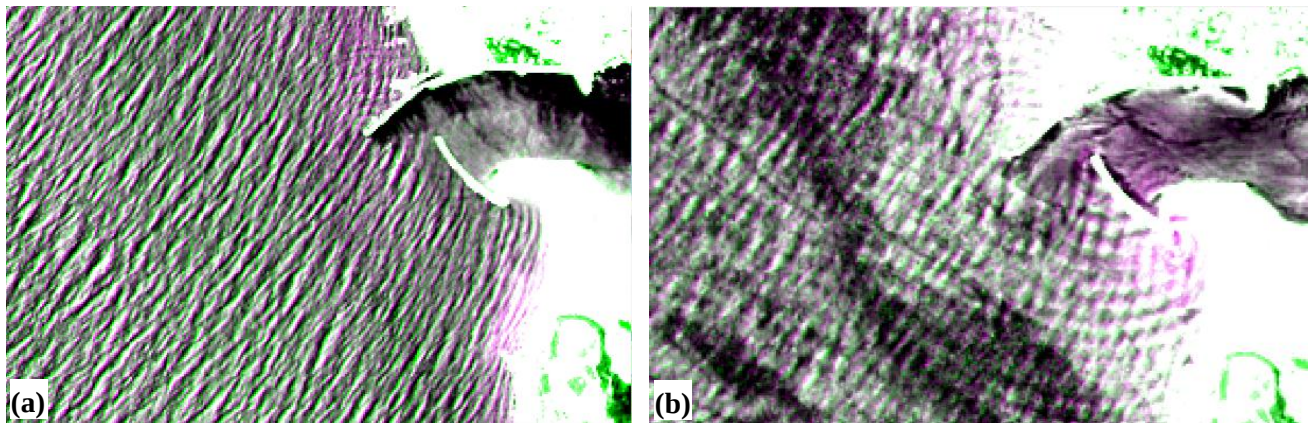


Figure 20 - Douro estuary b2 and b4 overlapped: (a) 2020/07/03; (b) 2020/07/31.

In order to determine which image yields the most accurate and stable results, a first processing phase shall apply S2Shores algorithm on a coarser scale of 100 m for Furadouro beach and 50 m for the Douro estuary, as the case area on Furadouro is larger. This strategy allows to save (important) computational time at this phase. Following this pre-selection process, the most suitable images will be reprocessed at a higher (10 m) resolution to enhance bathymetric detail and accuracy in the areas of interest.

3.2 S2SHORES CONFIGURATION

The S2Shores tool for estimating coastal bathymetry is subject to several physical and methodological constraints that impact its accuracy and applicability. These constraints are primarily related to the image resolution, wave characteristics, and environmental conditions. However, in this study, the focus is specifically on the physical constraints associated with wave characteristics.

To account for wave linearity, S2Shores applies restrictions based on the parameter:

$$\gamma = \frac{c^2 k}{g} \quad (3)$$

where c is the wave celerity, k the wavenumber, and g gravitational acceleration.

This constraint is used to identify suitable waves for depth estimation, ensuring that selected waves correspond to the appropriate depth zones. The algorithm restricts allowable γ values to manage the transition from deep to intermediate and intermediate to shallow water conditions. As $\gamma \rightarrow 1$, the wave approaches the deep-water limit, while $\gamma \rightarrow 0$ corresponds to waves reaching the coastline (Bergsma *et al.*, 2021).

S2Shores is configured to analyse wavenumbers associated with offshore wave periods (T) ranging from 3 to 25 s. This range ensures that the algorithm operates within conditions where wave patterns can be reliably detected by Sentinel-2 imagery and where the linear dispersion relation remains valid for accurate depth estimations. These limits are influenced by the satellite's spatial resolution, the algorithm's processing framework, and the physical properties of wave propagation in coastal environments (Almar *et al.*, 2024).

For this study, linearity constraint between 0.2 and 0.8 and a wave period range of 3 to 25 s were applied. These settings are intended to ensure that the S2Shores tool selects appropriate waves for bathymetric estimation while maintaining accuracy in shallow-water zones.

3.3 POST-PROCESSING: VERTICAL CORRECTION

Accurate vertical referencing is essential when comparing satellite-derived bathymetry (SDB) with *in-situ* measurements, as different methods use distinct reference levels.

The COSMO surveys use the chart datum as their vertical reference, which is positioned 2 m below the mean sea level (MSL) (COSMO, 2018)⁵. In contrast, the S2Shores algorithm, once water depths are derived, the bathymetry has no vertical reference: i.e., it just represents the water depth calculated at that instance. To ensure consistency between the two datasets, the tidal elevation at the time of satellite image acquisition must be accounted for the analysis.

To align S2Shores-derived depths with COSMOS bathymetric surveys, the 2-meter offset relative to MSL must be subtracted. Additionally, the tidal elevation at the moment of satellite observation should be either added or subtracted, depending on whether the tide was above or below MSL. This correction ensures a standardized reference framework, allowing for the bathymetric comparison and analysis.

This dissertation considers the astronomical tidal elevation extracted for each date and location provided by the open-source program Delft Dashboard (DDB), part of the OpenEarth initiative (Ormond et al., 2020). Point locations centred nearshore were chosen for both case studies. The program delivers the tidal elevation with a 30-minute interval.

⁵ https://cosmo.apambiente.pt/download_pdf/5 accessed in 10/01/2025

4

CHARACTERIZATION OF CASE STUDY

4.1. INTRODUCTION

This thesis aims to assess the evolution of the coastal morphology of two distinct locations: Furadouro beach and Douro's sandspit (Figure 21). These two different sites represent the diverse geomorphological characteristics of Portugal's coastline. The Furadouro beach is a typical sandy beach with low elevations, making it particularly vulnerable to coastal erosion and flooding. In contrast, Douro's sandspit is a sand deposit formation located at the estuary of Douro River, showcasing the dynamic interaction between fluvial and marine processes. The comparative analysis of these areas provides valuable insights into the challenges and management strategies required for distinct coastal environments.



Figure 21 - Case studies: (a) Douro sandspit; (b) Furadouro's coast (Google Earth 2025).

The **Furadouro** beach belongs to the long 13 km sandy shore of Esmoriz-Cortegaça-Furadouro (NW of Portugal), known for its alarming increase in erosion rates and for its many defensive maritime works, involving in total 8 revetments and 6 groins. Furadouro is especially a critical region having already registered 3 emergency situations, from 1998 to 2015 (Veloso Gomes, 2023).

Furadouro has been the subject of extensive research due to its high vulnerability and risk (Pinto, 2022). Problems in the area have been recorded since 1857, when the first records of the sea's advancement appeared (Bastos et al., 2015). With natural and human-induced variables coupled with increasing implications of climate change, Furadouro presents a focal point that really puts the area under study as one of Portugal's most risk-prone coastal zones (Lima et al., 2021).

The sandy shoreline represents one of the most significant examples of real-world scenarios related to littoral management. The problems of Furadouro can be understood as an essential source to increase knowledge for urban adaptation due to overtopping and coastal flooding. It characterizes all the problems of littoral management concerning the degree of exposure to hazards. Furadouro presents chronic erosion and retreat of the coastline that has been occurring since the middle of the 19th century (Freitas et al., 2015). This effect motivated research into efficient management actions capable of reducing such losses. The urban front of Furadouro is located next to the coastline and, consequently, presents high exposure to hazards. Accidents caused by overtopping and flooding have led to damage to the infrastructures and consequently to residents and economic activities. These negative impacts frequent in the winter season encourage studies that seek an understanding of the processes and measure their consequences. Besides, climate change exacerbates the challenges in Furadouro. Rising sea levels and increased frequency/intensity of extreme events can aggravate situations in the future, making it an object of special interest to vulnerability and risk analyses. Such factors combined with the existence of historical records make Furadouro an excellent site for studying the processes of a coast and its morphological evolution.

In recent years, the town of Furadouro has experienced several overtopping events during the winter season. The frequency and magnitude of these events depends on the robustness of the beach. Therefore, coastal management assessments could be significantly enhanced through bathymetric surveys conducted before and after storm surge events, effortlessly utilizing data derived from satellite imagery.

The **Douro estuary** is a critical natural system at NW Portugal, characterized by a dynamic sandspit acting as a natural barrier against storm impacts and controlling hydrodynamic processes at the estuary mouth. This sandbank is a touristic beach named “Cabedelo do Douro” (it can be simply referenced to as “Cabedelo”). The system is naturally influenced by the river discharges, waves, and wind action, as well as human activities, which include the breakwaters and the dam constructions upstream the river.

The shape and position of the sandspit affects the width and the depth of the adjacent Douro navigation channel. Therefore, it was decided to build two breakwaters to stabilise the estuary's banks, especially at the sandspit and the estuary inlet, improving the navigability and navigation safety under any tide conditions.

Studying the Douro estuary is crucial from a coastal defence perspective, with extreme meteorological events, ecological and economic relevance. Sandspits are very dynamic, continually changing their position and shape, migrating in response to eustatic fluctuations and revealing short term changes related to meteorological events and long-term changes due to events that take place at larger temporal scales. The shape of a spit is influenced by the space available for its growth, the formation of recurves and by the adjacent sea bottom topography, as well as the source proximity, amount available and material type.

Therefore, the bathymetric and topographic analysis of the nearshore provides a supporting interpretation of the morphological changes, erosive/accretive trends, and responses to natural and engineered changes within the estuary, such as the construction of breakwaters. Hence, short-term data collection is beneficial to the long-term analysis for a better understanding of the morphological changes of the sandspit.

This chapter provides a comprehensive description of the coastal morphodynamics drivers of Furadouro beach (4.2) and Douro estuary's sandspit (4.3), each case study examined separately.

The geological and anthropogenic features of each location are highlighted in the chapter, such as the specific formations and attributes, providing insights into the sites geological structure and the human activities that have defined the landscape. The maritime forces that influence the coast are also explored, including wave dynamics, tidal activity, and sediment transport. These natural processes are crucial in understanding the behaviour of the coastline and its response to external pressures and its impacts on the evolution of the shoreline. This integrated approach provides a clear understanding of the physical and human influences shaping each case study area.

4.2. FURADOURO BEACH

4.2.1 INTRODUCTION

The Furadouro beach belongs to the municipality of Ovar in the northwest coast of Portugal and faces significant challenges, mostly linked to coastal erosion due to its exposure to the North Atlantic Ocean. This touristic beach is geographically located in the Aveiro region, belongs to the watershed of river Vouga and can be divided in three zones (Figure 22): being zone 1 and 2 classified as beach type I (beach surrounded by a consolidated urban core and subjected to a strong demand), and zone 3 usually described as “Furadouro Sul” and classified as type V (beach with restricted use) (APA⁶).



Figure 22 - Furadouro Beach (Google Earth, 2025)

The Furadouro beach north, Zone 1 (Figure 22), is part of an 8-kilometer reach of sandy shoreline bounded on the north by a groin at the southern end of Cortegaça beach.

Zones 1 and 2 are directly adjacent to the urban area of Furadouro. For example, residential blocks in Zone 1 are about 20 to 25 m seaward of the beach. The main road running parallel to the beach, the Avenida do Infante Dom Henrique, in the most eroded area, is only separated from the sea by a revetment constructed between groins in zone 2, Figure 23.

6

https://apambiente.pt/sites/default/files/SNIAMB_A_APA/Comunicacao/Epoca_balnear/PerfisAB/ARH_Centro/PerfisAguasBalnearesBilingues/OVAR/Furadouro_PTCU9X.pdf accessed in 03/01/2025



Figure 23 - Zone 2 of Furadouro Beach in Figure 22 – Revetment. (Photo by Piqueiro, 2015)

Zone 3 of the beach corresponds to the southern area, located circa 400 m from the urban area of Furadouro south with wooden pedestrian accesses and raised walkways.

The study carried out in the dissertation focuses on the analysis of bathymetric surveys conducted by COSMO, complemented by comparisons with satellite imagery data, thus confining the main study area within the limits of the land and navigational bathymetric surveys that were undertaken. This area includes the shoreline of zone 1 and 2 (Figure 22), reaching southward to the southernmost revetment and reaching up to 1 nautical mile offshore as its show in Figure 24.

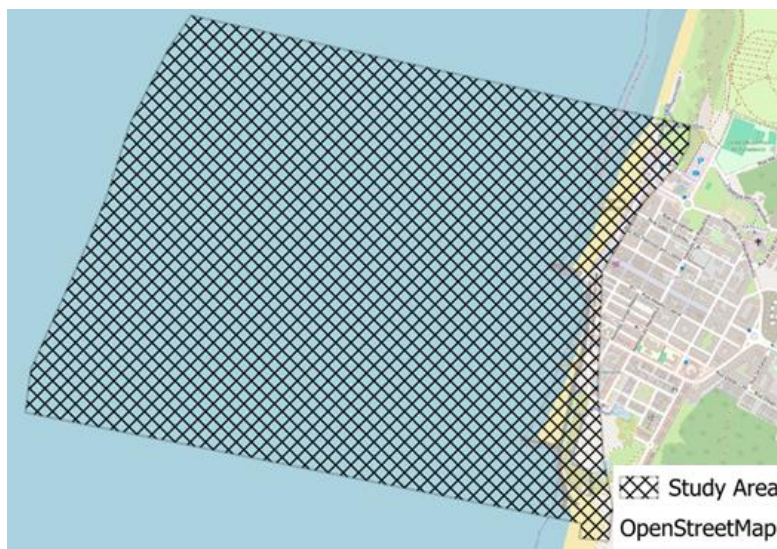


Figure 24 - Bathymetry study area.

4.2.2 COASTAL DEFENCE WORKS

Furadouro beach is one of the beaches in Portugal that suffers the most from erosion problems. Furthermore, the frequent overtopping events in the marginal zone are responsible for the destruction of walls and infrastructures (Marques, 2021). To overcome this problem, many coastal protection structures were built (and rebuilt) along the years. There are two groins, and three longitudinal sea defences located to the north and south of the groins and between them, respectively as it is shown in Figure 25.



Figure 25 - Coastal defence works at Furadouro Beach (Câmara Municipal de Ovar, 2012, adapted from (Marques, 2021)).

The construction of groins has been a primary measure in a broader set of coastal defences aimed at mitigating erosion and preserving the coastline. This subsection briefly examines their construction context at Furadouro, basing off the information available on Database #4⁷ and Database #5⁸ of the INCCA project, between the years of 1857 and 2020. It documents the history of these interventions and the damage events caused by maritime action in the area, as well as interventions works for the past 10 years and the more recent future planning projects.

Furadouro beach has been the target of several coastal defence interventions over the last few decades. Analysis of the sources reveals a clear correlation between the construction of coastal defence works, and the reduction of damage caused by extreme weather events in Furadouro beach. According to Database #4, the first major coastal

⁷ <https://drive.google.com/file/d/1I1StBOJazNGYs4VTWZCaub30nITerviW/view> accessed in 07/01/2025

⁸ <https://drive.google.com/file/d/1HzsnNqXHMX5S59GP72fXGAiwTfoysbF/view> accessed in 07/01/2025

defence works were implemented in the 1970s, with the construction of groins and longitudinal sea defences. These structures aim, mainly, to interrupt the coastal current and promote the accumulation of sediment. Database #5, on the other hand, shows that before the construction of these defence works, the beach was frequently affected by coastal erosion events, overtopping and damage to infrastructure. For example, in 1958, the destruction of 150 m of a terrace and a deep cut in Avenida Marginal as well as in 1969 the displacement of 15 families (57 people), demonstrated the area's vulnerability to maritime action. Following the implementation of coastal defence works, there has been a significant **reduction** in the frequency and intensity of **damage events** (Lima *et al.*, 2021).

Coastal erosion is an ongoing process and defence structures are subject to wear and damage over time. Lack of proper maintenance can compromise the effectiveness of these structures and increase the vulnerability of the coast to extreme weather events (Lima *et al.*, 2021).

In the past 10 years

Actions from the 2015 coastal management program (Programa da Orla Costeira Ovar - Marinha Grande, i.e., POC-OMG) have pointed to the following measures:

- Reinforcement of the dune system from the south of Furadouro to Torrão do Lameiro;
- Correction of the geometry of E5 and E6 groins at Furadouro.
- Rehabilitation and maintenance of the revetments DA8, DA9, DA10.
- Rehabilitation and maintenance of the groins E5 and E6.
- Artificial sand nourishment - north of E5 groin to E6.

The frontal dune has been heavily eroded in some stretches of the coast, with oceanic overtopping occurring. This program also emphasizes that studies should be conducted to include: “i) the constant evaluation and monitoring of the conservation status of coastal defense works, to identify the needs for rehabilitation or maintenance; ii) the constant evaluation of the size of the beach in areas subject to artificial nourishment (monitoring the evolution of the coastline); iii) the constant evaluation of the state of the dune systems, to identify the needs for reinforcement” (APA, POC-OMG, 2015)⁹.

This coastal intervention program encompassed several key actions aimed at mitigating erosion and enhancing shoreline stability:

- In 2015, two groins and an adherent longitudinal structure of approximately 800 m in length were “slightly rehabilitated” at Furadouro Beach (Afaplan, 2015)¹⁰.
- Between 2017 and 2019, dune restoration projects were completed both north and south of Furadouro Beach (APA, Plano de Ação Litoral XXI, 4º update, 2024)¹¹.
- From 2024 to 2027, plans are underway for the implementation of artificial sand nourishment between Esmoriz and Furadouro (APA, Plano de Ação Litoral XXI, 4º update, 2024).

More recently (December of 2024), the opening of a public tender for the ‘*Rehabilitation and Reinforcement of the Longitudinal Adherent Structure and Groins at Furadouro Beach*’ was announced. APA¹² pointed to a project of rehabilitation and reinforcement with the following characteristics:

- the southern groin (structure E6 in Figure 25) over a length of 120.0 m at a variable elevation between 5.87 and 7.84 m ZH;

⁹ https://www.cm-vagos.pt/uploads/writer_file/document/604/20151104150022825726.pdf accessed in 05/01/2025

¹⁰ <https://afaplan.com/projecto?id=32&lang=en> accessed in 07/01/2025

¹¹ https://apambiente.pt/sites/default/files/_Agua/DLPC/Acao_valorizacao/PAL-XXI_Actualizacao-20240607.pdf accessed in 05/01/2025

¹² <https://www.jornaln.pt/lancado-concurso-publico-para-a-empresada-de-reabilitacao-e-reforco-da-estrutura-longitudinal-adherente-e-dos-esporoes-na-praia-do-furadouro/> accessed in 05/01/2025

- the northern groin (structure E5 in Figure 25) over a length of 140.0 m at a variable elevation between 7.00 and 8.13 m ZH;
- the revetment in between groins (structure DA9 in Figure 25) over a length of 540 m;
- the revetment on the north of the northern groin (structure DA8 in Figure 25), which extends for 724.78 m.

4.2.3 GEOLOGICAL CHARACTERISTICS

The geology of Furadouro is essential to understand the vulnerability of the area to coastal erosion and flooding (Santos, 2016). The studied area presents some geological characteristics that influence those vulnerabilities:

- Lusitanian Basin: Furadouro stands on the northern flank of the Lusitanian Basin, which is a **Mesozoic sedimentary basin**, 200 km long in the NNW-SSE direction and 100 km in an E-W direction. This basin is roughly two-thirds exposed on mainland and one-third as a continental shelf beneath the sea. This basin has a maximum depth of about 5000 m and large-sized sedimentary deposits make up the substratum in this basin (Mesuras, 2018; Pereira et. al, 2014).
- Sandy Coastal Plain: The beach of Furadouro developed into homogeneous relief corresponding to a sandy coastal plain composed of **unconsolidated or poorly consolidated Cenozoic sediments** (Mesuras, 2018). This low-lying, sandy morphology makes the area highly susceptible to the energetic action of the sea as these **sediments** show very high **erodibility** and are easily mobilized by winds and waves (Araújo, 1999).
- The dominant surface geology of Furadouro is composed of **Quaternary sediments** (Figure 26), such as beach sands and gravels (present along the shoreline, these deposits are constantly reworked by wave action and currents), dune sands (transported by the action of wind, these sands constitute the dune systems, which are vital for coastal protection and sediment dynamics), and alluvial deposits (located mainly in the eastern parts of the study area, these deposits are associated with the nearby Aveiro Lagoon and its channels, characterised by fine sediments and the possible presence of kaolinitic clays) (Santos, 2016).

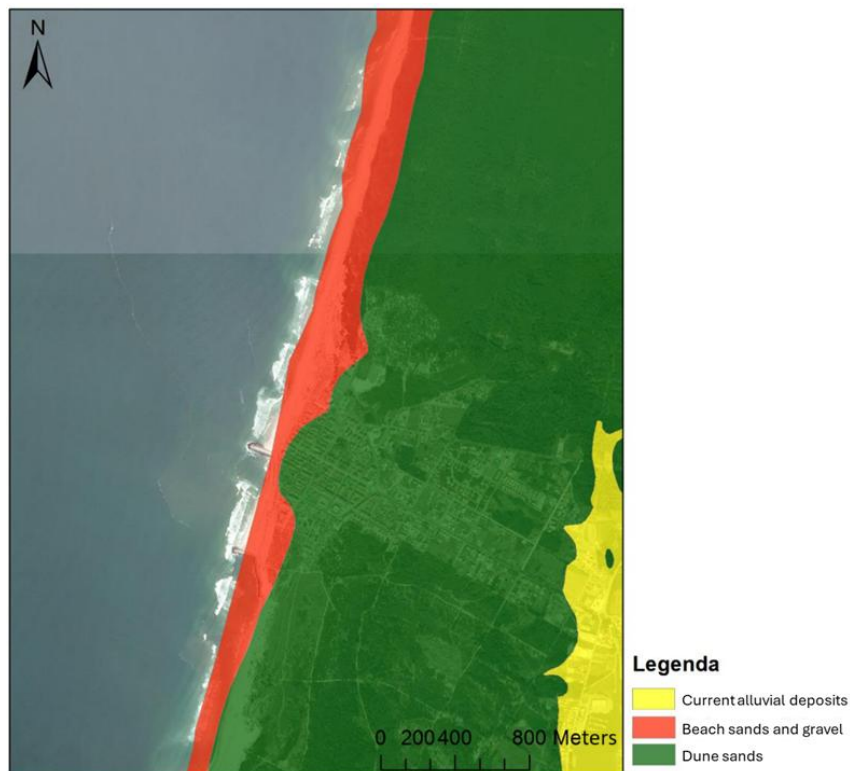


Figure 26 - Geologic map of Furadouro adapted from (Santos,2016).

4.2.4 DUNE SYSTEMS

Dune systems stabilize the active beach profile by limiting the landward extension of wave wash and play also a crucial role in protecting low-lying coastal areas. Dunes work as a barrier to wave energy and protect coasts from flooding, i.e., they are dynamic buffers that store and exchange sediment with the beach, supplying nutrients for vegetation and favouring stabilization processes in coastlines (Taveira-Pinto et al., 2011).

At Furadouro Beach, the dune system is an important natural coastal feature that provides protection against the sea. However, this critical system is getting increasingly fragile owing to the natural and anthropogenic pressures.

The beach has a few embryonic dunes (first line of defence against the sea), followed by the primary dune system (unstable and with some areas without vegetation), and a secondary dune system of greater size, and with more vegetation. The dunes in the northern part of Furadouro Beach are inserted in a high-erosion area. This results in a high level of sand removal and low accumulation, so the dunes in this location receive most of the supply from ancient dunes or through deposits destroyed by the sea (Santos, 2016).

Dune vegetation plays a vital role in holding up the sand. However, owing to human interference, the destruction of vegetation cover contributed to increasing the fragility of the dune system.

The reinforcement of the dune system aims the preservation of existing natural defences, maintaining sediment volumes available to be transported by maritime action during extreme events. In this way, the reinforcement of the dune system should be carried out whenever a weakness in the dune is identified, and it should be subject to frequent monitoring. Therefore, the last work of this nature was completed in 2018 in the south and north beach of Furadouro, where the reconstruction of the dune systems was done with the use of geotubes (Figure 27).



Figure 27 - Furadouro dune reconstruction in 2018 (OvarNews, 2018)¹³.

Analysing the dune systems at site (Figure 28 and Figure 29), it is possible to identify vegetation, pedestrians walking paths, sand fences and wooden walkways. The characteristics of this low-lying sandy coastal plain with unconsolidated sediments, underdeveloped dune systems, and negative sediment balance gives Furadouro beach its high vulnerability towards erosion, wave overtopping, flooding and shoreline retreat. From the geology point of view, it constitutes an important constraint to the problems of coastal management, and careful interventions are to be designed to avoid continuous risk and the destruction of the beach.

¹³ <https://www.ovarnews.pt/reconstituicao-dunar-do-furadouro-em-fase-de-conclusao/> accessed in 08/01/2025



Figure 28 - Dune's view north of Furadouro beach (Google Earth, 2025).



Figure 29 - Dune's view south of Furadouro beach (Google Earth, 2025).

4.2.5 WAVE CONDITIONS

For the characterization of the local wave dynamics at Furadouro coast, results from a high-resolution numerical model made with SWAN (Simulating WAVes Nearshore) spectral wave model are employed (Ramos *et al.*, 2022). This model was used to generate a 30-year dataset spanning from January 1, 1991, to December 31, 2020. The model output provides hourly wave parameters, including significant wave heights (H_s), wave periods, and wave direction, at a chosen reference point approximately 1.3 km offshore, as illustrated in Figure 30.

This dataset enables the characterization of the average wave climate at Furadouro beach by computing long-term statistics of wave height, period, and direction. The wave rose (Figure 31) derived from these decades of data confirms that the predominant wave direction at Furadouro Beach is northwest (NW)-oriented.

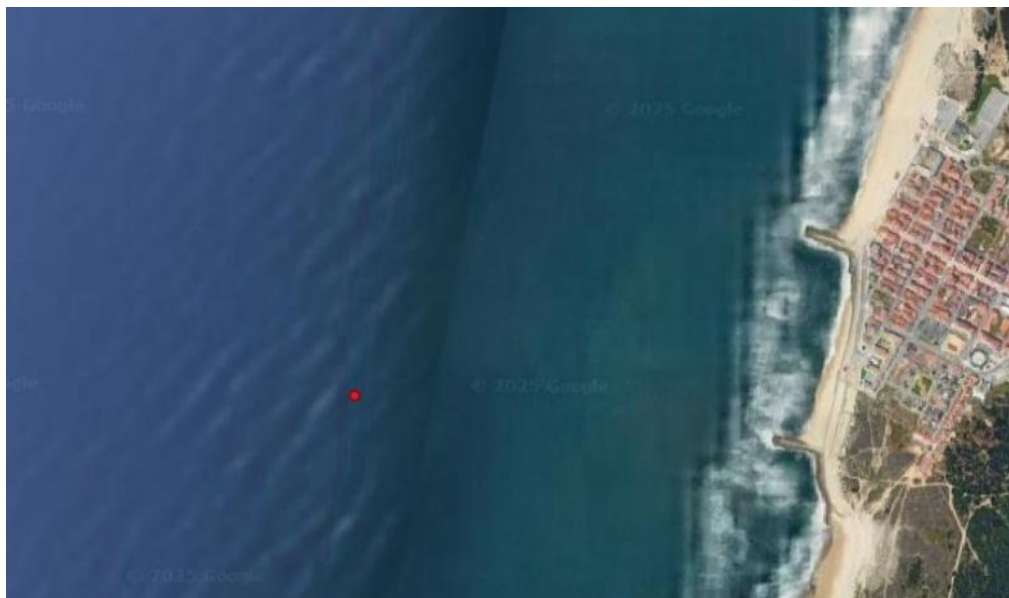


Figure 30 - Wave parameters were generated for the point (red).

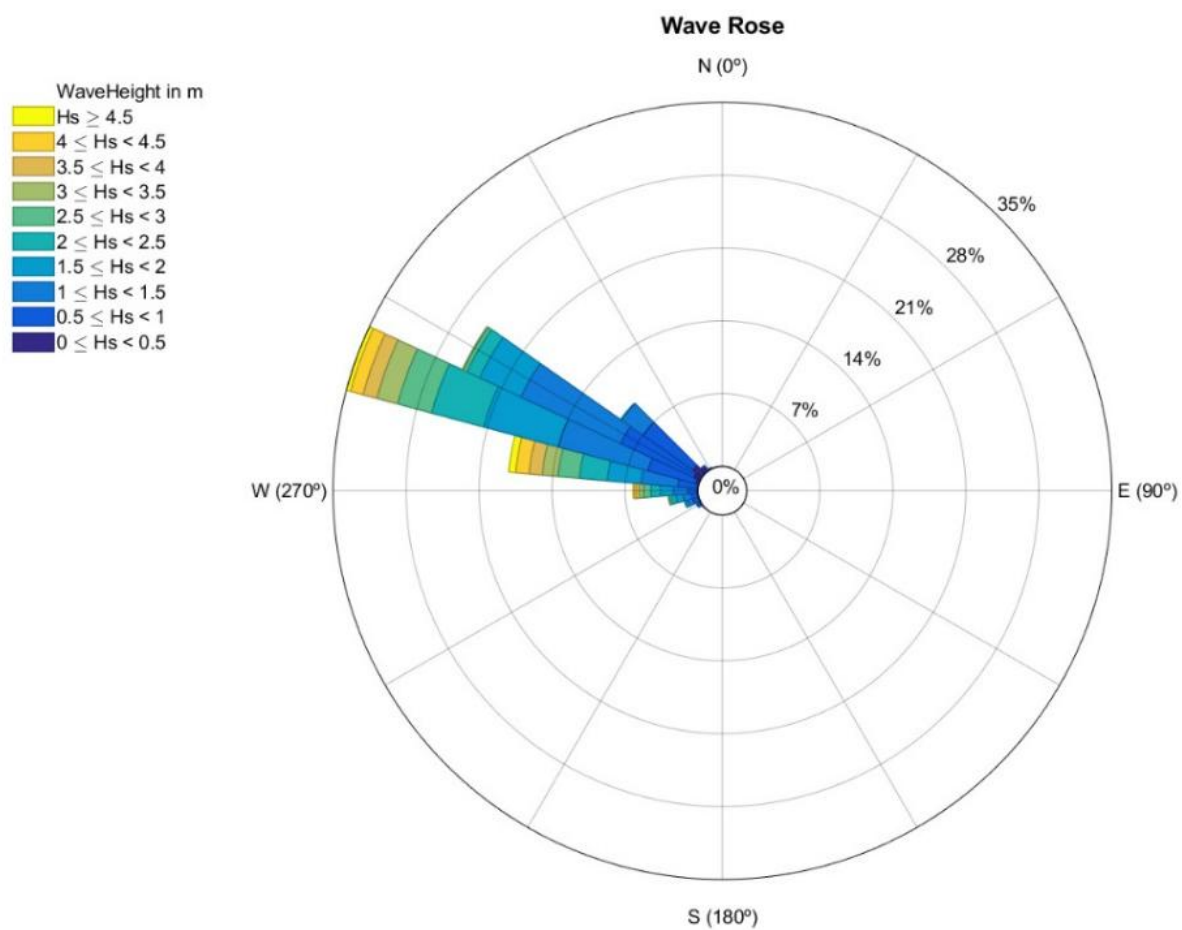


Figure 31 - Furadouro beach wave rose (data from 1991 to 2020).

For the analysis of local morphodynamics in time, it is interesting to include the parameter wave power, calculated according to:

$$P = \frac{\rho g^2}{64\pi} H_{mo}^2 T_e \quad (4)$$

Where P , is the wave power per unit width of wave crest, ρ , the seawater density, H_{mo} , the significant wave height and T_e represents the wave energy period defined as:

$$T_e = \frac{T_p}{1.15} \quad (5)$$

A historical analysis of wave conditions was conducted, as summarized in Table 5, where key parameters such as average wave power, significant wave height, wave period, and wave direction were computed. Additionally, the number of occurrences in which the significant wave height exceeded 4.5 m as quantified. In the classification of storm events, waves are typically considered storms when H_s exceeds 5 m in offshore regions. However, given that the study location is in a nearshore environment, a threshold of 4.5 m was adopted for this analysis.

Notably, the years 2013, 2014, 2018, and 2019 stand out as having the highest average wave power, along with the greatest number of occurrences where H_s exceeded 4.5 m. This suggests that these years experienced particularly energetic wave conditions, which may have influenced coastal morphological changes and sediment dynamics in the study area.

Table 5 - Average wave characteristics in Furadouro coast for the various periods.

Period	Power (kW/m)	H_{mo} (m)	T_P (s)	Dir (°)	$H_{mo} > 4.5m$
1991-2020	19.81	1.679	10.475	289.836	2995
2010	13.92	1.432	9.764	287.587	67
2011	18.52	1.613	11.006	291.009	90
2012	17.18	1.628	10.858	289.046	12
2013	26.80	1.894	11.090	289.042	421
2014	29.55	1.957	11.206	288.438	303
2015	21.35	1.771	11.185	289.305	38
2016	22.97	1.809	10.971	288.660	94
2017	18.38	1.621	10.908	289.989	73
2018	29.81	1.991	11.874	289.805	110
2019	25.61	1.885	11.254	289.778	113
2020	24.37	1.832	11.363	289.996	82

Focusing specifically on the time intervals between the bathymetric surveys—September 2018 to July 2019 and July 2019 to July 2020. The results presented in Table 6 indicate that the wave characteristics, including significant wave height, wave power, and dominant direction, remained relatively consistent across both periods. This suggests that any morphological changes observed in the surveyed profiles are likely attributed to other factors rather than significant variations in wave energy.

Table 6 - Average wave characteristics in Furadouro coast for the time period between surveys.

Period	Power (kW/m)	H_{mo} (m)	T_p (s)	Dir (°)	$H_{mo} > 4.5m$
01/09/18 – 31/07/19	25.98	1.891	11.703	289.224	74
01/07/19 – 31/07/20	24.43	1.838	11.125	290.059	69

An analysis of significant wave height and wave power for each survey period provides insights into how wave forcing may have influenced the observed morphological changes. Therefore it was designed the wave power (Figure 33 and Figure 35) and significant wave height graphs (Figure 32 and Figure 34) for each time period in between the surveys.

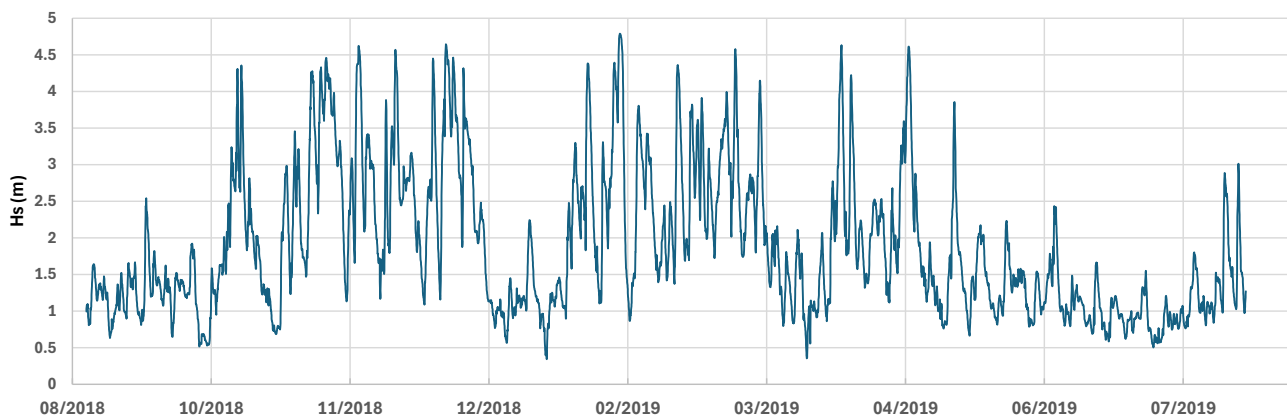


Figure 32 - Significant wave height for the period 09/2018 to 07/2019 – Furadouro coast.

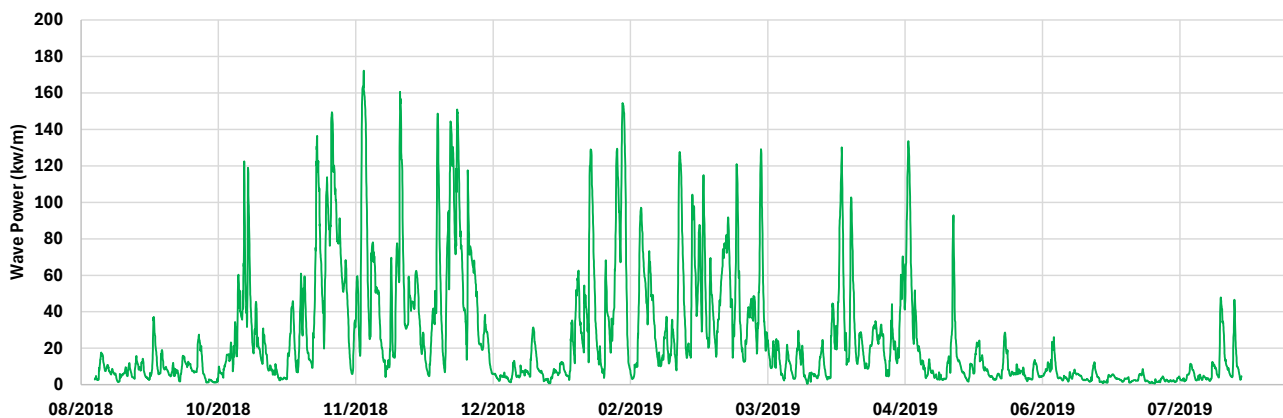


Figure 33 - Wave power for the period 09/2018 to 07/2019 – Furadouro coast.

During the September 2018 – July 2019 period, Furadouro Beach experienced wave power exceeding 120 kW/m and $H_s > 4.6$ m up until May 2019, approximately two months before the July 2019 survey.

In contrast, in the July 2019 – July 2020 period, the last significant high-energy event of comparable magnitude occurred in February 2020, nearly four months before the July 2020 survey.

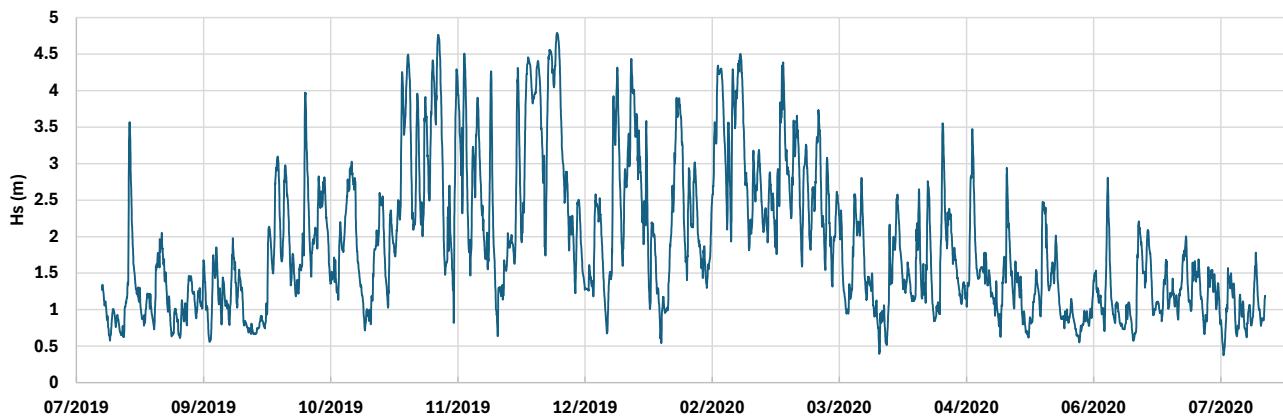


Figure 34 - Significant wave height for the period 07/2019 to 07/2020 – Furadouro coast.

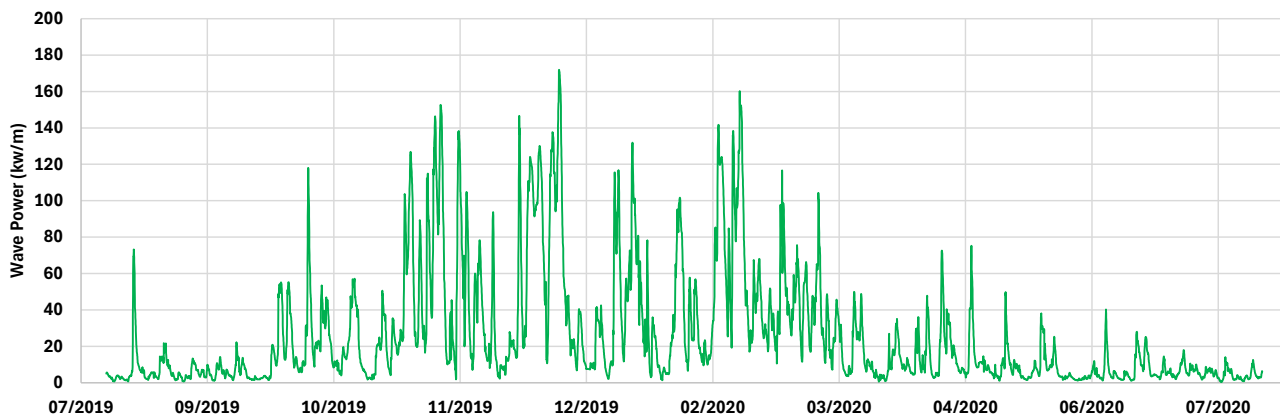


Figure 35 - Wave power for the period 07/2019 to 07/2020 – Furadouro coast.

4.2.7 COASTAL EROSION

The advancement of the sea and the narrowing of the beach at Furadouro have become increasingly visible (Figure 36), with the region's susceptibility to erosion well-documented since the second half of the 19th century (Freitas et al., 2015). The causes of coastal erosion in this sector stem from a combination of natural factors and the direct and indirect impacts of human activities.

The coastal area of Furadouro is subjected to significant pressure from natural factors, such as wave action, tidal forces, and longshore drift, which contribute to the continuous erosion of its sandy beaches. Sediment transport is predominant from north to south on the Atlantic coast, especially in northwest Portugal, with a high-energy swell at the west coast inducing a net potential littoral drift directed southward that can reach up to $10^6 \text{ m}^3 \text{ year}^{-1}$ (Lira et al., 2016). This process removes sediments from the beaches in northern areas, depositing them further south creating the typical sedimentary cycle. Generalized sea level rise and other effects of climate change disturb natural factors, increasing the vulnerability of Furadouro to storms that are more frequent and of higher intensity. Andrade (2007) projects that by the end of the 21st century, changes in wave climate along the western coast of Portugal may include a mean wave direction rotation of approximately 6° , which can impact sediment transport dynamics.

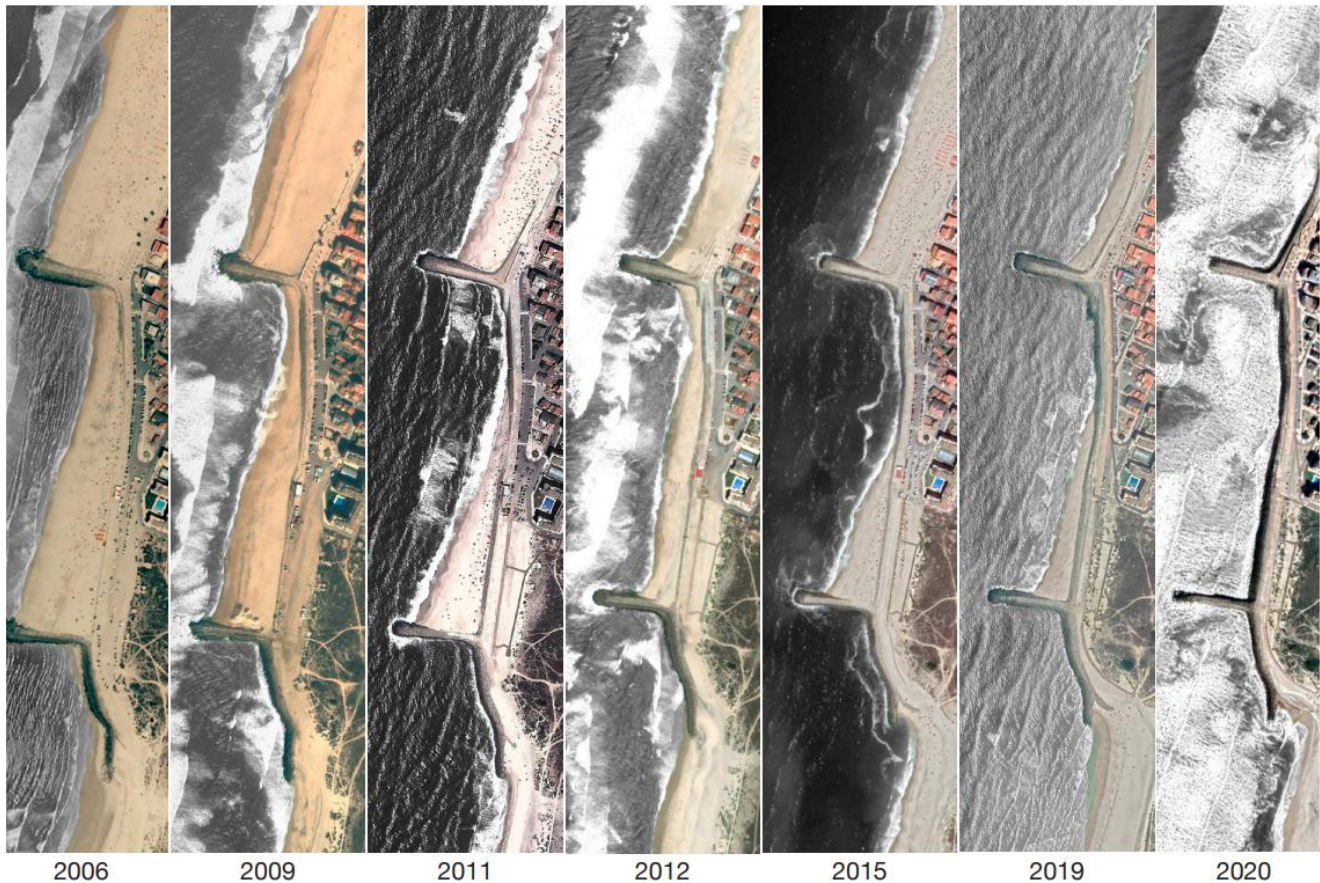


Figure 36 - Furadouro coastal morphology temporal evolution (Ferreira, 2023).

According to the EUROSION resolution nº 1, by European Commission in 2004, the sediment balance of each coastal sediment cell must be considered independently. Sediment cells are self-contained in terms of sediment transfers, meaning interventions within one cell affect only its internal sections and not adjacent cells (Lira et al., 2016).

The Furadouro case study is part of sub-cell 1b, which spans from the Douro River mouth to Figueira da Foz. Historically, the Douro River was the primary sediment source for this sub-cell. However, in the last two decades, coastal erosion has emerged as the dominant sediment source due to the reduced fluvial sediment supply from the Douro River (Santos et al., 2014), essentially due to dam construction. In the past, it would have been possible for Douro River to supply almost single-handedly the amount of sediment necessary to balance the situation (Coelho et al., 2009).

Figure 37 shows reduced sediment input associated with a very significant decrease in the solid flow of the Douro River (estimated to be a reduction from 9 to $2 \times 10^5 \text{ m}^3 \text{ year}^{-1}$), creating a sediment deficit that is compensated by strong erosion of the coastline south of Espinho (Santos et al., 2014).

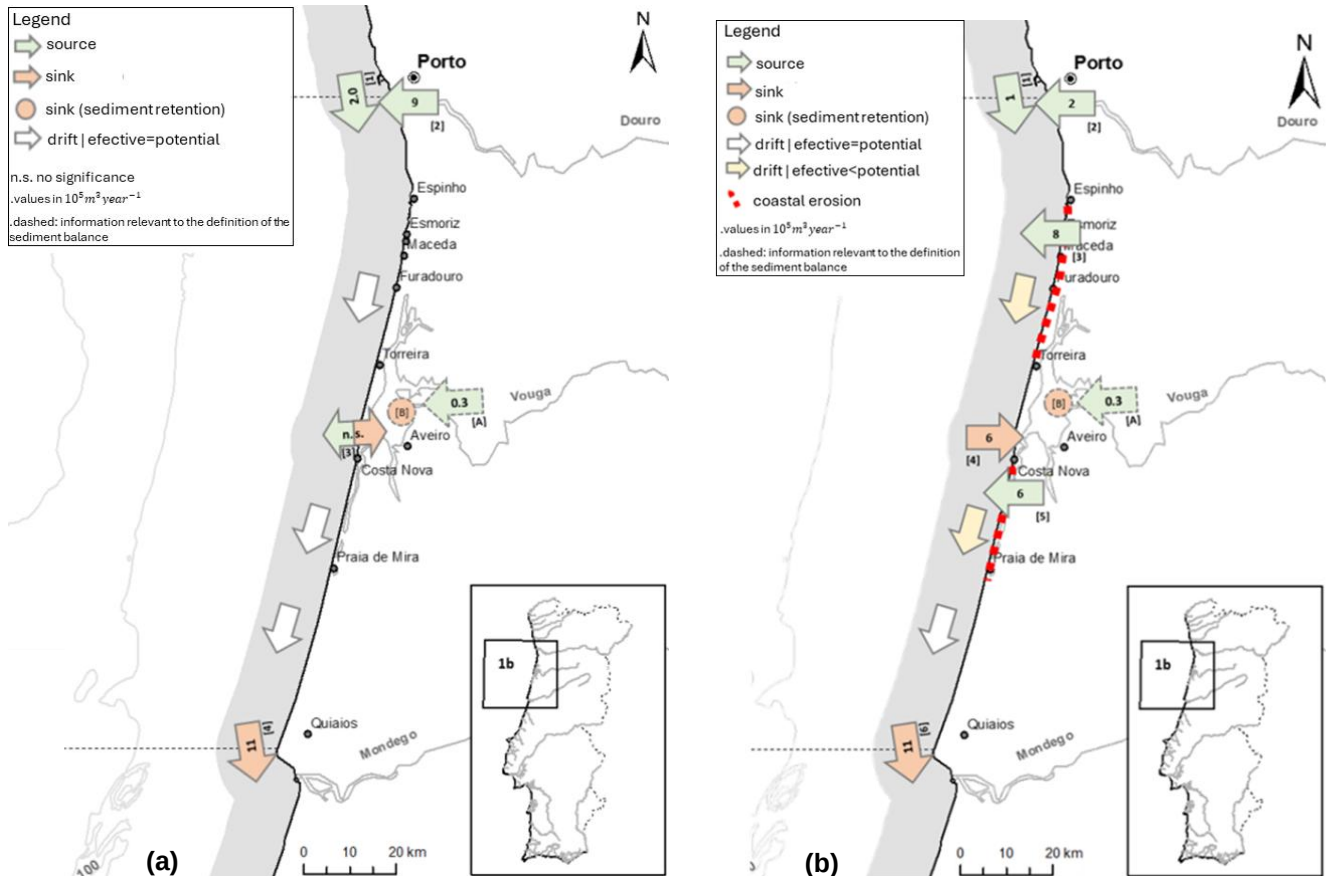


Figure 37 - Sediment balance and direction of littoral drift in sub-cell 1b: a) Reference situation; b) Current situation (adapted from Santos et al., (2014))

Human activities, both direct and indirect, have significantly disrupted the sedimentary balance, leading to the general shoreline retreat caused by:

- Reduction in sediment supply to the coast caused by the construction of dams along the Douro River and its tributaries, which restrict sediment transport downstream;
- Dredging of navigation channels, which removes sediment that would otherwise contribute to coastal sediment budgets;
- Sand extraction from riverbeds and beaches;
- Construction of major coastal engineering structures (Port of Leixões, Douro River jetties and Espinho groins) which disrupt natural sediment transport processes;
- Intensive occupation of the coastline, including urbanization and infrastructure development, which exacerbate erosion and reduce the system's ability to maintain sedimentary equilibrium.

In essence, a regular feed of sediments at the coast is essential for any beach to keep in a position of stability and conservation. The exact opposite has been happening on Furadouro Beach due to the high reduction in sediment input from the Douro River, supposedly, the main sediment supplier of this part of the coastline. Dam building and the regulation of rivers have drastically reduced this sediment transport to the coast, effectively "starving" Furadouro beach of natural replenishment, hence increasingly making it more susceptible to erosion.

Anthropogenic interventions, such as groins and seawalls, are designed to mitigate erosion and protect coastal areas. However, these structures can also profoundly change natural morphodynamic processes, often yielding unintended consequences. Along the urbanized coastline of Furadouro, the emplacement of groins and seawalls

has been effective in retaining sediment locally and combating erosion. However, these structures frequently disrupt the natural sediment flow, leading to imbalances that exacerbate erosion in adjacent, unprotected areas.

4.2.7 COASTLINE EVOLUTION

Given that the study area is a low-lying sandy coast, the assessment of coastline evolution relies on a single, reliable indicator: the foredune toe. This indicator, which remains largely unaffected by short-term morphodynamic variations, provides a robust basis for long-term analysis. The foredune toe is defined by a slope break or by the seaward extent of vegetation (in case slope break is not clearly recognizable) (Lira et al., 2016).

An important coastal erosion evaluation done by the European Commission (European Commission, 2004) under the EUROSION project framework, mapped the coastlines of 1958 and 2010, compared them and estimated the long-term linear change rates at a 250 m interval (Figure 38). Particularly on the coastal stretches of Espinho–Torreira, a maximum retreat of circa -5.6 m/year^{-1} was estimated (Pinto et al., 2020).

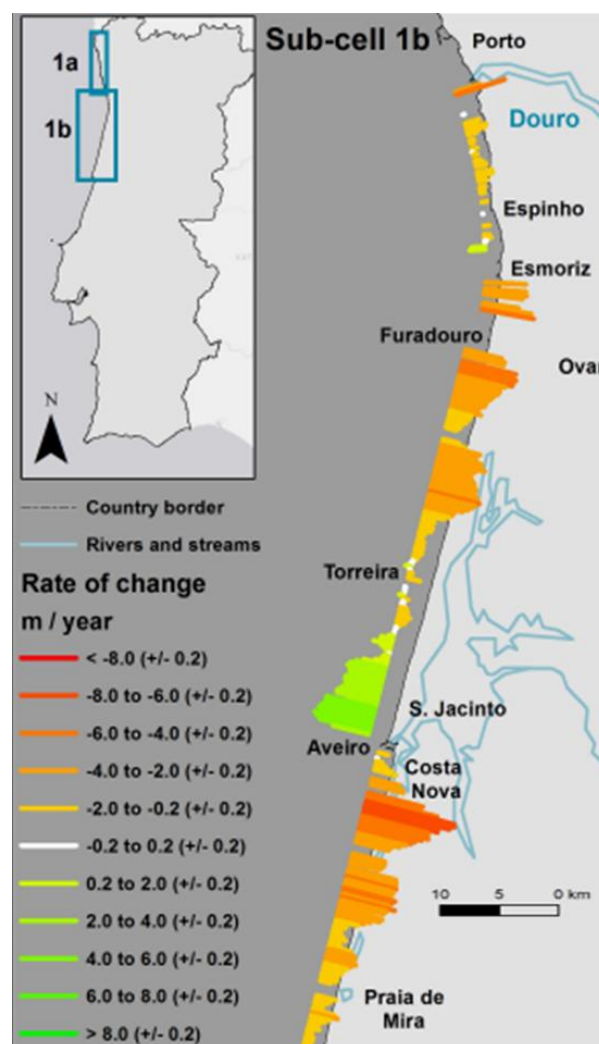


Figure 38 - Long-term coastline rates of change for sediment sub-cell 1b, adapted of (Lira et al., 2016)

Another coastline assessment, spanning the period from 2001 to 2020, indicates that the area north of Furadouro is experiencing extreme erosion, with sediments being transported southward. Consequently, in the coastal stretch south of Furadouro, extending from Torreira to Aveiro, sediment accretion is observed in certain areas (Figure 39).

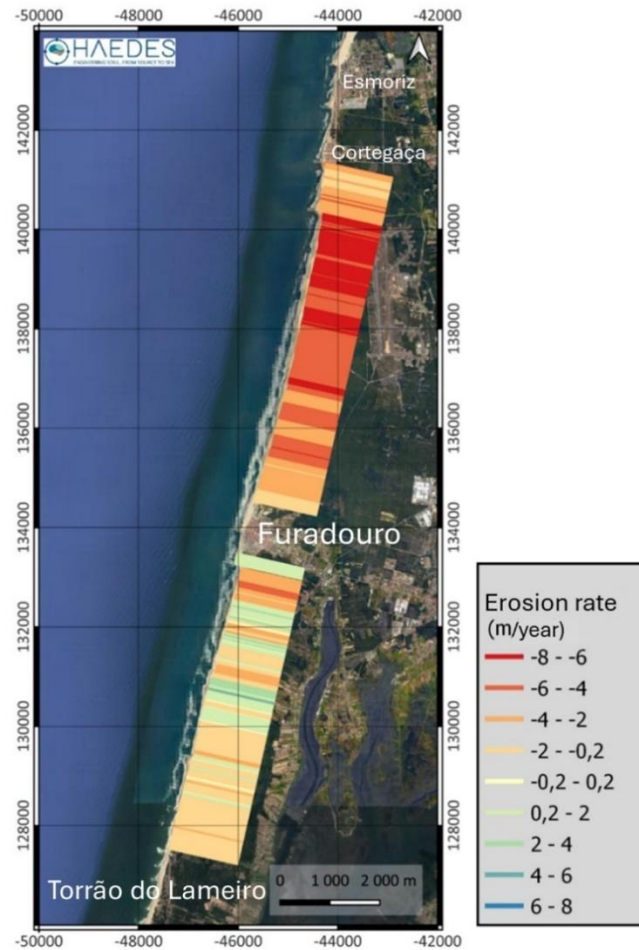


Figure 39 - Variation rate of the coastline between 2001 and 2021 for the Esmoriz - Torrão do Lameiro stretch. "Warm colours indicate retreat and cool colours indicate advance", compared to the 2001 position (adapted from APA¹⁴)

Focusing now on shoreline retreat over a shorter and recent time frame, between 2018 and 2021, the most affected coastal stretch between Cortegaça Beach and Furadouro Beach, spanning 8 km, shows that 83% of the section is eroding. Within this eroding portion, 56% is classified as experiencing "Extreme Erosion" or "Severe Erosion". The maximum retreat observed in this section during this period (Figure 40) was -33.5 m, with an average retreat rate of -3.6 m per year (APA¹⁵).



Figure 40 - Evolution of the coastline between 2018 and 2021- Cortegaça Beach to Furadouro Beach. (APA¹⁶)

¹⁴ https://apambiente.pt/sites/default/files/_Agua/DLPC/Acoes/COBE/Imagem2.jpg accessed in 06/02/2025

¹⁵ <https://apambiente.pt/destaque2/apa-atualiza-diagnostico-do-estado-da-faixa-costeira> accessed in 18/01/2025

¹⁶ https://apambiente.pt/sites/default/files/_A_APA/Comunicacao/Destaques/2022/Diagn%C3%B3stico%20do%20estado%20da%20faixa%20costeira/figura%202.jpg accessed in 06/02/2025

Analysing the long-term coastline position along this specific stretch reveals notable trends (Figure 41):

- From 1958 to 2010, the average rate of coastline retreat was -2.9 m/year ensuring a 149 m shoreline retreat.
- Between 2010 and 2018, this rate more than doubled to -6.6 m/year resulting in a 50.2 m coastal land loss.
- From 2018 to 2021, the rate decreased to -3.6 m/year accumulating 211.1 m of shoreline recession in approximately 70 years.

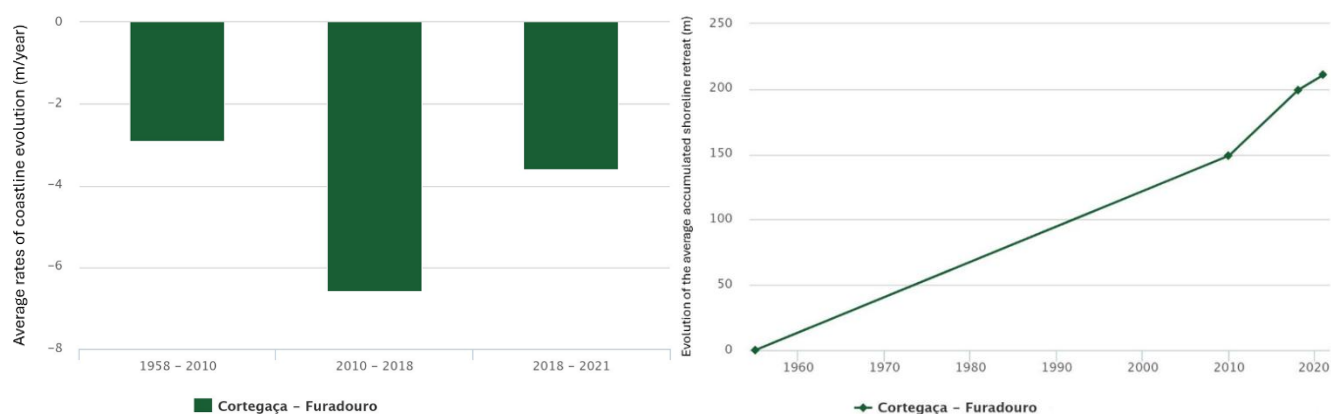


Figure 41 - Average rate of coastline evolution and average accumulated shoreline retreat in the Cortegaça to Furadouro stretch. (APA¹⁷)

4.3. DOURO ESTUARY'S SAND SPIT

4.3.1 INTRODUCTION

The Cabedelo sand spit is one of the Douro River estuary's most relevant landforms, located along the northwest Portuguese coast. The Douro River is a 927-km-long granitic drowned valley river and, being the largest Iberian Peninsula hydrographic basin, extending over an area of 97,682 km². Its estuary is placed on the Portuguese western coast and is highly conditioned by the North Atlantic meteorological and hydrodynamic regimes. The river forms a mesotidal estuary with funnel-shape for 21.6 km from the Crestuma-Lever Dam up to the river mouth (Figure 42), set in a steep valley, its general morphology is a controlling factor in tidal and wave dynamics. Of especial interest is the fact that two-thirds of the river mouth lies in the lee of the Cabedelo sand spit, a highly dynamic form constituting a microecosystem of vast biological interest. Established on the southern bank of the Douro River, this sand spit bounds effectively the opening of the estuary to the sea and controls its hydrodynamic operation and sediment transport processes (Bastos et al., 2012; Teodoro et al., 2015; Teodoro et al., 2014).

The banks of the Douro estuary are characterized by extensive and nearly continuous urban occupation, with increasing pressure to expand urbanization toward the water's edge and into undeveloped areas. Over the years, the banks and marginal roadways have seen significant urban and environmental rehabilitation.

The riverbanks, particularly the Ribeira and Foz areas in Porto and the Gaia quay, represents a site of remarkable natural, scenic, and cultural heritage. These areas are renowned for their ecological significance, historical charm, and cultural richness, attracting both residents and visitors.

These areas are indeed subject to intense anthropogenic activity, both for locals and tourists for festive and sporting events, mainly in their banks at the lower estuary. This set of natural features and others of anthropogenic

¹⁷ <https://rea.apambiente.pt/content/linha-de-costa-em-situa%C3%A7%C3%A3o-de-eros%C3%A3o> accessed in 08/01/2025

origin represents very well the complexity of the management of such a highly ecologically valuable and socioeconomically important significant area (Veloso Gomes , 2014)

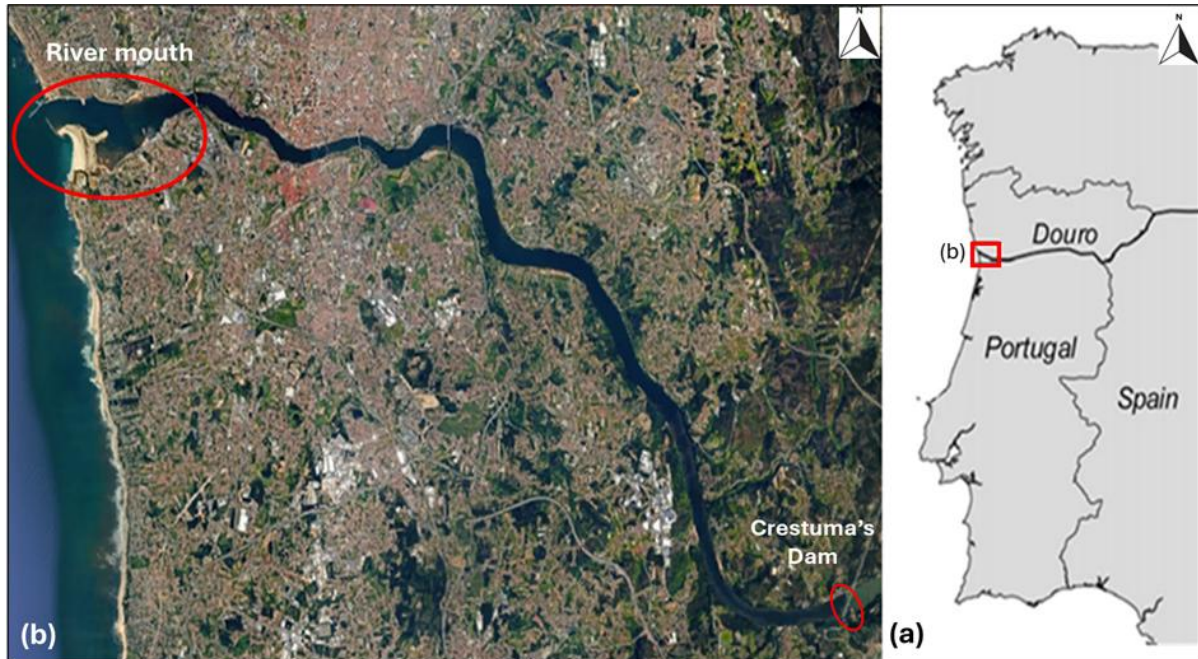


Figure 42 - Geographic setting of the case study: (a) Location of the Douro estuary; (b) View of estuary from Crestuma's dam to the river mouth.

This study focuses on the analysis of bathymetric surveys conducted by COSMOS, complemented by comparisons with satellite imagery data, thus confining the main study area within the limits of the topographic and bathymetric surveys that were undertaken. This area (Figure 43) encompasses the entire surface area of the sand spit, as well as the full width of the estuary channel, including both the southern sand spit and the northern bank. In terms of seaward extent, the study area extends less than one kilometre offshore. This small defined spatial framework allows for a focused investigation of bathymetric changes and sediment dynamics within the estuarine and coastal system.

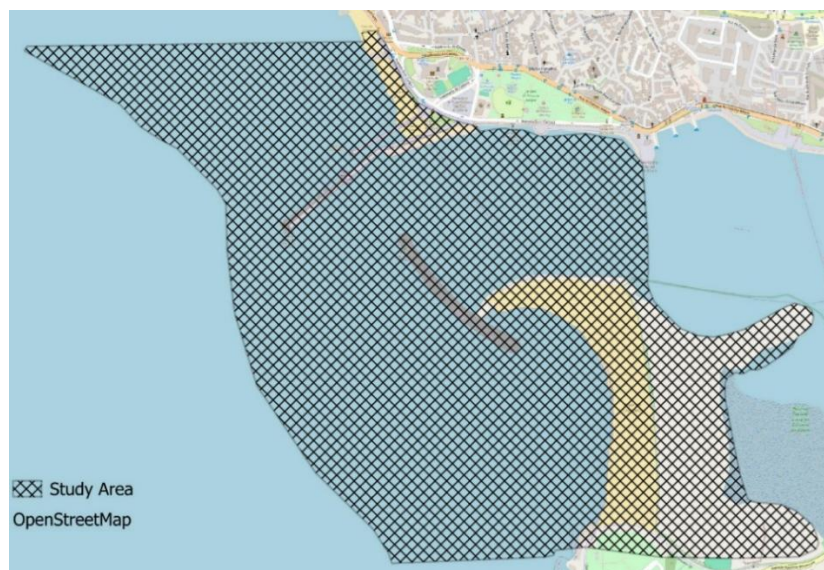


Figure 43 - Douro sandspit area covered by topo-hydrographic surveys.

4.3.2 COASTAL DEFENCE WORKS

In the case of the Douro River estuary, human intervention became essential to address key challenges, such as improving navigation safety, stabilizing the estuary's banks, and safeguarding the São Paio Nature Reserve. These efforts were driven by the need to balance environmental preservation with the functional and economic demands of the region, leading to a series of strategic engineering projects over the centuries.

The first big intervention occurred in the 1820s with the construction of the Luís Gomes de Carvalho wall, 600 m long, serving as a barrier between São Paio Bay and the estuary channel. It was conceived with the aim of improving navigation conditions and ended also serving as a foundation for subsequent structures, deemed very important for the long-term development of infrastructure in the estuary.

Between 1790 and 1886, the jetties of Touro and Felgueiras were built at the northern edge of the Douro River mouth. The nearly parallel jetties had the installation of a lighthouse on the Felgueiras jetty for maritime navigation facility. In the end, the 19th century saw Leixões Harbor being built north of the Douro River mouth and became an important factor for the impactful changes in adjacent coastal stretches, changing the coastal dynamics, influencing sediment transport and local hydrodynamics.

In October 2004, there was a prolongation of about 350 m to the northern jetty at the river mouth. Its objective was to connect with the already existent Felgueiras jetty. This guaranteed continuity to the urban waterfront and had a 200 m landward extension to enhance the pedestrian road. It was 7 m above mean sea level. March 2005 marked the beginning of a significant project: the construction of a 450 m long, curved detached breakwater positioned approximately 350 m seaward of the sand spit's current location. Oriented southeast to northwest, this breakwater was designed with a low crest to allow wave overtopping, with its exterior reinforced by concrete blocks enriched with high-density ore. The structure's primary purpose was to restore the protective function of the sand spit, shielding the right bank of the Douro River from wave action.

Between March 2005 and October 2008, a secondary structure was built to complement the detached breakwater. Measuring 460 m in length and nearly perpendicular to the breakwater, this structure connected the breakwater to the sand spit, reinforcing the spit's stability. Additionally, the northern limit of the sand spit head was fortified with an EeW stone revetment, linking the Luís Gomes de Carvalho wall to the newly constructed breakwater (Bastos et al., 2012; Gonçalves, 2022; Santos et al., 2011; Santos et al., 2014).



Figure 44 - Main components of the estuary.

These interventions aimed to (Bastos et al., 2012; Gonçalves, 2022; Santos et al., 2011; Santos et al., 2014):

- Stabilize the estuary banks, particularly the sand spit and estuary inlet. This includes maintaining the sand spit as a naturalised area.
- Improve navigability and navigation safety under all tidal conditions. The structures ensure safer access to the port of Leixões.
- Reduce the propagation of storm waves into the estuary. The breakwaters act as a physical barrier against the predominantly north-westerly wave action.
- Preserve environmental values, especially within the Nature Reserve that includes the sand spit and the adjacent São Paio Bay.
- Reduce the dredging effort required to maintain the navigation channel by preventing sediment accumulation in the channel.
- Recover the protective function of the sand spit and protect the estuary banks.
- Prevent waves from reaching the right bank of the Douro River.

The construction of these structures has significantly changed the morphology of the sand spit, as well as the dynamics of erosion and accretion in the area.

According to the work of Bastos et al., (2012) about the morphodynamic of this estuarine sand spit before and after the breakwater construction, it revealed that the sand spit was experiencing accretion before construction but afterwards, erosion became more dominant. Furthermore, the breakwaters have led to increased sediment deposition near the structures while erosion primarily occurs on the west and north sides of the sand spit. The construction of the breakwater caused the sand spit to change from a shape with a head or finger pointing inland to one with an inland arm along the Carvalho wall and a branch towards the São Paio Bay. This new shape has altered the circulation of water in the São Paio Bay. There seems to be a stabilizing effect of the breakwater on the shape and topography of most of the sand spit, suggesting that the breakwater protects this area against rough conditions (Figure 45).



Figure 45 - View of maritime work temporal evolution (2004-2007): (a) Before construction; (b) During construction; (c) After construction (Google Earth).

The northern breakwater acts as a physical barrier, shielding the access channel and estuary from waves predominantly originating from the northwest quadrant. Meanwhile, the structures on the southern bank reinforce the sandbank and prevent sediment transport from the sandbank into the navigation channel, reducing silting and maintaining navigability (Gonçalves, 2022).

4.3.3 GEOLOGICAL CHARACTERISTICS

The Douro estuary is a confined system, characterized by steep slopes and a substrate composed primarily of sand- and gravel-sized sediments. It is situated within a drowned valley characterized by an elongated morphology, shaped by the predominance of erosion-resistant pre-Mesozoic rocks, such as granites and metamorphic formations. This geological framework constrains the estuary's width and inhibits the formation of extensive intertidal mudflats, a feature more typical of low-relief coastal plain estuaries. Consequently, the Douro estuary remains narrow throughout its length, maintaining its confined nature (Portela, 2008).

The sediment composition within the estuary varies along its length. Upstream, sediments primarily consist of sandy gravels and gravelly sands with minimal fine particles, containing less than 1% silt and clay. In the middle and lower sections of the estuary (km 9–2 from river mouth), sediments become slightly finer, occasionally incorporating some silt and clay. At the estuary mouth, subtidal sediments are predominantly coarse gravelly sands, while the nearshore zone and inner shelf (<15 m) are composed of coarse to fine sands. The thickness of the sediment fill overlying the bedrock is approximately 40 m (Portela, 2008).

The Cabedelo spit is composed of fine to medium-coarse sand (Bio *et al.*, 2015), sediments on the banks consist mainly of sand and gravel (Portela, 2008).

After the breakwater's construction, the spit has become more stable, increasing in area and volume. The spit has developed a T-shape, which does not obstruct the navigation channel. However, this stabilisation has led to the silting up of the wetland area to the southeast of the spit. The spit connects with the São Paio Bay, a mostly submerged wetland that is ecologically important (Bio *et al.*, 2015).

4.3.4 ESTUARY DYNAMICS

The Douro River estuary, located in Portugal, is a dynamic environment influenced by hydrodynamic processes, sediment transport, and human interventions (Avilez-Valente *et al.*, 2020). It extends 21.6 km from the Crestuma-Lever Dam to its mouth at the Atlantic Ocean, forming a narrow, funnel-shaped system within a drowned valley setting (Bastos *et al.*, 2012). The estuary is bordered by the cities of Porto and Vila Nova de Gaia, which have played a significant role in its anthropogenic modifications.

The hydrodynamics of the estuary are primarily governed by river discharge and tidal influence. The construction of breakwaters, particularly the extension of the northern breakwater, has significantly altered local sediment transport and hydrodynamic patterns (Avilez-Valente *et al.*, 2020). The estuary experiences semidiurnal tides with a period of 12.4 hours and is classified as mesotidal, with tidal ranges between 2 and 4 meters (Iglesias *et al.*, 2018). Freshwater inflow is controlled by the Crestuma-Lever Dam and is further influenced by hydroelectric power generation, leading to variable discharge conditions. Under peak events, river flows can exceed 13,000 m³/s (Bastos *et al.*, 2012), causing the estuarine structure to shift from a vertically homogeneous system to having a saline wedge configuration (Almeida, 2013).

Sediment transport within the estuary is largely driven by river discharge, with flood events playing a crucial role in sediment redistribution and coastal sediment budgets. However, human activities, such as dam construction and sand extraction, have considerably reduced sediment availability. The sediment transport capacity is estimated at approximately 0.1 x 10⁶ m³/year in most of the estuary and 0.5 x 10⁶ m³/year near the inlet (Portela, 2008). One of the most prominent morphological features of the estuary is the Cabedelo sand spit, located along the southern margin. This sand spit plays a crucial role in estuarine hydrodynamics and sedimentation, acting as a natural barrier, accumulating coarser sediments and protecting the estuary banks from wave action (Teodoro *et al.*, 2014). Its morphology is shaped by river discharge, wave climate, and human interventions, particularly jetty construction (Santos *et al.*, 2011).

The Douro estuary has undergone extensive anthropogenic modifications, including the construction of marinas, quays, and breakwaters, as well as sediment dredging and bank modifications (Iglesias *et al.*, 2018). While breakwaters have contributed to the stabilization of the Cabedelo sand spit, they may also reduce the likelihood of breaching during extreme floods, potentially intensifying flood impacts upstream (Avilez-Valente *et al.*, 2020). Despite the role of dams in mitigating flood frequency and intensity, the estuary remains susceptible to extreme flood events, which pose risks to riverside communities and navigation.

4.3.5 WAVE CONDITIONS

For the characterization of the local wave dynamics at the Douro estuary, results from a high-resolution numerical model made with SWAN (Simulating Waves Nearshore) spectral wave model are employed (Ramos *et al.*, 2022). This model was used to generate a 34-year dataset spanning from January 1, 1990, to December 31, 2023. The model output provides daily wave parameters, including significant wave heights, wave periods, and wave direction, at a chosen reference point approximately 800m offshore, as illustrated in Figure 46.

This dataset enables the characterization of the average wave climate by computing long-term statistics of wave height, period, and direction. The wave rose (Figure 47) derived from these decades of data confirms that the predominant wave direction at the estuary is west (W)-oriented.



Figure 46 - Wave parameters were generated for the point (red).

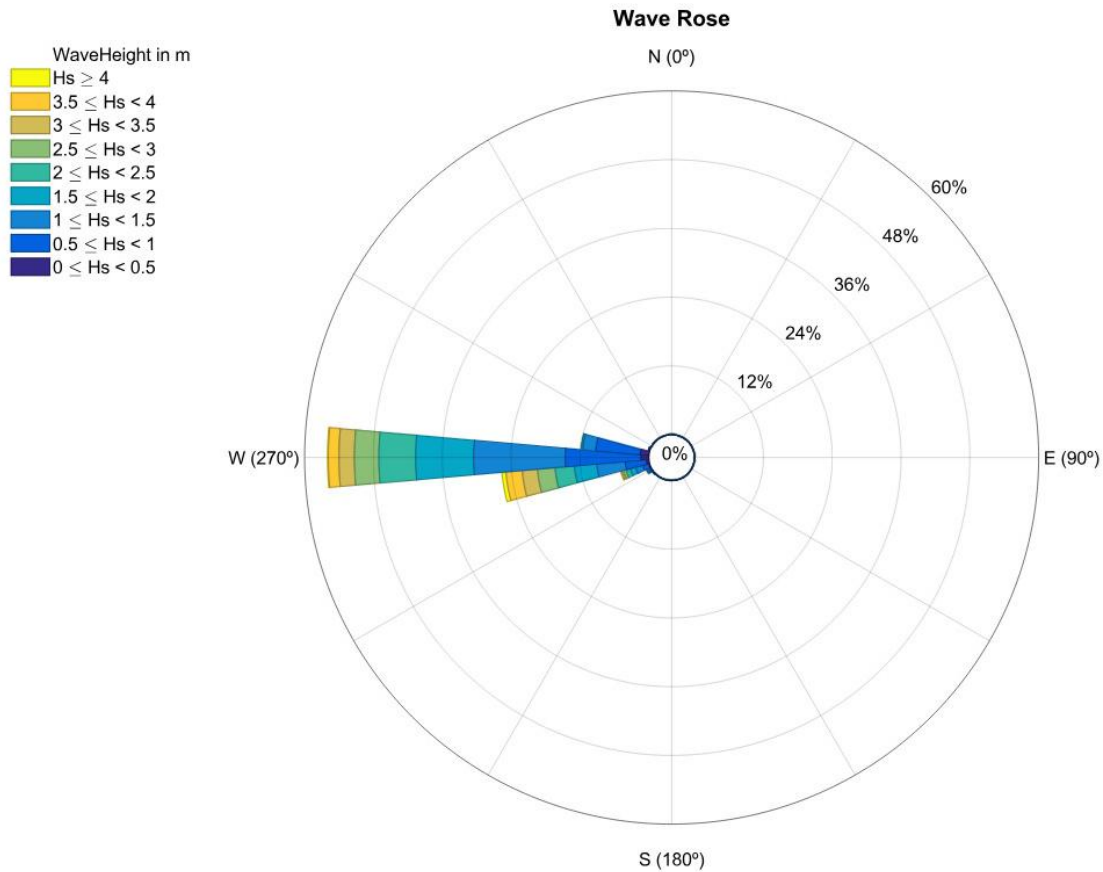


Figure 47 - Douro estuary wave rose (data from 1990 to 2023)

A historical analysis of wave conditions was conducted, as summarized in Table 7, where key parameters such as average wave power, significant wave height, wave period, and wave direction were computed. Additionally, the number of occurrences in which the significant wave height exceeded 5 meters was quantified. Notably, the years 2014 and 2018 stand out as having the highest average wave power, yet only in 2014 is registered the greatest number of occurrences where significant height has exceeded 5 m. This suggests that these years experienced particularly energetic wave conditions.

Table 7 - Average wave characteristics in Douro estuary's sandspit coast for the various periods.

Period	Power (kW/m)	H_{mo} (m)	T_P (s)	Dir (°)	$H_{mo} > 5m$
1990 - 2023	21.56	1.653	11.660	275.363	118
2010	15.35	1.459	10.878	267.846	2
2011	21.22	1.646	11.996	271.756	5
2012	18.32	1.611	11.931	274.756	1
2013	23.30	1.737	12.121	274.799	5
2014	35.21	1.992	12.351	274.653	15
2015	23.07	1.753	12.245	275.419	0
2016	23.69	1.746	12.024	274.587	2
2017	20.04	1.609	11.978	274.991	2
2018	33.64	1.985	13.351	275.855	3
2019	26.62	1.821	12.675	275.193	2
2020	26.69	1.811	12.689	275.485	3

Focusing specifically on the time intervals between the bathymetric surveys—September 2018 to August 2019 and August 2019 to July 2020. The results presented in Table 8 indicate that the wave characteristics, including significant wave height, wave power, and dominant direction, remained relatively consistent across both periods. This suggests that any morphological changes observed in the surveyed profiles are likely attributed to other factors rather than significant variations in wave energy.

Table 8 - Average wave characteristics in Douro estuary's sandspit coast for the time period between surveys.

Period	Power (kW/m)	H _{mo} (m)	T _P (s)	Dir (°)	H _{mo} >5m
01/09/2018 -31/08/2019	26.49	1.793	12.948	275.296	2
01/08/2019 -31/07/2020	27.54	1.856	12.679	274.996	1

To further investigate the potential influence of river flow on the morphological evolution of the estuary, an analysis of river discharge data was conducted. The Crestuma Dam, the final dam upstream before the estuary, provides daily inflow data, which can be obtained from the Sistema Nacional de Informação de Recursos Hídricos (SNIRH). Using this dataset, a time series was constructed to represent the dam's daily inflow from August 1, 2018, to July 31, 2020. The results, presented in the graph below (Figure 48), indicate a period of significantly increased inflow during December 2019 and January 2020, with the peak value approaching 7000 m³/s (22/12/2019).

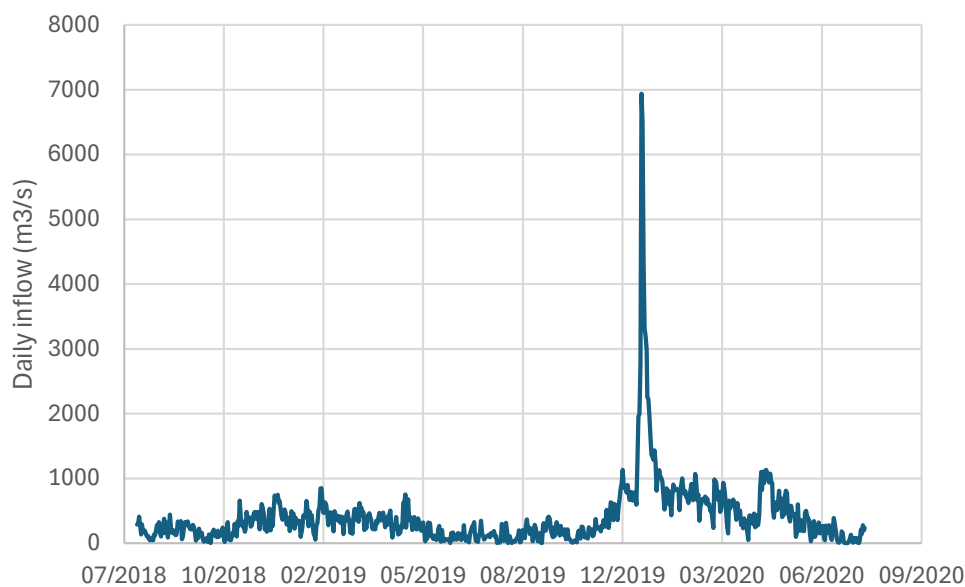


Figure 48 - Crestuma dam's daily inflow from 08/2018 to 07/2020.

According to the work by Teodoro et al., (2014) the river discharge and the wave climate parameters have an influence on the Cabedelo spit area. The influence of the tide level was not proven and the tidal level had little evolutionary impact and the significant wave height has an important contribution for the Cabedelo spit behaviour.

An analysis of significant wave height and wave power for each survey period provides insights into how wave forcing may have influenced the observed morphological changes. Therefore it was designed the wave power (Figure 50 and Figure 52) and significant wave height graphs (Figure 49 and Figure 51) for each time period in between the surveys.

A comparative analysis of wave conditions during the two survey periods provides insight into their potential influence on morphological changes within the Douro Estuary. In the first period (September 2018 – August 2019), there were two occurrences where H_s exceeded 5.0 m, with the highest recorded value reaching $H_s = 5.2$ m. However, the last of these events was associated with wave power below 200 kW/m, indicating moderate energy conditions despite the high wave height.

In contrast, the second period (August 2019 – July 2020) experienced only one event where H_s exceeded 5.0 m, but this event was significantly more intense, with significant wave height reaching 5.9m and a wave power exceeding 250 kW/m (20/12/2019). Additionally, this period exhibited a higher frequency of waves exceeding 4.5 m, associated with wave power surpassing 150 kW/m, suggesting that the estuary was subjected to more energetic and sustained wave forcing.

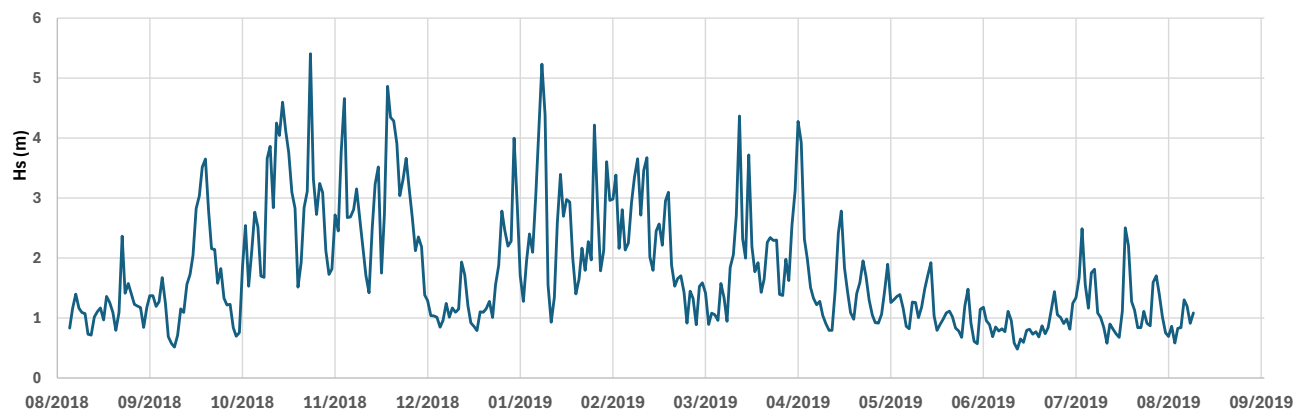


Figure 49 - Significant wave height for the period 09/2018 to 08/2019 – Douro estuary.

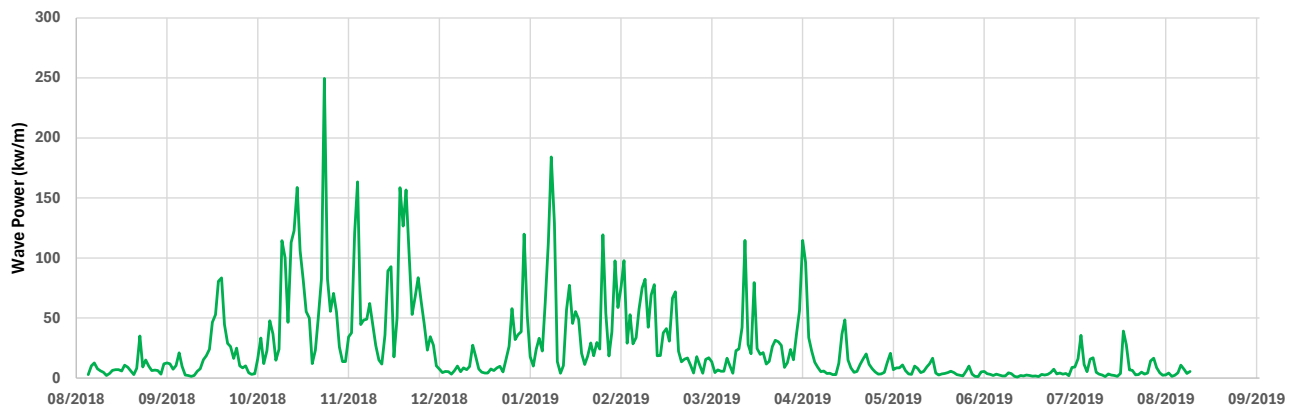


Figure 50 - Wave power for the period 09/2018 to 08/2019 – Douro estuary.

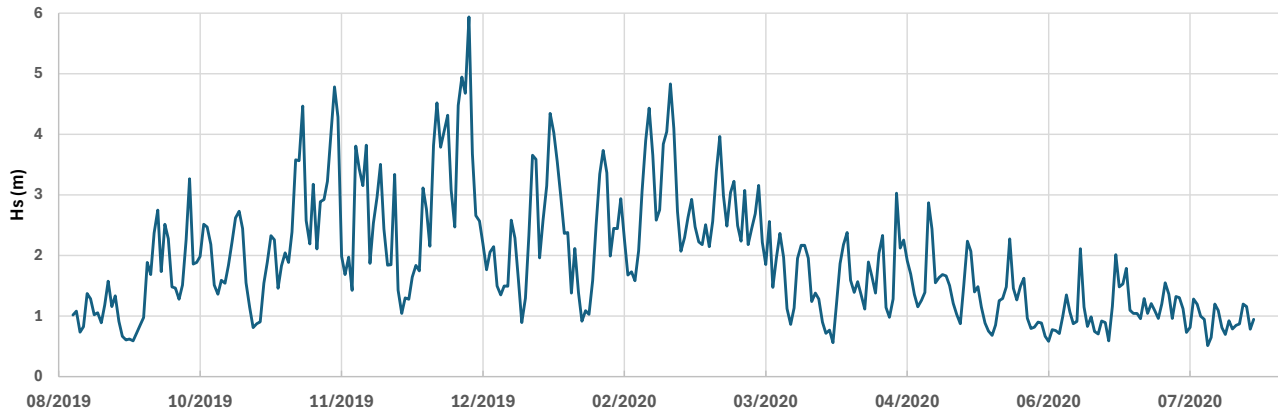


Figure 51 - Significant wave height for the period 08/2019 to 07/2020 – Douro estuary.

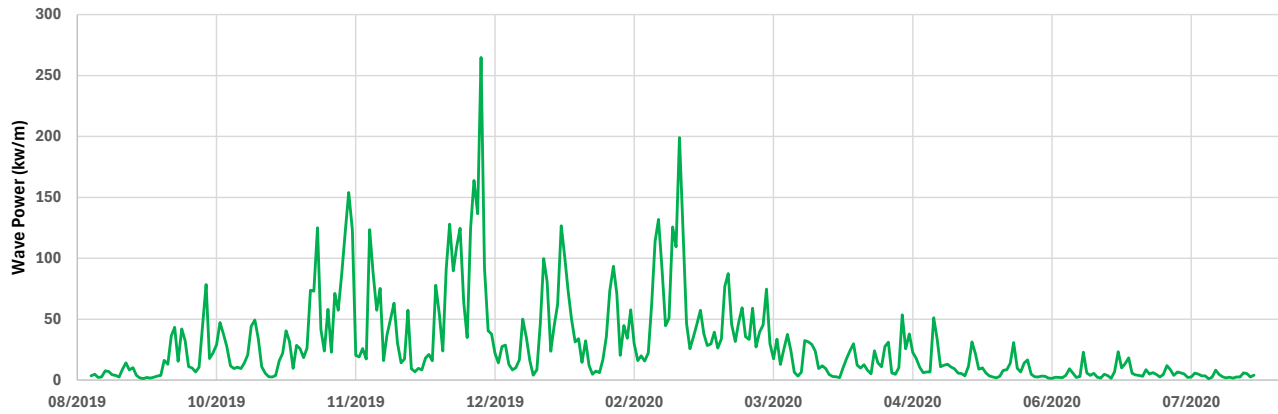


Figure 52 - Wave power for the period 08/2019 to 07/2020 – Douro estuary.

5

MORPHODYNAMIC ANALYSIS

5.1. SATELLITE DERIVED BATHYMETRY

This study focuses on analysing the feasibility of S2Shore to obtain good quality bathymetry and its validation, ensuring its reliability before generating monthly bathymetric datasets. This validation process involves comparing satellite-derived bathymetry with *in-situ* acoustic bathymetric surveys conducted by COSMO to assess the accuracy and applicability of the S2Shores algorithm in the study areas.

To achieve this, a selection of satellite images captured around the same dates as the COSMO surveys (as outlined in section 3.1) was used as input for the S2Shores algorithm. The algorithm was initially run using lower-resolution grids (100 m and 50 m) to evaluate overall performance and identify suitable imagery. Subsequently, for the most promising images, higher-resolution processing (10 m) was applied to enhance bathymetric detail. This approach was implemented for both study sites—Furadouro Beach and the Douro Estuary—across three selected dates.

In this chapter, the results of this validation process are presented, comparing the best-performing S2Shores-derived bathymetric outputs with the corresponding *in-situ* surveys. This comparison serves as the foundation for assessing the feasibility of using satellite-derived bathymetry (SDB) for high-frequency coastal monitoring and guiding the methodology for generating monthly bathymetric datasets in subsequent phases of the study.

5.1.1 FURADOURO

For the validation process, the S2Shores algorithm was initially applied to satellite images captured on July 6th, 11th, 16th, and 31st of 2020 (as mentioned in Table 4), covering an area of 5.28 km². These dates were pre-selected to assess the consistency and feasibility of SDB outputs in relation to *in-situ* measurements:

- SENTINEL2B 2020/07/06 at 11:39:58
- SENTINEL2A 2020/07/11 at 11:40:00
- SENTINEL2B 2020/07/16 at 11:39:57
- SENTINEL2A 2020/07/31 at 11:40:02

To facilitate a detailed comparison, three longitudinal profiles were extracted from the SDB results, corresponding to Zones 1, 2, and 3 of Furadouro Beach (previously defined in Figure 22). These profiles, presented in Figure 53, provide a spatially distributed cross-section of the derived bathymetric data, allowing for a direct comparison between the S2Shores water depth estimates and the *in-situ* COSMOS surveys. By analysing these longitudinal

profiles (Figure 54 to Figure 56), it becomes possible to evaluate the differences of the S2Shores outputs across different locations within the study area.

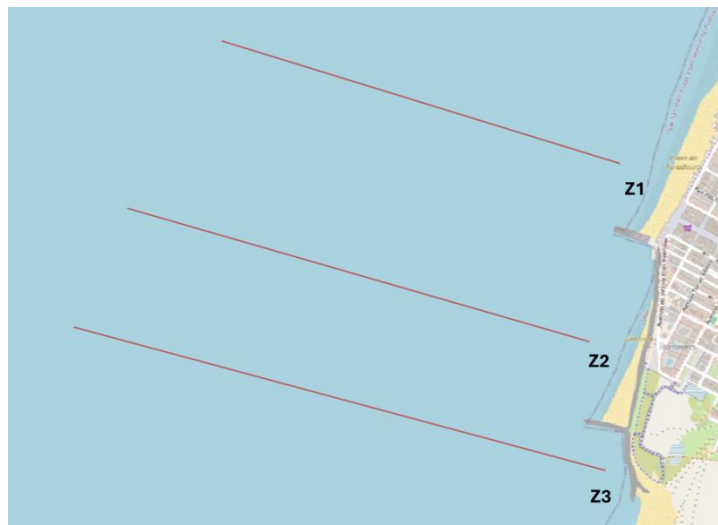


Figure 53 - Profiles for evaluation – Furadouro beach.

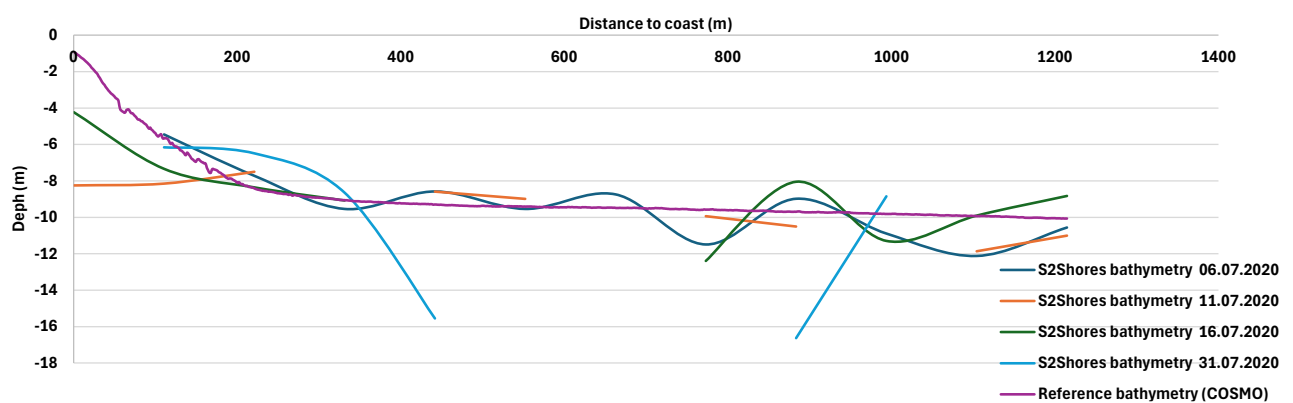


Figure 54 - Longitudinal profile in zone 1 – Furadouro beach 2020/07 (100m resolution).

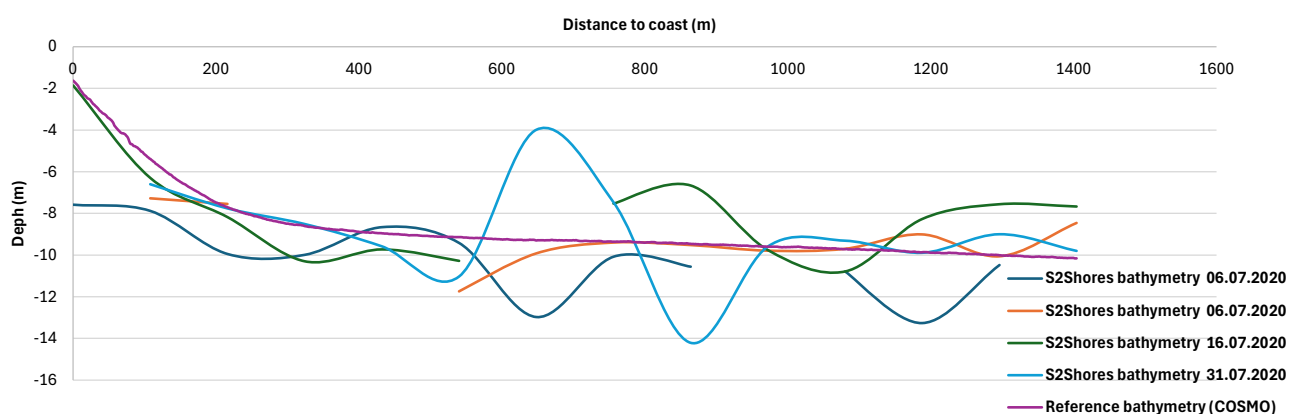


Figure 55 - Longitudinal profile in zone 2 – Furadouro beach 2020/07 (100m resolution).

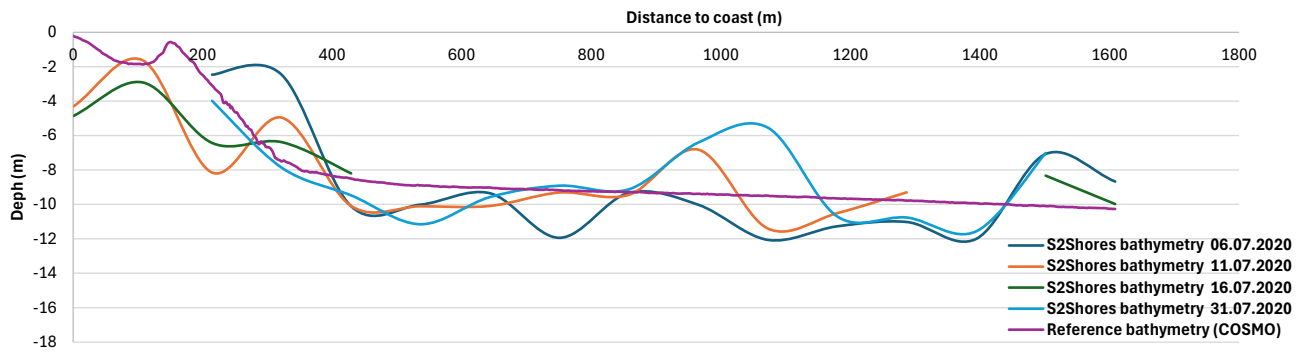


Figure 56 - Longitudinal profile in zone 3 – Furadouro beach 2020/07 (100m resolution).

The initial analysis indicates that the bathymetric results exhibit significant variability across the selected dates. However, the outputs from July 11th and July 16th show the smallest difference, making them the most reliable for further refinement.

For these two dates, the S2Shores algorithm was reprocessed at a higher resolution (10 m) to enhance bathymetric detail. Additionally, a vertical correction was applied to align the satellite-derived depths with the *in-situ* reference system. This correction involved subtracting both the 2.0 m mean sea level (MSL) offset and the corresponding tidal elevation at the time of satellite image acquisition.

Table 9 provides the tidal elevation measured and referenced to MSL, nearshore Furadouro Beach near the time each satellite image was taken, ensuring that depth estimates are accurately referenced for comparison with COSMO surveys.

Table 9 - Tidal elevation Furadouro 2020/07.

date	time	tide level (m)
20200716	11:30:00	0.697
20200711	11:30:00	-0.561

Finished the post-processing, the longitudinal profiles were re-generated to allow for a more accurate evaluation of the water depth estimates obtained from S2Shores (Figure 57 to Figure 59). Additionally, a bathymetric map was represented to provide a visual depiction of the differences between the satellite-derived bathymetry and the *in-situ* COSMO measurements. These comparisons (Figure 60 to Figure 62) facilitate a clearer assessment of the algorithm's performance and its potential for the monthly coastal monitoring application.

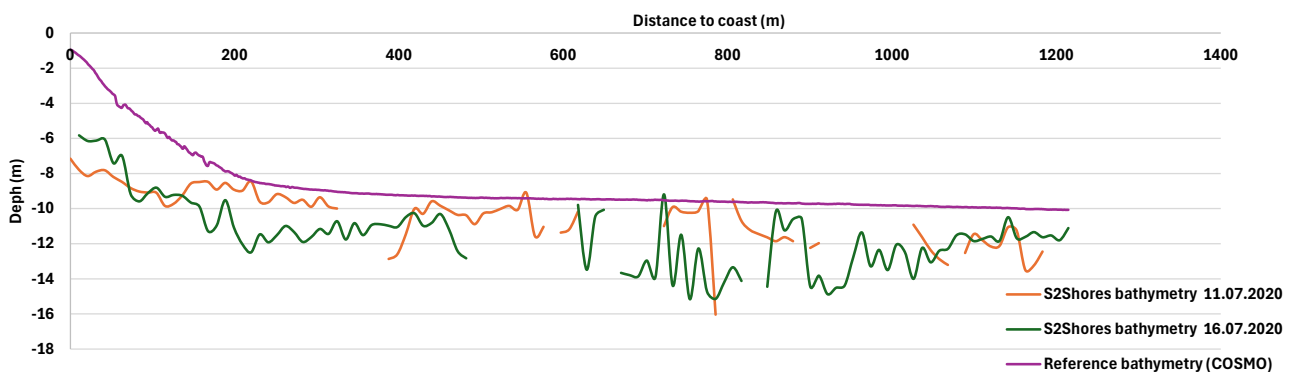


Figure 57 - Longitudinal profile in zone 1 – Furadouro beach 2020/07 (10m resolution).

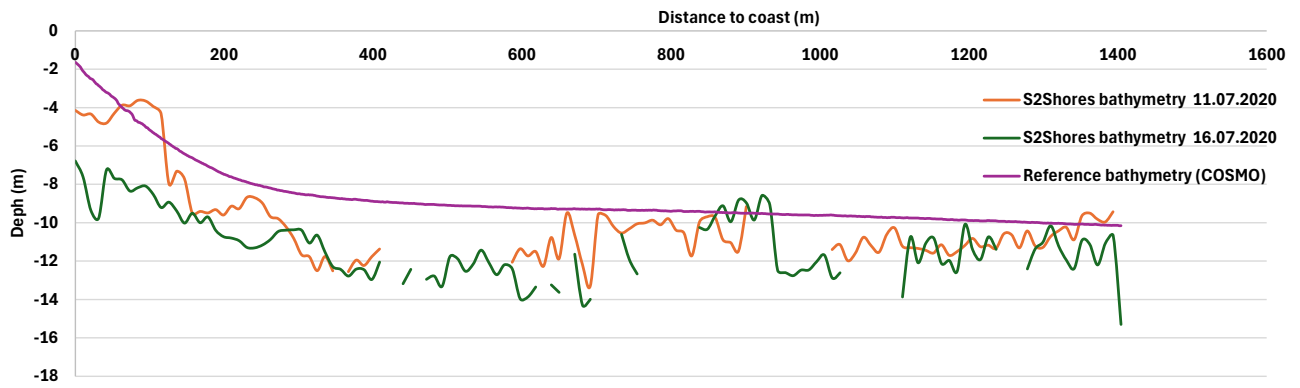


Figure 58 - Longitudinal profile in zone 2 – Furadouro beach 2020/07 (10m resolution)

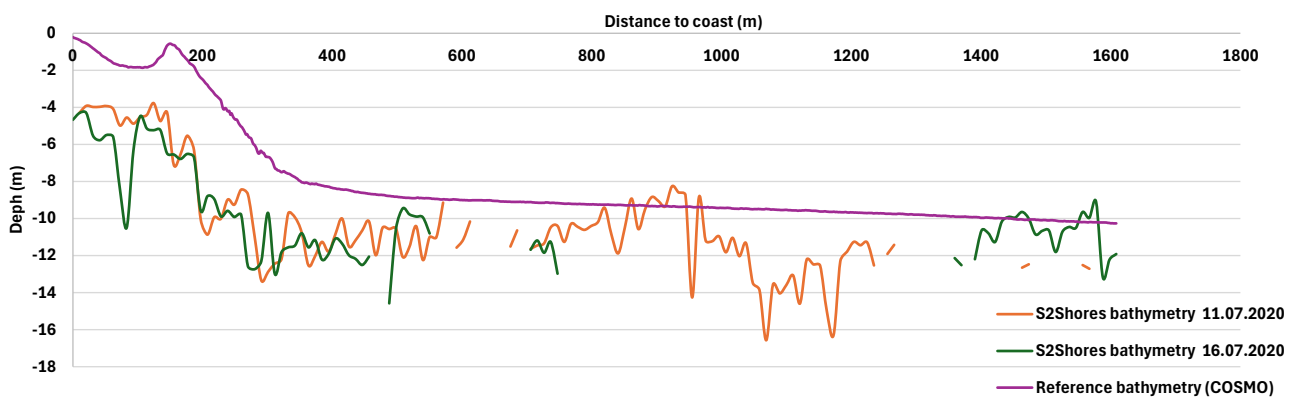


Figure 59 - Longitudinal profile in zone 3 – Furadouro beach 2020/07 (10m resolution)

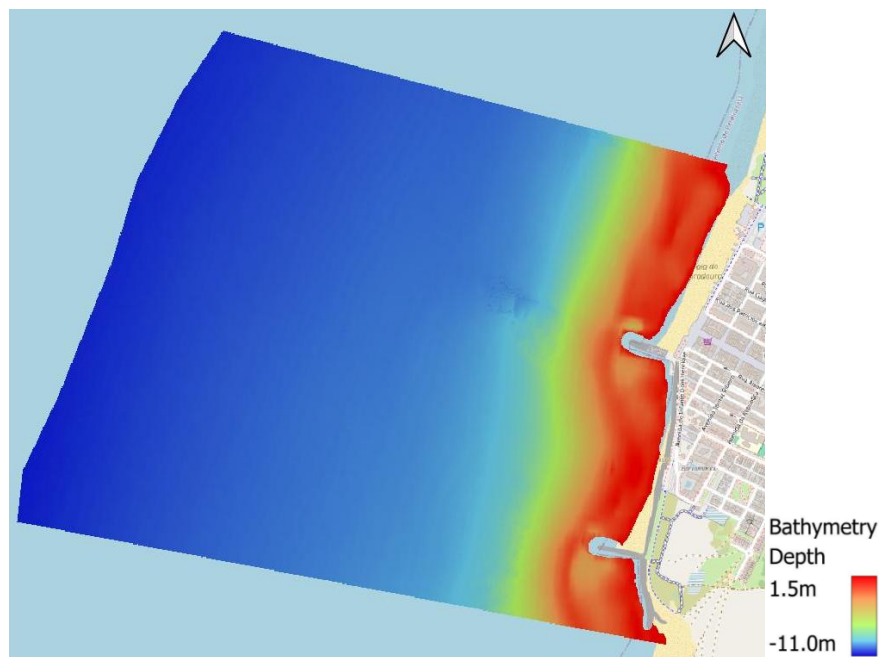


Figure 60 - Reference bathymetric data (*in-situ* measurements) – Furadouro 07/2020.

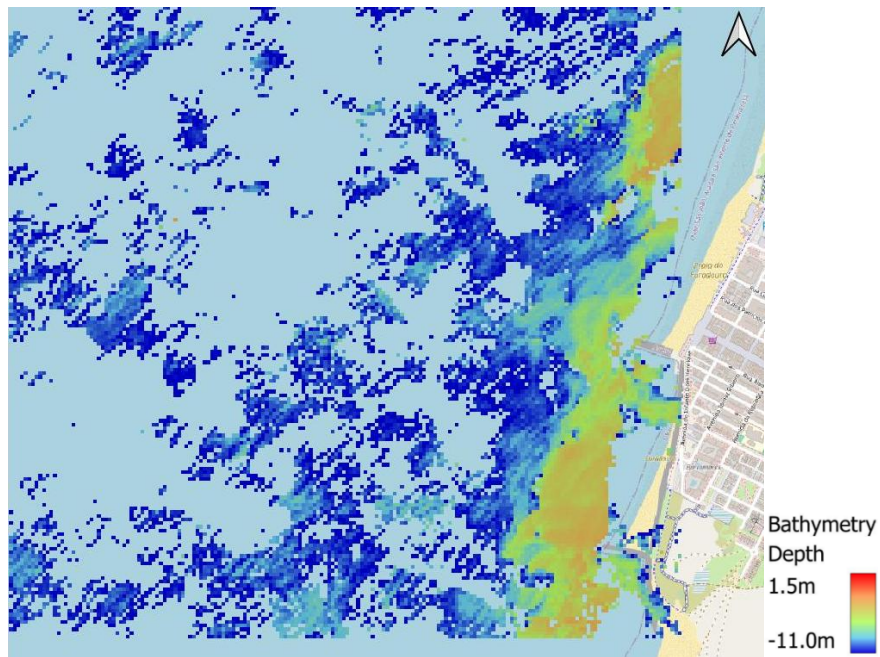


Figure 61 - Bathymetry output (from S2S) – Furadouro 11/07/2020

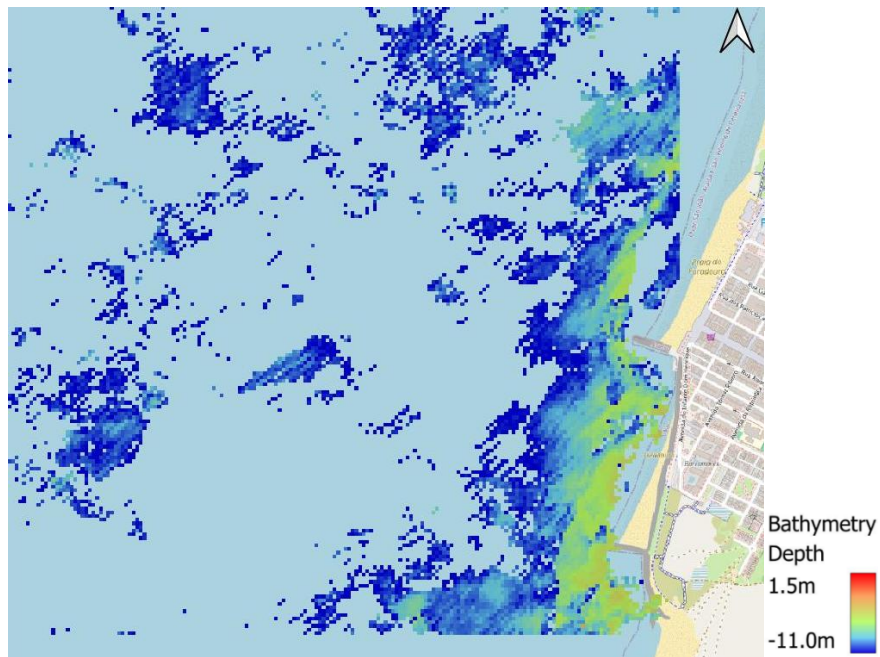


Figure 62 - Bathymetry output (from S2S) – Furadouro 16/07/2020

Repeating the process for July of 2019, the pre-selected satellite images are:

- SENTINEL2X 2019/07/15 at 00:00:00
- SENTINEL2A 2019/07/17 at 11:40:01
- SENTINEL2B 2019/07/29 at 11:30:08

The S2Shores algorithm was applied to this satellite images at a 100-meter resolution, generating bathymetric outputs for the study area. From these results, cross-sections were extracted as represented in Figure 63 to Figure 65.

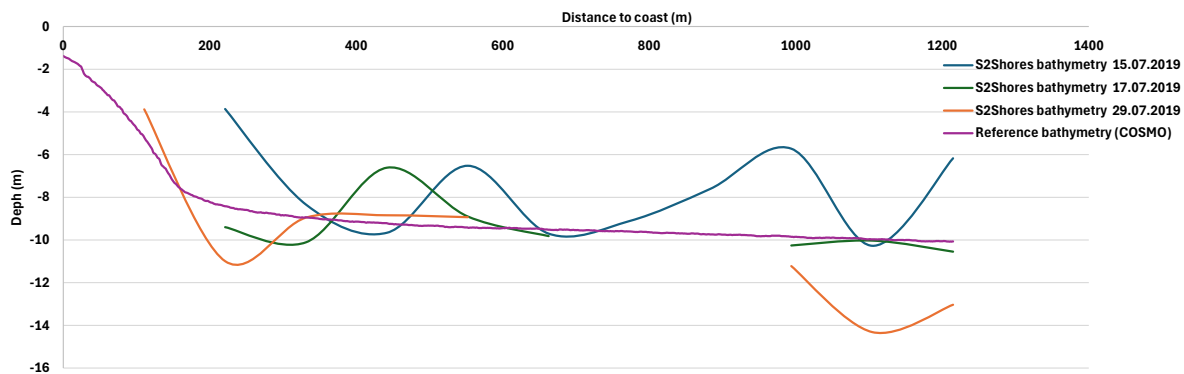


Figure 63 - Longitudinal profile in zone 1 – Furadouro beach 2019/07 (100m resolution)

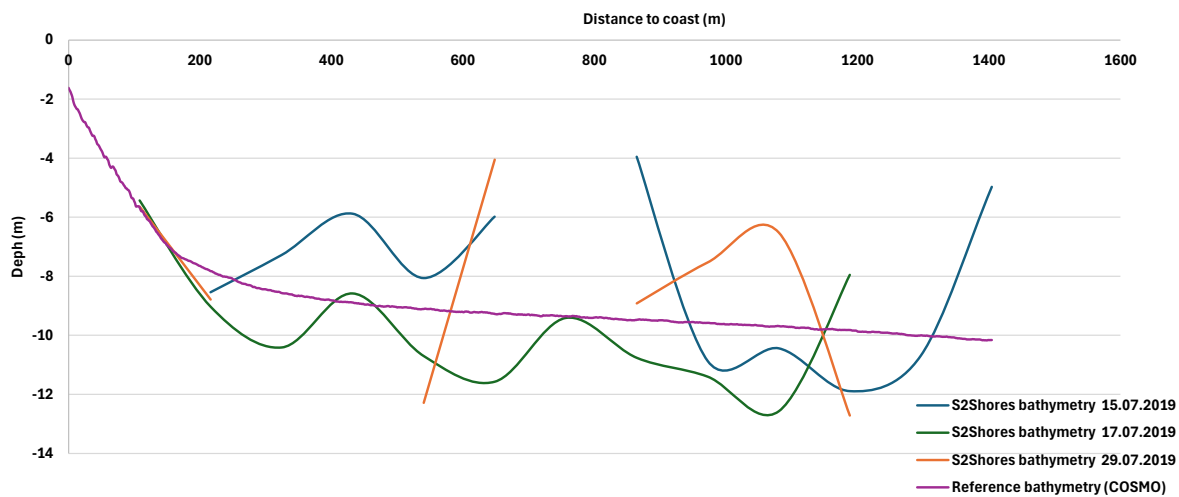


Figure 64 - Longitudinal profile in zone 2 – Furadouro beach 2019/07 (100m resolution)

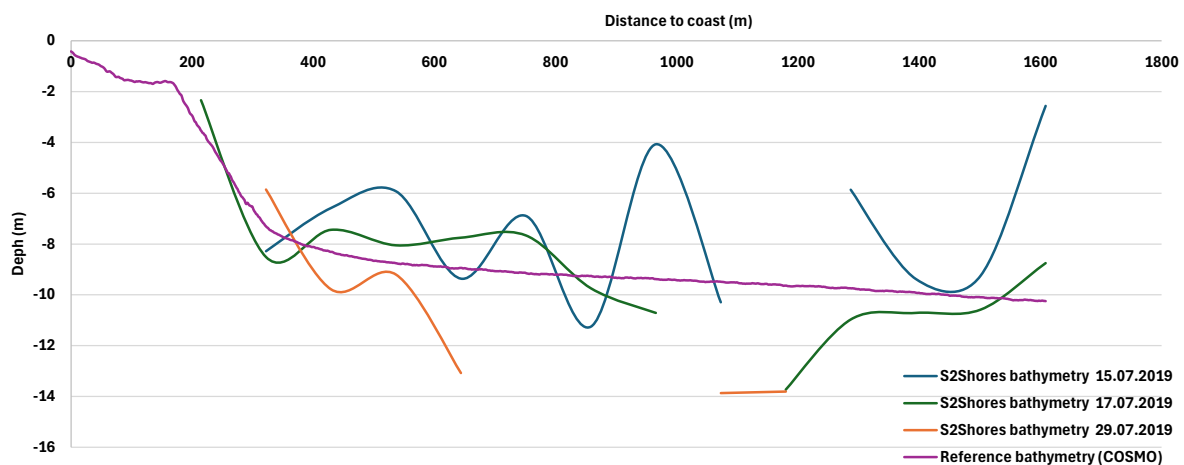


Figure 65 - Longitudinal profile in zone 3 – Furadouro beach 2019/07 (100m resolution)

Among the analysed profiles, the one corresponding to July 17th was selected for high-resolution processing (10 m) using the S2Shores algorithm. A vertical correction was applied to the water depth estimates by adjusting for mean sea level (MSL) and tidal elevation (Table 10) near the time of satellite image acquisition.

The resulting bathymetry, after correction, is presented in the following figures, providing the longitudinal profiles (Figure 66, Figure 67, Figure 68) and seafloor depth map (Figure 69) representations for its comparison with *in-situ* measurements.

Table 10 - Tidal elevation Furadouro 2019/07.

date	time	tide level (m)
20190717	11:30:00	-0.363

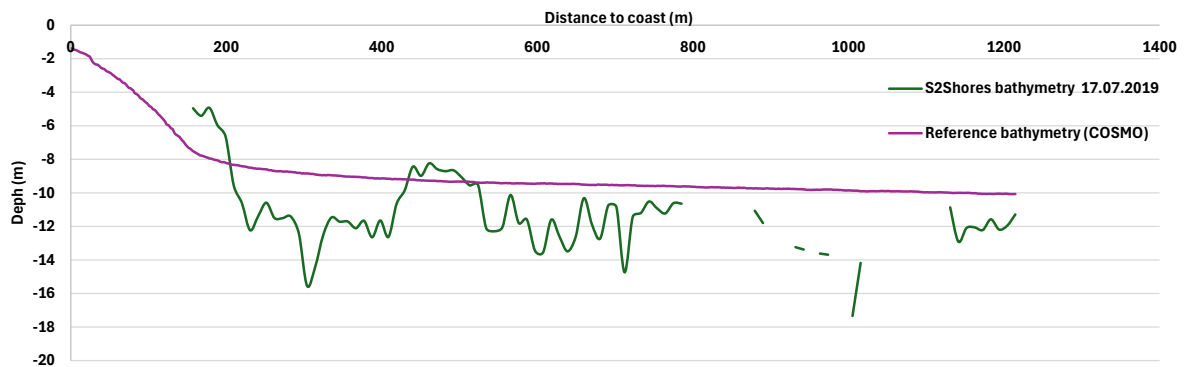


Figure 66 - Longitudinal profile in zone 1 – Furadouro beach 2019/07 (10m resolution)

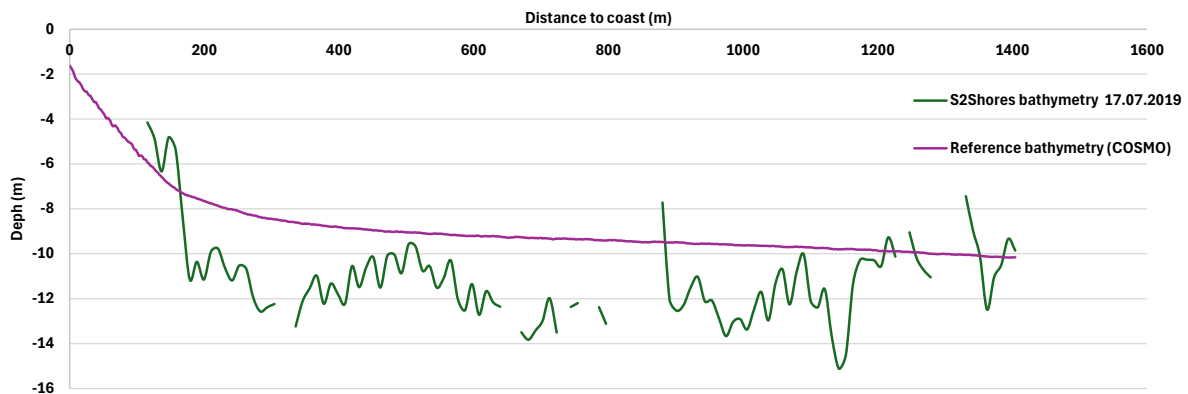


Figure 67 - Longitudinal profile in zone 2 – Furadouro beach 2019/07 (10m resolution)

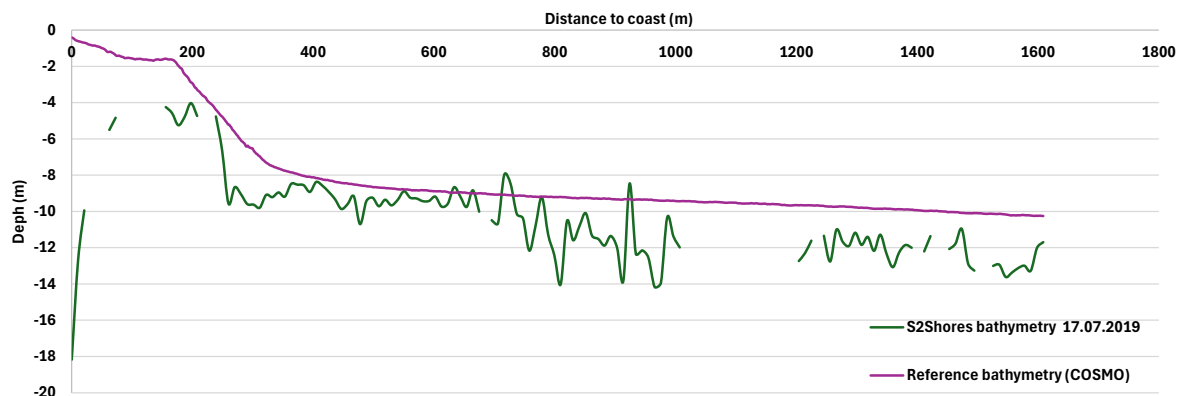


Figure 68 - Longitudinal profile in zone 3 – Furadouro beach 2019/07 (10m resolution).

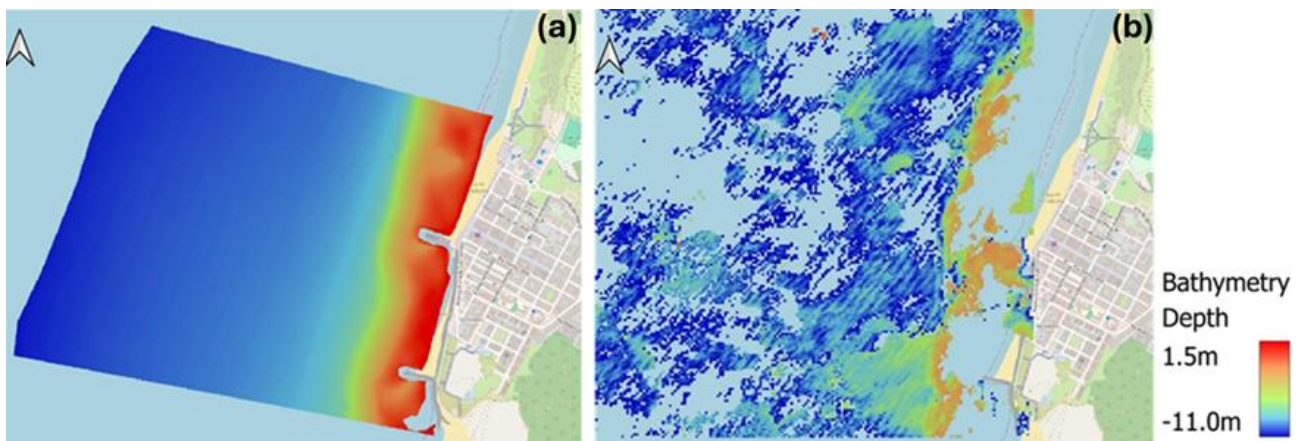


Figure 69 - Bathymetric data in Furadouro 2019/07: (a) Referential *in-situ* method (from COSMO); (b) SDB (from S2S).

The application of S2Shores for September 2018 presented significant challenges due to adverse atmospheric conditions. This month was characterized by extensive cloud cover, severely limiting the availability of usable satellite imagery. Among the two only pre-selected images where cloud coverage did not obscure the study sites, wave patterns were not clearly distinguishable, preventing the extraction of reliable wave kinematics necessary for bathymetric estimation.

Consequently, generating admissible bathymetric outputs for validation or further analysis was not possible. The absence of visible waves in Figure 71 and Figure 72, compared to the clearly distinguishable wave patterns in the July 17th of 2019 image (Figure 70), underscores the limitations of optical satellite-derived bathymetry (SDB) under these conditions.

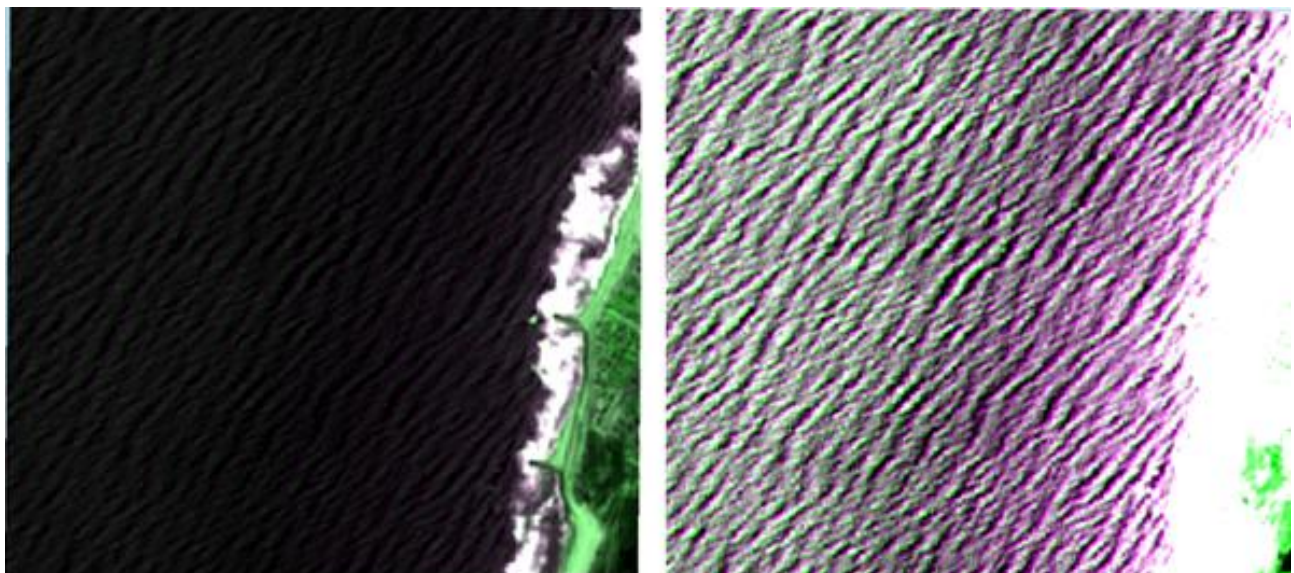


Figure 70 - Satellite image of 2019/07/17 – visual result of bands 2 and 4 overlap.

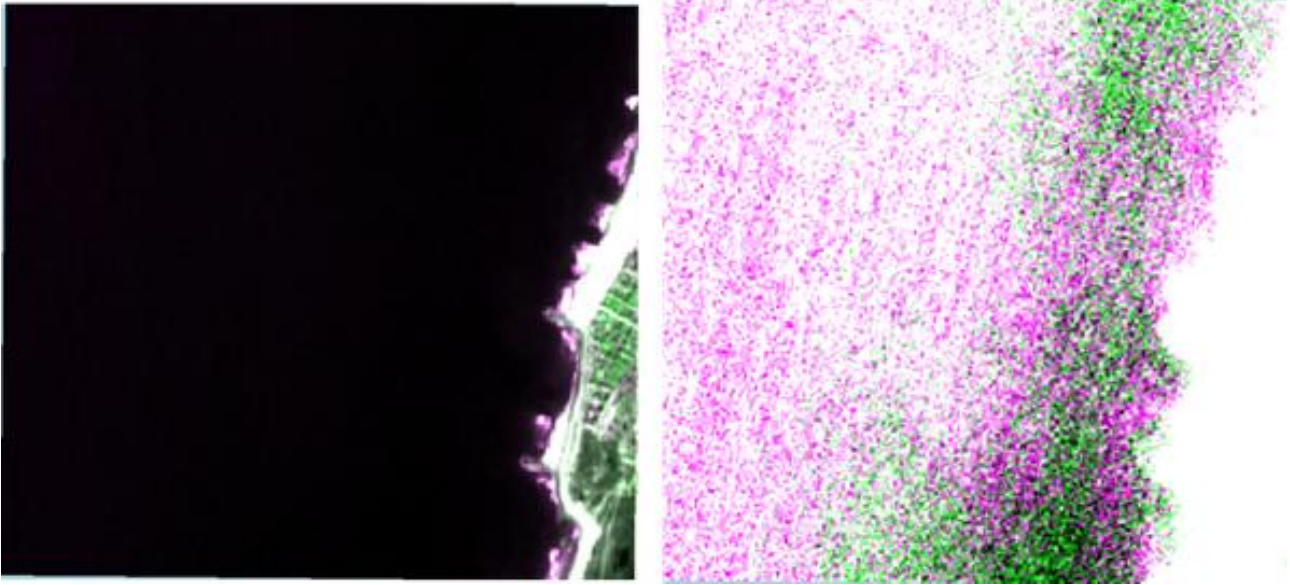


Figure 71 - Satellite image of 2018/09/02 – visual result of bands 2 and 4 overlap.

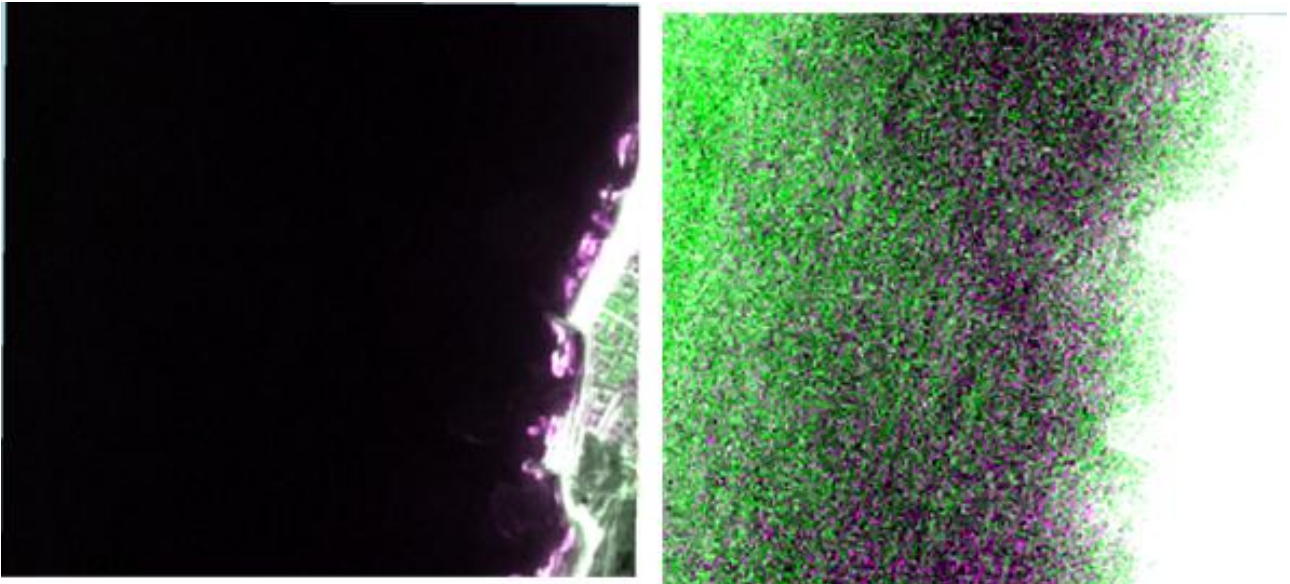


Figure 72 - Satellite image of 2018/09/25 – visual result of bands 2 and 4 overlap.

5.1.2 CABEDELLO SPIT

To enable a detailed assessment of the S2Shores-derived bathymetry (SDB) results, five longitudinal profiles have been obtained, corresponding to those defined in Figure 73. These profiles represent spatially distributed cross-sections along the river mouth, capturing variations in bathymetric depth across different regions of the estuary. By aligning these profiles with *in-situ* measurements, a direct comparison can be made between the S2Shores water depth estimates with the on-ground bathymetric surveys, allowing for a comprehensive evaluation of the algorithm's accuracy and performance in this dynamic coastal environment (Figure 74 to Figure 78).



Figure 73 - Profiles for evaluation – Douro estuary.

For the validation process, the S2Shores algorithm was initially applied to satellite images captured on July 3rd, 11th, 16th, and 31st of 2020 (as mentioned in Table 4). These dates were pre-selected to assess the consistency and feasibility of satellite-derived bathymetry (SDB) outputs in relation to *in-situ* COSMO surveys:

- SENTINEL2B 2020/07/03 at 11:30:02
- SENTINEL2A 2020/07/11 at 11:40:00
- SENTINEL2B 2020/07/16 at 11:39:57
- SENTINEL2A 2020/07/31 at 11:40:02

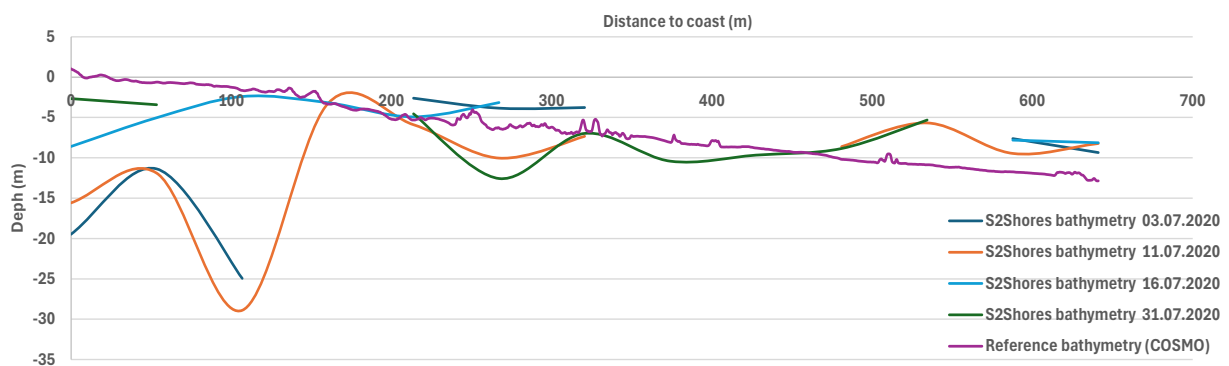


Figure 74 - Longitudinal profile 1 – Douro estuary 2020/07 (50m resolution).

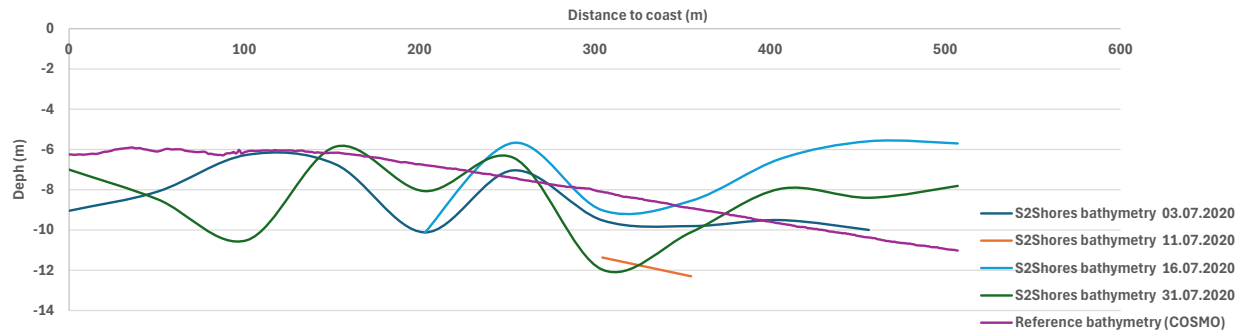


Figure 75 - Longitudinal profile 2 – Douro estuary 2020/07 (50m resolution).

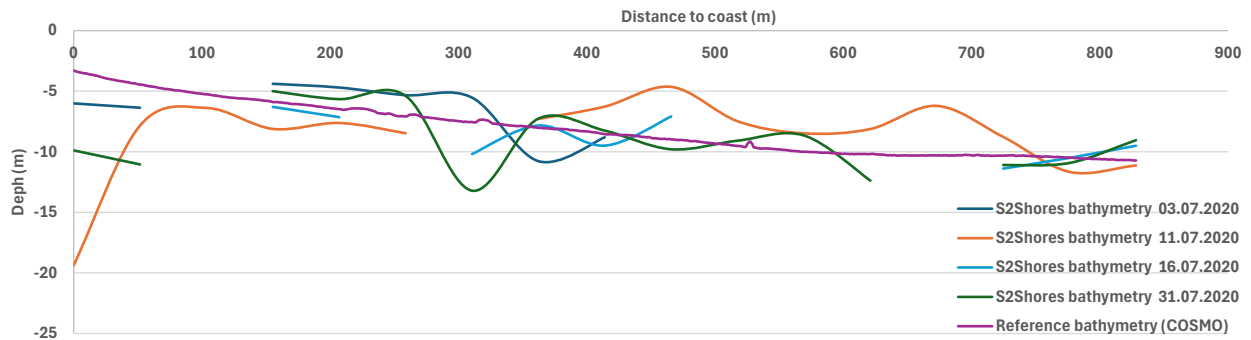


Figure 76 - Longitudinal profile 3 – Douro estuary 2020/07 (50m resolution).

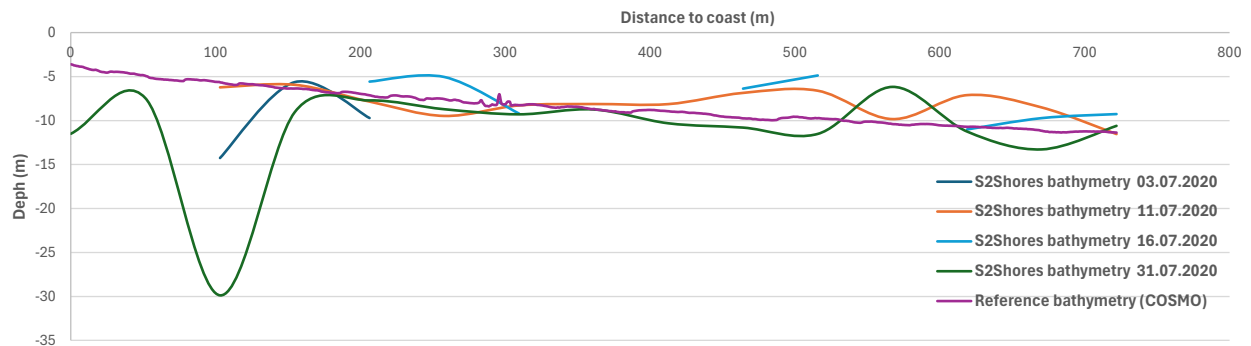


Figure 77 - Longitudinal profile 4 – Douro estuary 2020/07 (50m resolution).

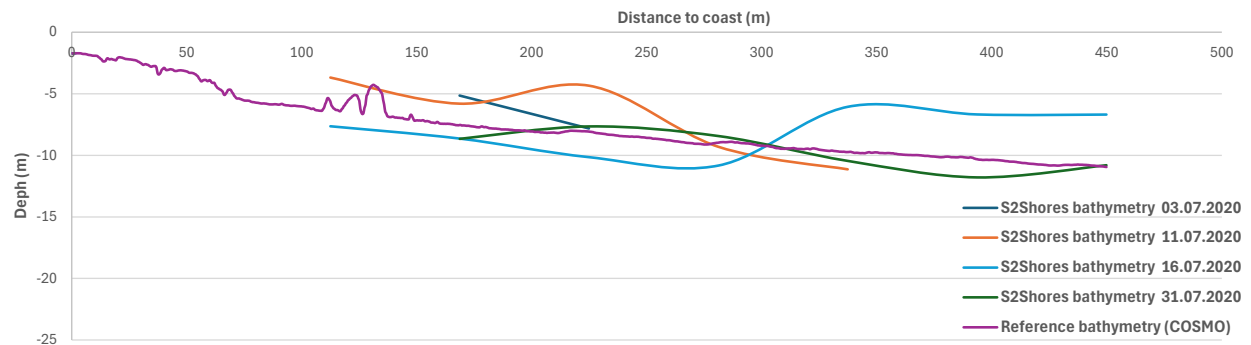


Figure 78 - Longitudinal profile 5 – Douro estuary 2020/07 (50m resolution).

For detailed bathymetric analysis, the satellite image acquired on July 31st of 2020 was selected for high-resolution processing (10 m grid resolution) using the S2Shores algorithm. Following depth estimation, a vertical correction was applied to align the satellite-derived bathymetry (SDB) with *in-situ* reference levels. This correction involved subtracting the 2-meter mean water level (MWL) offset and the tidal elevation of 1.023 m expected near the time of satellite image acquisition.

Table 11 - Tidal elevation Douro estuary 2020/07.

Date	Time	Tide level (m)
20200731	11:30:00	1.023

The resulting bathymetry, after correction, is presented next, *i.e.*, the longitudinal profiles (Figure 79 to Figure 83) and seafloor depth map (Figure 84) representations for its comparison with *in-situ* measurements.

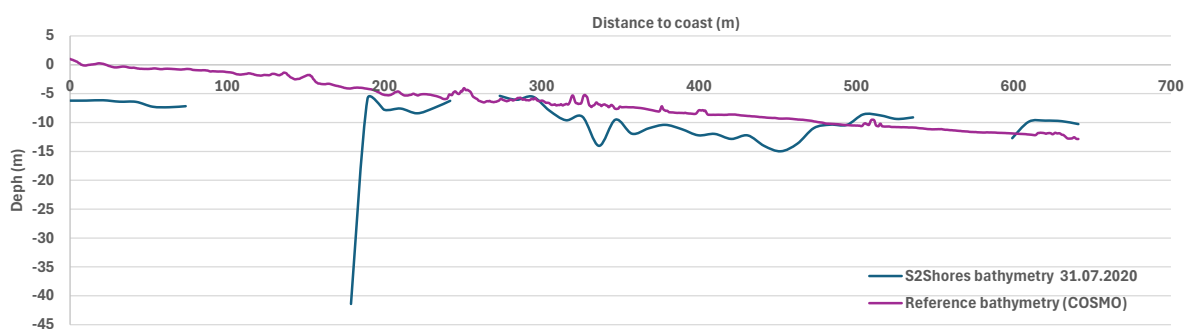


Figure 79 - Longitudinal profile 1 – Douro estuary 2020/07 (10m resolution).

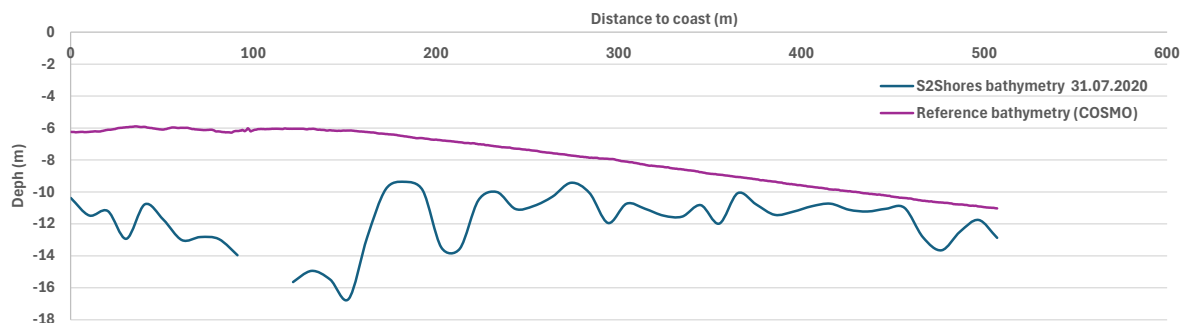


Figure 80 - Longitudinal profile 2 – Douro estuary 2020/07 (10m resolution).

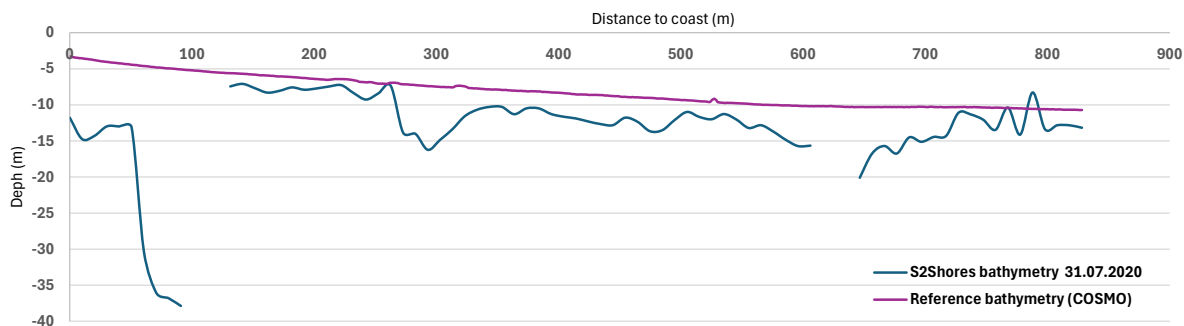


Figure 81 - Longitudinal profile 3 – Douro estuary 2020/07 (10m resolution)

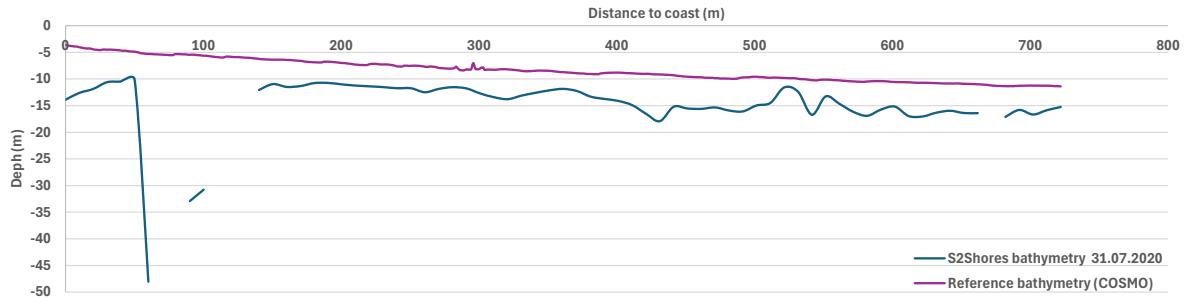


Figure 82 - Longitudinal profile 4 – Douro estuary 2020/07 (10m resolution)

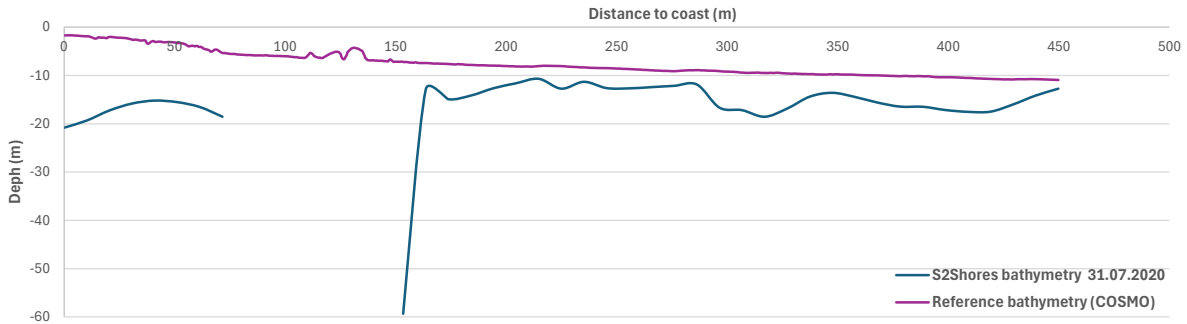


Figure 83 - Longitudinal profile 5 – Douro estuary 2020/07 (10m resolution).

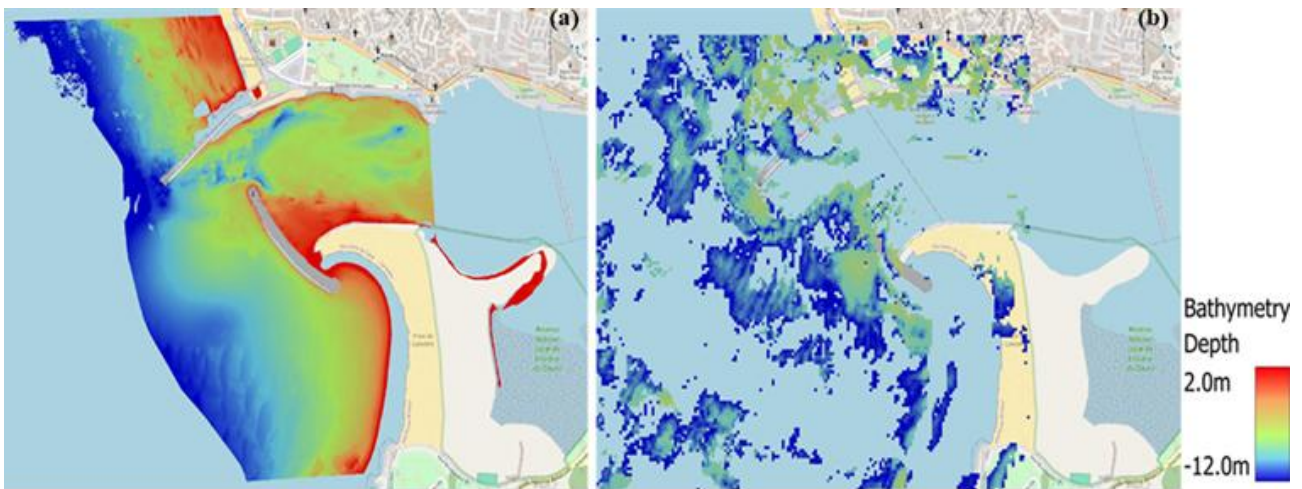


Figure 84 - Bathymetric data in Douro estuary 2020/07: (a) Referential *in-situ* method (from COSMO); (b) - SDB (from S2S).

Repeating the process for **August of 2019**, the pre-selected satellite images are:

- SENTINEL2X 2019/08/15 at 00:00:00
- SENTINEL2A 2019/08/16 at 11:39:59
- SENTINEL2B 2019/08/21 at 11:40:01
- SENTINEL2A 2019/08/26 at 11:39:57

Starting with the initial pre-selection approach, the S2Shores algorithm was processed at a 50-meter resolution, generating a set of bathymetric outputs. The resulting cross-sections, presented at Figure 85 to Figure 89, provide a representation of depth variations, allowing for an initial assessment of the algorithm's performance in nearshore bathymetric estimation.

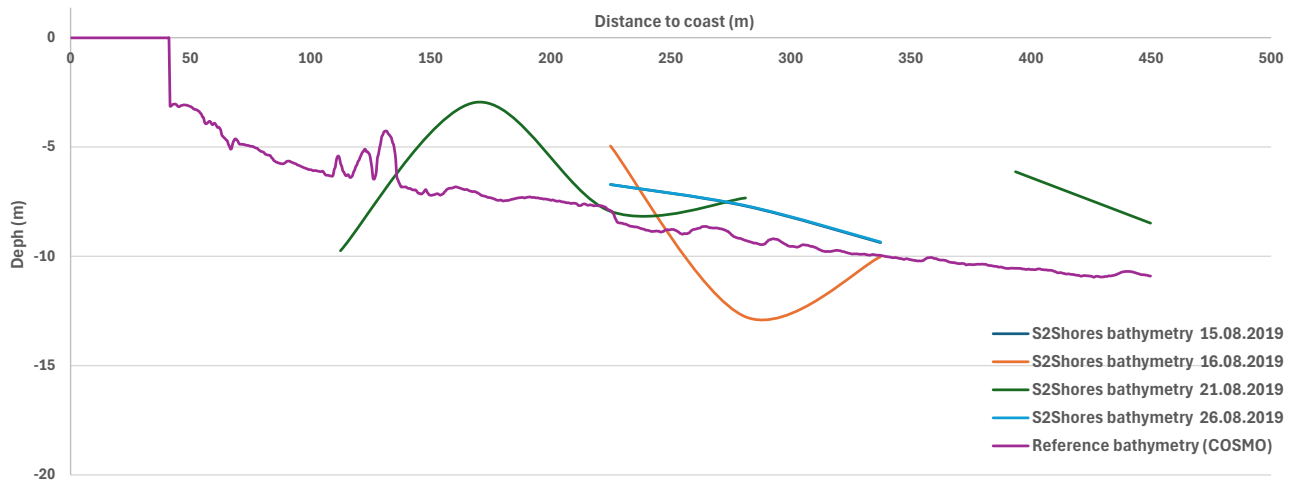


Figure 85 - Longitudinal profile 1 – Douro estuary 2019/08 (50m resolution).

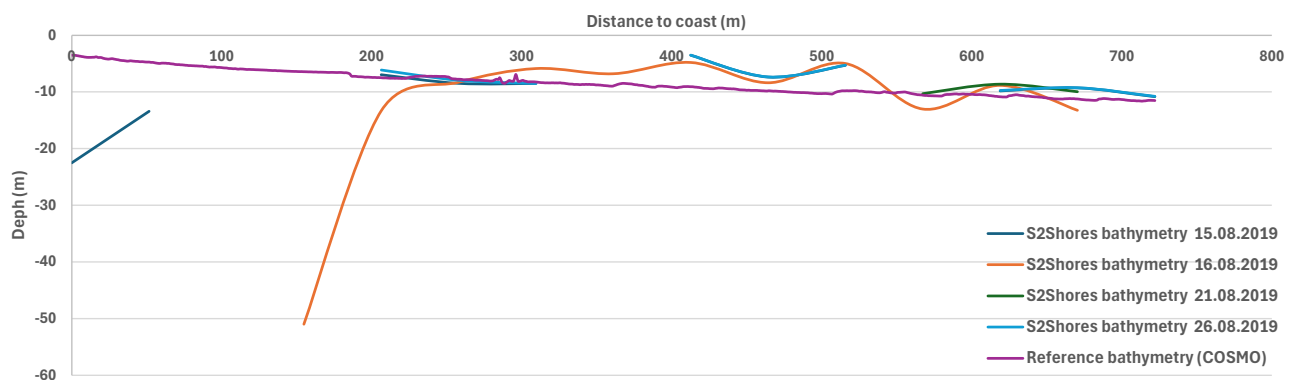


Figure 86 - Longitudinal profile 2 – Douro estuary 2019/08 (50m resolution).

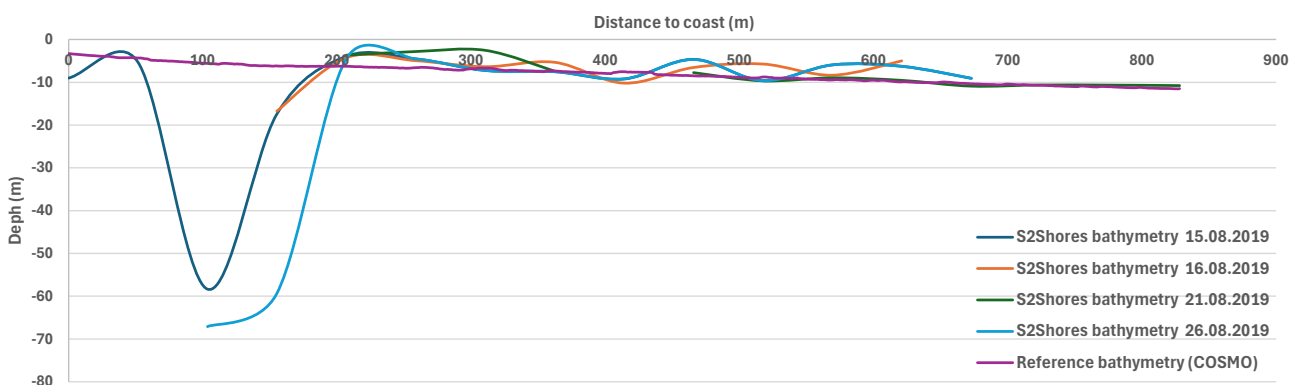


Figure 87 - Longitudinal profile 3 – Douro estuary 2019/08 (50m resolution).

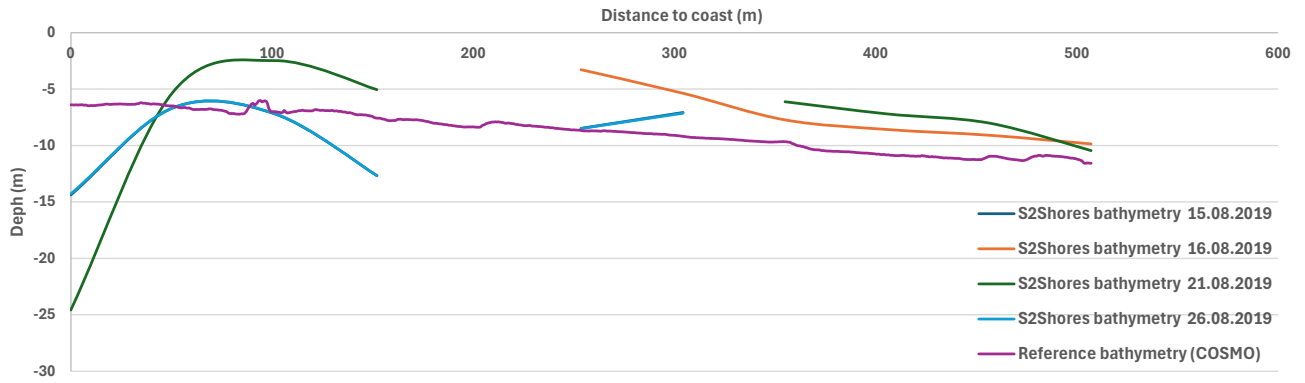


Figure 88 - Longitudinal profile 4 – Douro estuary 2019/08 (50m resolution).

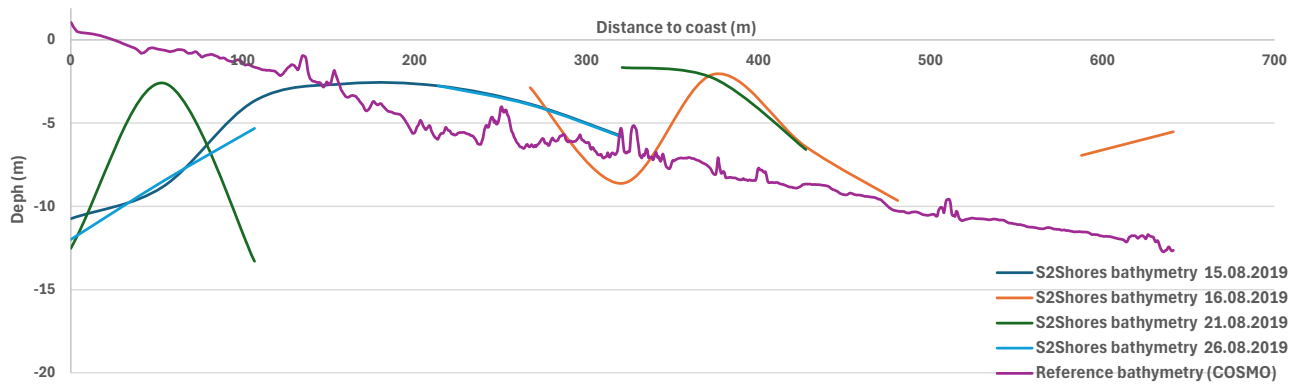


Figure 89 - Longitudinal profile 5 – Douro estuary 2019/08 (50m resolution).

The analysis of satellite-derived bathymetry (SDB) results reveals variability across different images, with certain cross-sections showing gaps in the calculated depth values. Among the available images, the August 21st, 2019, satellite image was selected for high-resolution processing at 10 m grid resolution, as it contained the highest number of valid depth estimates with the least dispersion in results. To ensure consistency with *in-situ* bathymetric measurements, the S2Shores-derived depth output was subjected to vertical correction. This process involved subtracting the 2 m mean water level (MWL) offset and adding 0.89 m from the tide level (Table 12).

The resulting bathymetry, after correction, is presented next, providing the longitudinal profiles (i.e., Figure 90, Figure 91, Figure 92, Figure 93, Figure 94) and the seafloor depth map (Figure 95) representations for its comparison with the *in-situ* COSMO surveys.

Table 12 - Tidal elevation Douro estuary 2019/08.

Date	Time	Tide level (m)
20190821	11:30:00	-0.89

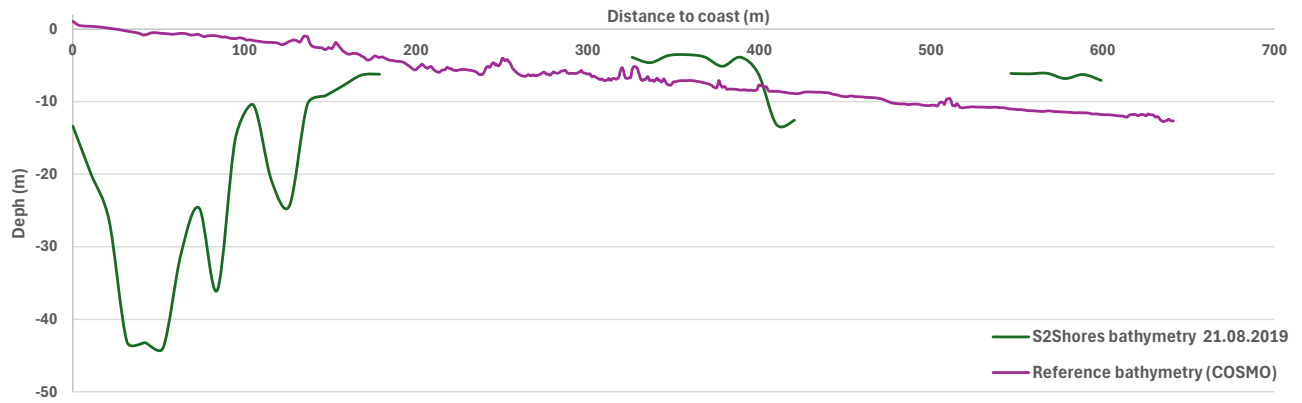


Figure 90 - Longitudinal profile 1 – Douro estuary 2019/08 (10m resolution).

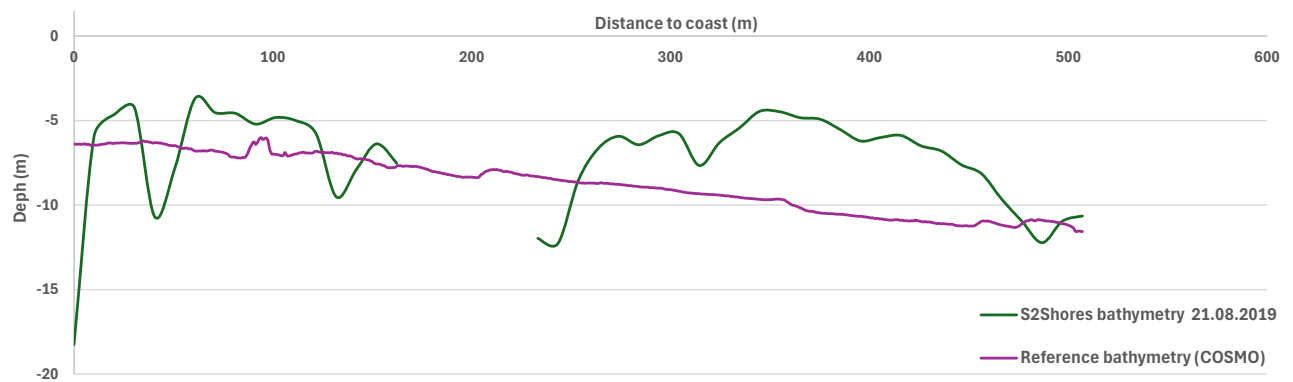


Figure 91 - Longitudinal profile 2 – Douro estuary 2019/08 (10m resolution).

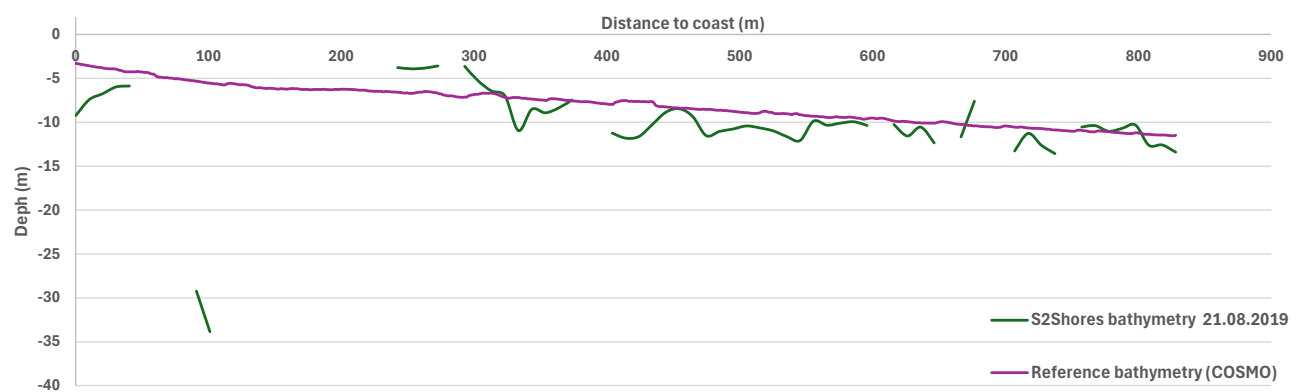


Figure 92 - Longitudinal profile 3 – Douro estuary 2019/08 (10m resolution).

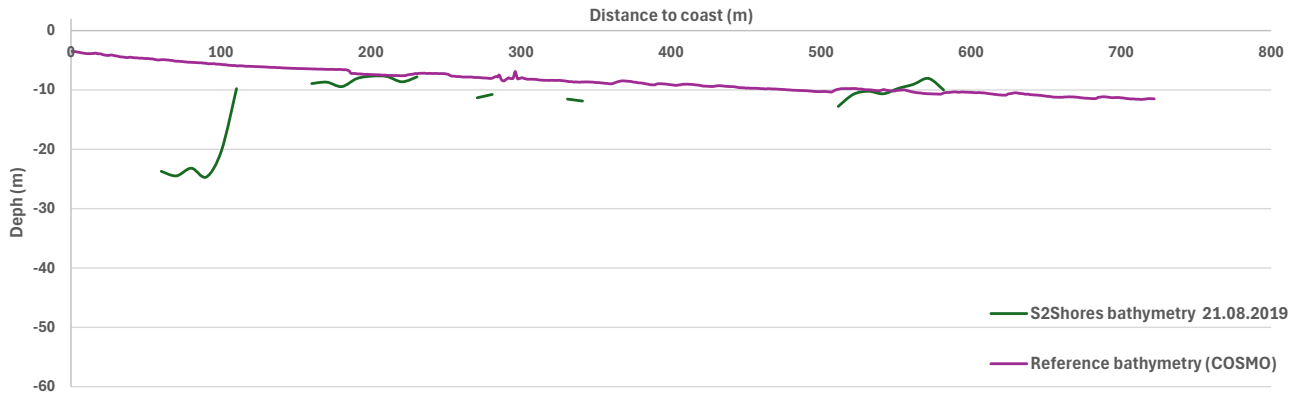


Figure 93 - Longitudinal profile 4 – Douro estuary 2019/08 (10m resolution).

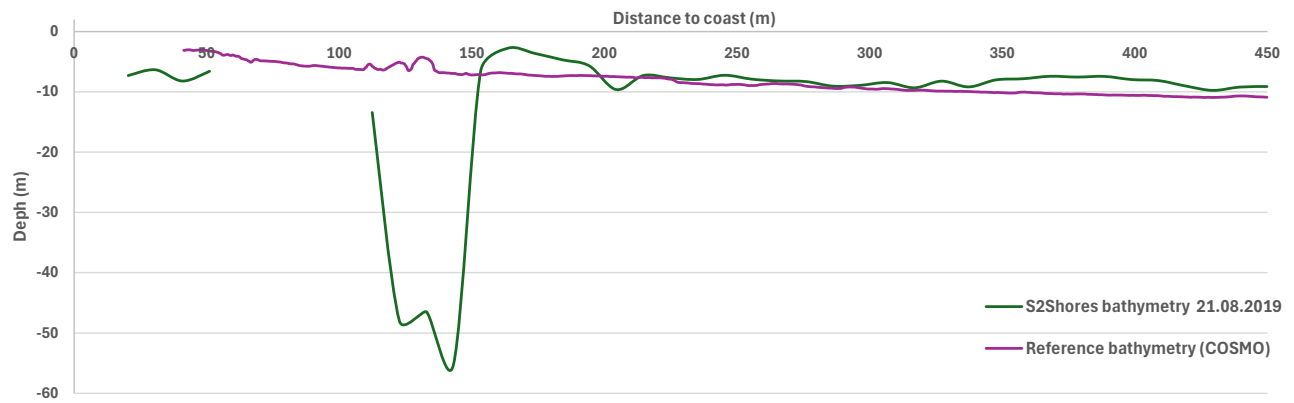


Figure 94 - Longitudinal profile 5 – Douro estuary 2019/08 (10m resolution).

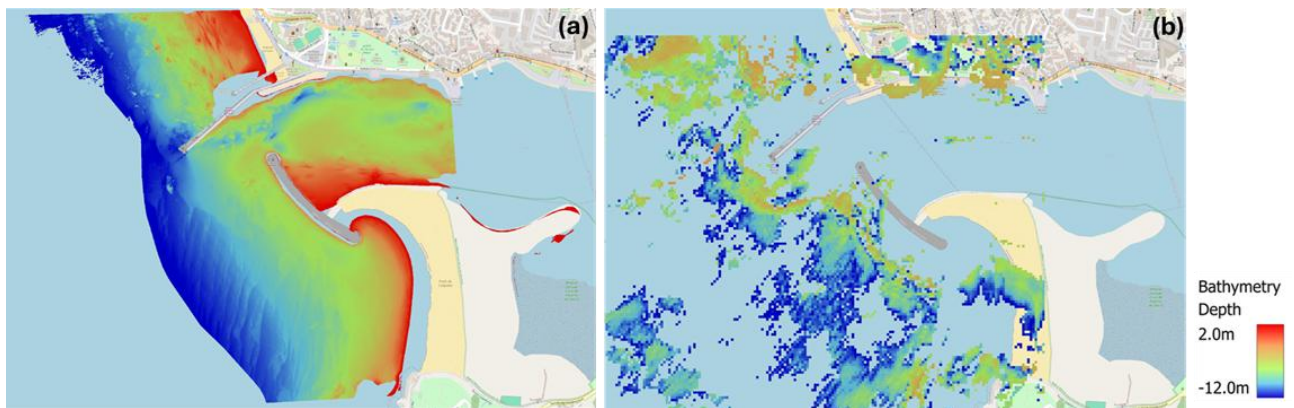


Figure 95 - Bathymetric data in Douro estuary 2019/08: (a) Referential *in-situ* method (from COSMO); (b) - SDB (from S2S).

5.1.3 ANALYSIS OF RESULTS

The S2Shores algorithm exhibits limitations in accurately estimating bathymetry near the shoreline, particularly in areas where wave breaking occurs. This behaviour was expected, as wave breaking disrupts wave kinematics, making it difficult for the algorithm to reliably compute depth in these regions. In these wave-breaking zones, the presence of gaps is encountered or/and unrealistic depth values near the shoreline, which was expected due to the inability of the algorithm to accurately compute water depth. The complex hydrodynamics in these areas introduce noise into the SDB processing, resulting in unreliable outputs.

The bathymetric outputs display significant inconsistencies and inaccuracies, with high variability in water depth estimates, even between points in close proximity. In some profiles, adjacent points display depth differences exceeding 5 m, highlighting the instability of the algorithm's results. Additionally, large portions of the study area contain null values, where the algorithm was unable to generate valid depth estimates.

When comparing the two study sites, the S2Shores results for Furadouro beach appear more stable than those obtained for the Douro estuary, where depth variations and null outputs are more pronounced. This discrepancy may be attributed to differences in wave conditions and hydrodynamic processes between the two environments.

While it was never expected that results of this satellite-derived bathymetry method would match perfectly the 30 cm resolution of *in-situ* traditional surveys, despite known challenges created by shallow water environments, it was projected that the algorithm would be able to draw isolines to a sufficient accuracy degree for the purposes of the present study. However, this expectation was not met with the used version of the algorithm since contours lacked consistency.

Given these limitations, this research findings indicate that the SDB is not yet a reliable method for bathymetric assessment in these locations, particularly beyond 2 km from the coast. As a result, it was not possible to validate the use of satellite imagery for this study and, consequently, it was not possible to conduct a monthly bathymetric assessment over the two-year period. Therefore, only the annual *in-situ* measurements will be used in the analysis. Further methodological improvements and refinements in data processing and validation techniques would be necessary before considering the S2shores method a viable tool for bathymetric monitoring in these challenging nearshore locations.

5.2. *IN-SITU* TOPO-HYDROGRAPHIC SURVEYS – MORPHODYNAMIC ANALYSIS

The COSMO surveys apply a combination of multibeam and single-beam echosounders for bathymetric mapping, complemented by topographic data acquired through UAV-based aerial photogrammetry, integrated with GNSS/RTK positioning. This multi-sensor approach results in a high-resolution Digital Elevation Model (DEM), freely accessible for coastal studies, with a 30 cm spatial resolution for both topography and bathymetry.

This dataset enables the direct measurement of key morphodynamic indicators, including sediment volume, dune and beach height, beach width, shoreline position, and total surface area. Quantifying parameters makes it possible to calculate sediment budgets, explore variations in shoreline at different rates, and evaluate morphological variations in seafloor and beach profiles. The current dissertation compares high-resolution topography and bathymetry for the years 2018, 2019, and 2020 and visualizes and analyses the data using QGIS software. The current research work puts emphasis on descriptive and quantitative research related to yearly morphodynamics at Douro estuary and Furadouro beach and intends to relate observed morphological variations to key driving parameters such as river discharge (in case of the Douro estuary) and wave energy variations.

The initial step in the analysis involves correcting the vertical reference of the COSMO Digital Elevation Model (DEM), as this dataset is referenced to chart datum, which is positioned 2 m below the mean sea level (MSL). To facilitate accurate sediment budget calculations, a 2 m subtraction is applied to the original data. From this point

forward, the data is analysed considering the 0 m level as the reference shoreline level, while accounting for tidal fluctuations of ± 1.5 m.

5.2.1 FURADOURO

By separating the COSMO Digital Elevation Model into distinct bathymetric and topographic datasets, and computing the difference between the 3 successive survey dates, it is possible to quantify morphological changes. The resulting analysis is presented in Figure 96 and Figure 97, which illustrate the bathymetric and topographic variations observed over two distinct time intervals: a 10-month period (September 2018 to July 2019) and a 12-month period (July 2019 to July 2020).

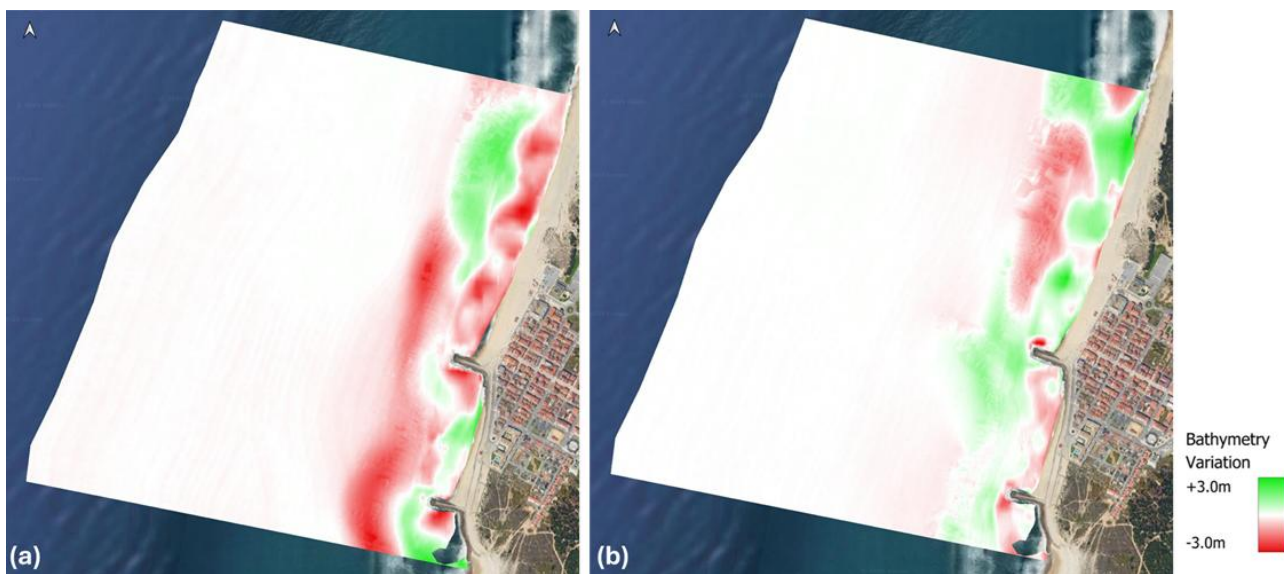


Figure 96 - Map view of bathymetric variation in Furadouro beach: (a) Variation between 09/2018 and 07/2019; (b) Variation between 07/2019 and 07/2020.

The bathymetric variation maps (Figure 96) illustrate changes in seabed elevation between September 2018 – July 2019 (a) and July 2019 – July 2020 (b). The colour scale represents sediment deposition (green, positive values), erosion (red, negative values) and no variation (white, null values). It is possible to identify:

- There is a noticeable reversal in erosion and accretion patterns between the two periods. Areas that experienced erosion (red) between 2018 and 2019 appear to have transitioned to accretion (green) in 2019–2020, particularly in the inter-groin zones and the nearshore region.
- Close to the shoreline, particularly along the wave-breaking zone, there is significant morphological instability, as shown by alternating regions of erosion and accretion in both panels.
- No consistent spatial pattern in sediment distribution.

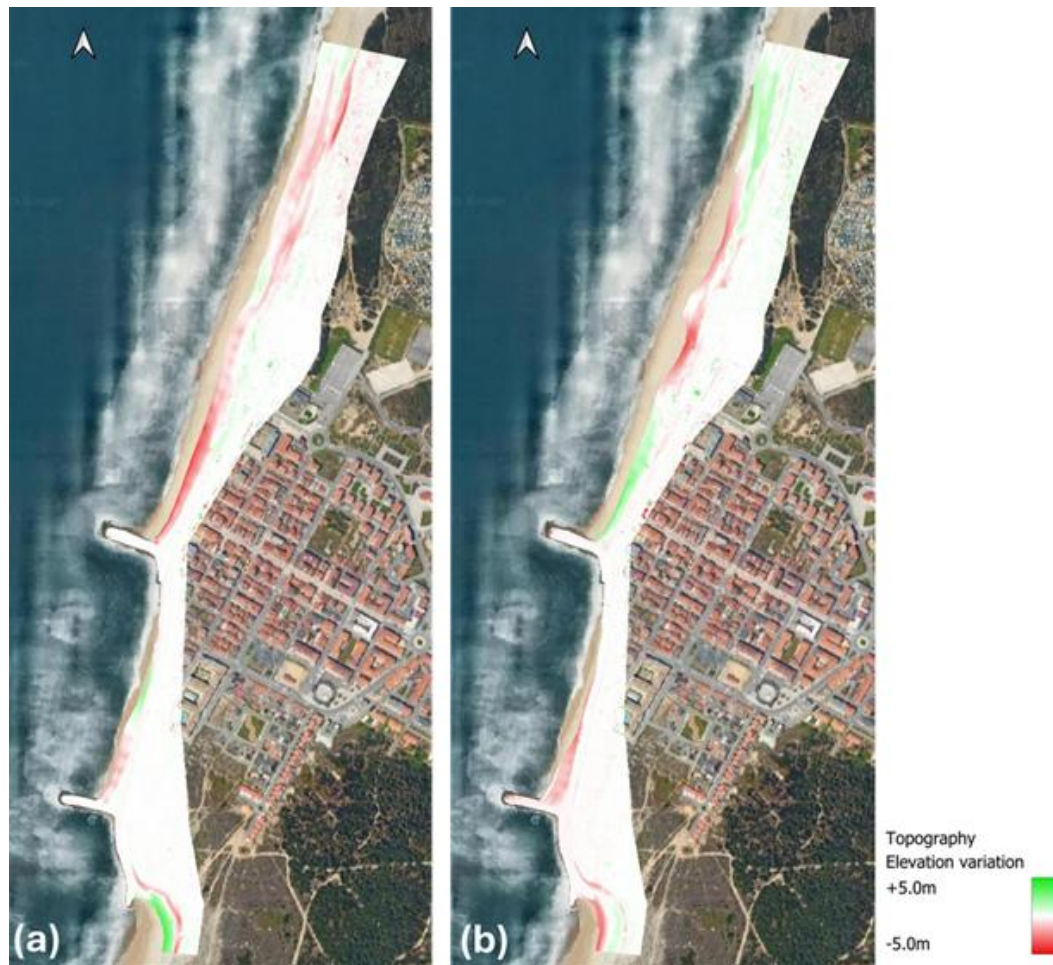


Figure 97 - Map view of topographic variation in Furadouro beach: (a) Variation between 09/2018 and 07/2019; (b) Variation between 07/2019 and 07/2020.

The topographic variation maps (Figure 97) illustrate elevation changes between September 2018 – July 2019 (a) and July 2019 – July 2020 (b). The colour scale represents sediment deposition (green, positive values), erosion (red, negative values) and no variation (white, null values). It is possible to identify:

- Seaward of the southern groin exhibits persistent erosion across both periods;
- Between 2018 and 2019 (a), erosion (red) dominates the upper beach and dune regions, particularly in the northern and central sections of the study area.
- In the following period, 2019–2020 (b), some previously eroded areas appear to have recovered (accretion in green).
- The foreshore and nearshore zones exhibit alternating patterns of erosion and accretion, suggesting seasonal sediment movement.

This region exhibits high morphodynamic variability, with significant shifts in sedimentary deposition and erosion patterns over time. To better analyse these changes, the study area has been subdivided into two main sectors: the northern sector and the southern sector. As illustrated in Figure 98, provides a structured approach for assessing volume variation across 2 distinct coastal segments. By separately calculating bathymetric and topographic volume changes within each sector, the values presented in Table 13 were obtained.



Figure 98 - Furadouro beach area sectorized.

Dividing Furadouro Beach into two sections, north and south, with the northern groin as a reference point, revealed intriguing patterns in sediment distribution. The analysis of topographic and bathymetric variations (Table 13) over the survey periods showed an inverse relationship between the north section and the southern area—when one lost sediment, the other gained volume. During the September of 2018 to July of 2019 period, the northern section experienced significant sediment loss, both in seabed and on the beach, while the beach between the groins exhibited a net gain in sediment volume. However, in the July 2019 to July of 2020 period, this distribution reversed. The coastal bathymetry and the northern section showed positive sediment accumulation, whereas the beach between the groins underwent a reduction in volume. Despite the southern section being smaller than the northern section, its sediment volume variations were significantly larger, indicating that this area is far more susceptible to morphological changes. This indicates that the southern section is more dynamically active, more susceptible to hydrodynamic forces and sediment transport processes.

Table 13 - Volume variation calculations – Furadouro beach.

	North	South
Topography	Volume variation (m ³)	Volume variation (m ³)
2019-2018	-36569.5	3800.8
2020-2019	9076.9	-13841.7
Bathymetry	Volume variation (m ³)	Volume variation (m ³)
2019-2018	-158470.9	-261333.7
2020-2019	13037.9	31786.3

To assess the elevation variations of the dunes and beach morphology at Furadouro Beach, a detailed evaluation was conducted using the selected profiles presented in Figure 99.



Figure 99 - Profiles for topographic analysis – Furadouro beach.

The first profile (Figure 100), representing the northern sector, captures the longitudinal elevation changes of the northern beach, including the secondary dunes. The analysis reveals a consistent erosion pattern over the two-year period, indicating sediment loss and a progressive retreat of the dune system. The X-coordinates refer to the PT-TM06 ETRS89 projected coordinate system (EPSG:3763) and elevations are relative to the local vertical datum.

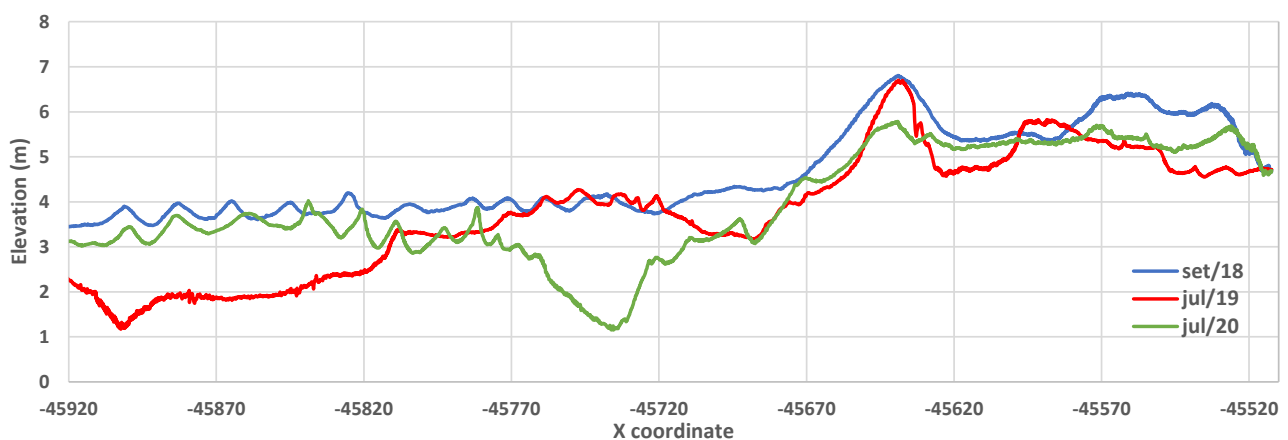


Figure 100 - Longitudinal profile 1 – Topography of Furadouro beach. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

The second profile (Figure 101) corresponds to the longitudinal profile of the beach in between groins. The data reveals a characteristic longshore sediment distribution pattern commonly associated with groin systems. Specifically, sediment accumulation is observed on the updrift side, near the southern groin, where wave-induced transport is interrupted, leading to deposition. While erosion is evident on the downdrift side, where sediment supply is restricted, resulting in a net loss of material.

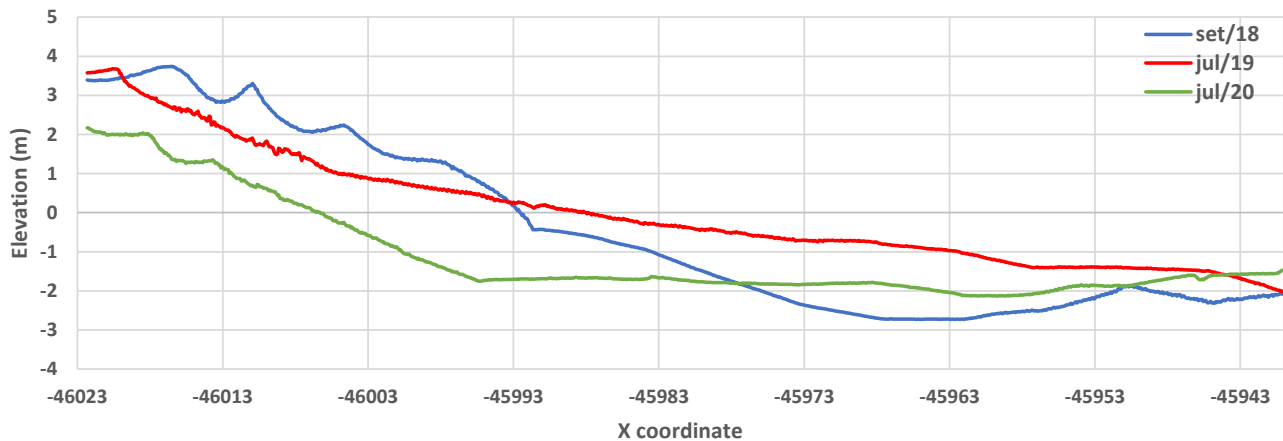


Figure 101 - Longitudinal profile 2 – Topography of Furadouro beach. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

Profile 3 (Figure 102) captures the beach berm edge and dunes located south of the revetment. Over the study period, the dune system exhibited a gradual decrease in elevation, indicating continuous erosion.

The beach berm, however, showed a more dynamic behaviour, experiencing accretion between September of 2018 and July of 2019, followed by sediment loss leading into July 2020, probably due to a redistribution of material influenced by wave and wind forces.

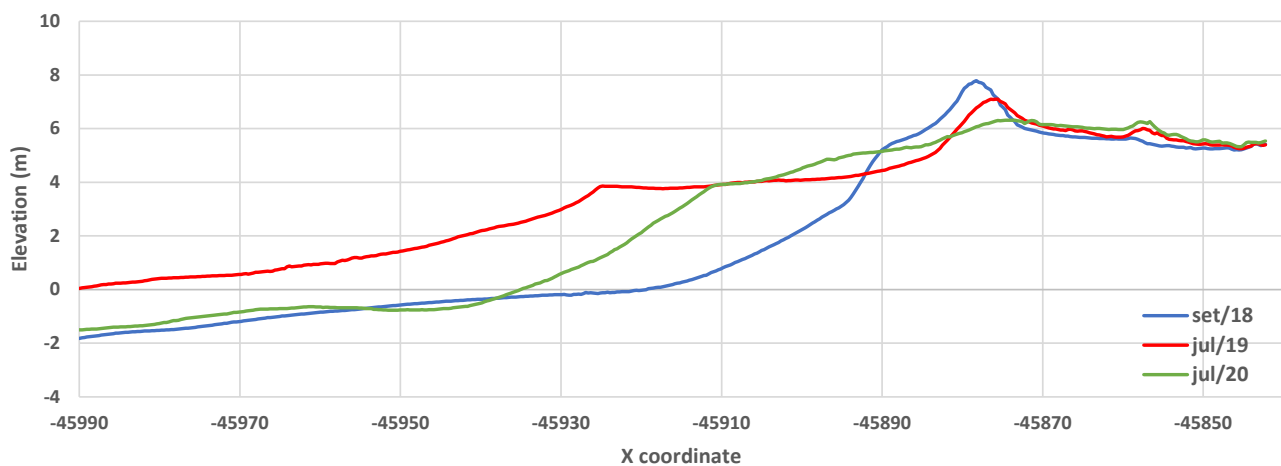


Figure 102 - Longitudinal profile 3 – Topography of Furadouro beach. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

Additionally for a more detailed and direct comparison of vertical elevation changes in both bathymetry and topography it was defined the cross-sections illustrated in Figure 103.

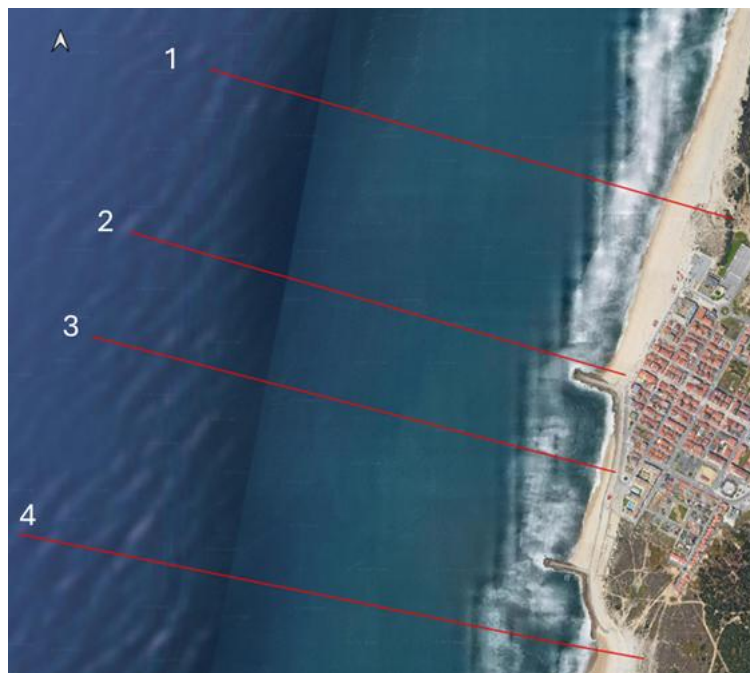


Figure 103 - Cross sections for bathymetry analysis – Furadouro beach.

Cross-section 1 is located on the northern beach, at the boundary of Furadouro village. Its longitudinal profile (Figure 104) reveals notable stability in the dune system, as well as a consistent slope in the swash zone over the analysed period. The July 2019 profile (represented in red) indicates the presence of a deeper trough, while simultaneously displays a more elevated longshore bar. This pattern may reflect sediment redistribution due to stronger wave-induced transport processes.

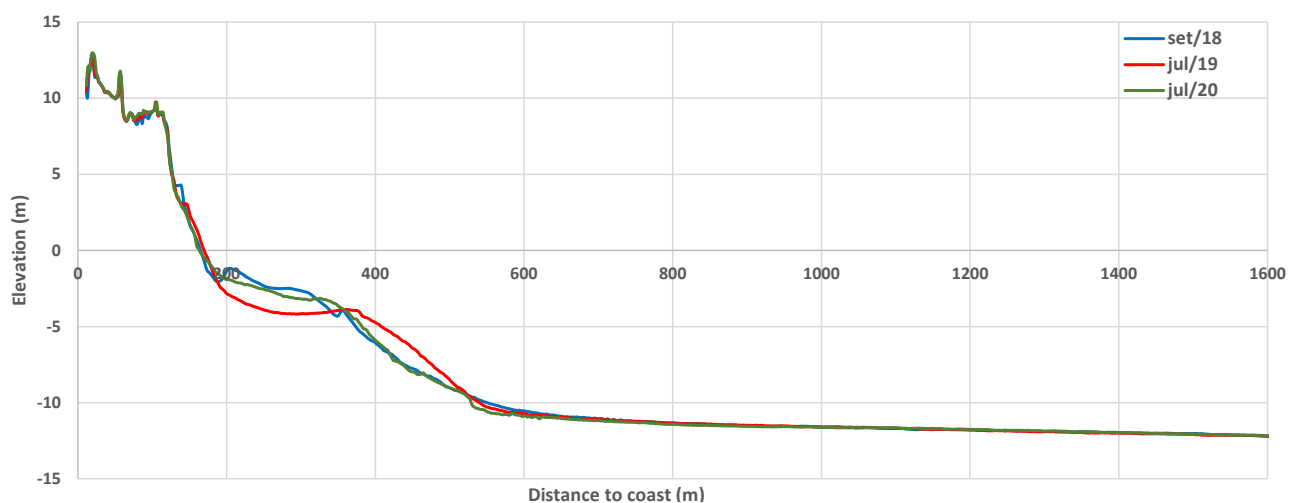


Figure 104 - Longitudinal profile 1 – Furadouro beach.

In Cross-section 2 (Figure 105), located seaward of the northern groin, distinct morphological variations can be observed over the analysed period. In 2018, the beach berm is more elevated, positioned approximately 50 m from the shoreline, whereas in 2019 and 2020, the berms appear at a similar, lower elevation. The beach slope in 2018 and 2020 looks relatively parallel, while the 2019 profile exhibits a significantly steeper gradient, indicating increased sediment loss and erosion during that period. Additionally, the 2020 profile reveals localized scouring near the tip of the groin (between 100 and 200m distance to coast), suggesting intensified hydrodynamic activity in this region. In the breaker zone, the seabed slope slightly varies across the years, and the 2019 profile, also presents to be positioned at a lower elevation, further supporting evidence of sediment erosion during that time frame.

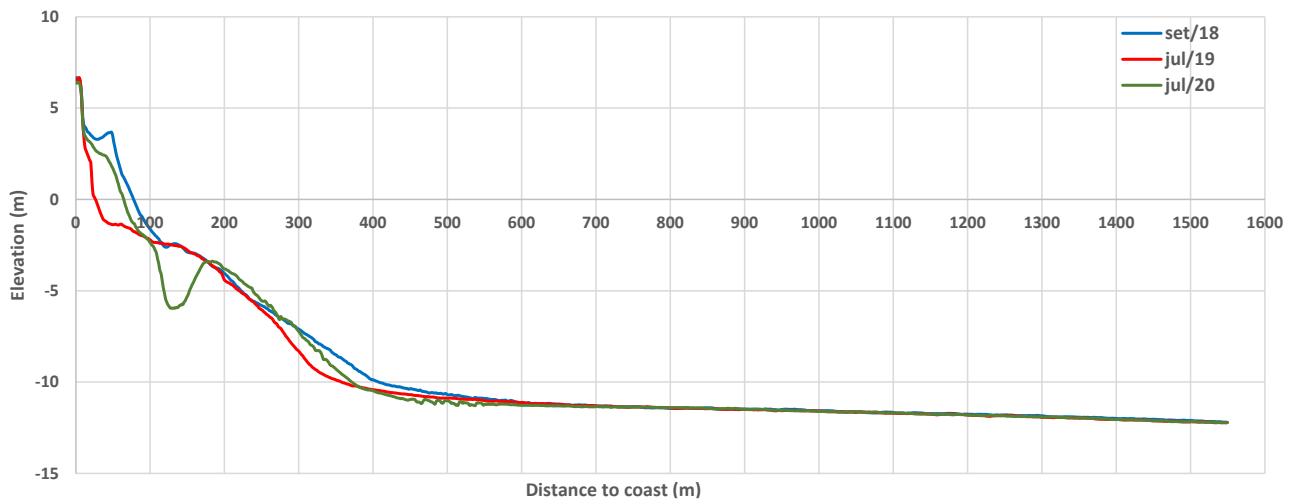


Figure 105 - Longitudinal profile 2 – Furadouro beach.

Cross-section 3 (Figure 106) located between the groins, further highlights the distinct morphological behaviour of the July 2019 profile compared to other years. Unlike the 2018 and 2020 profiles, the 2019 cross-section is the only one exhibiting a well-defined backshore with a distinct beach surface. In the breaker zone (>150 m distance to coast), the 2019 profile maintains a similar slope relative to the other years but is positioned at a lower elevation, indicating sediment loss. While the 2018 and 2020 profiles share a more comparable morphology, it is evident that the surf zone in 2020 has only partially recovered from the accretion observed in 2019.

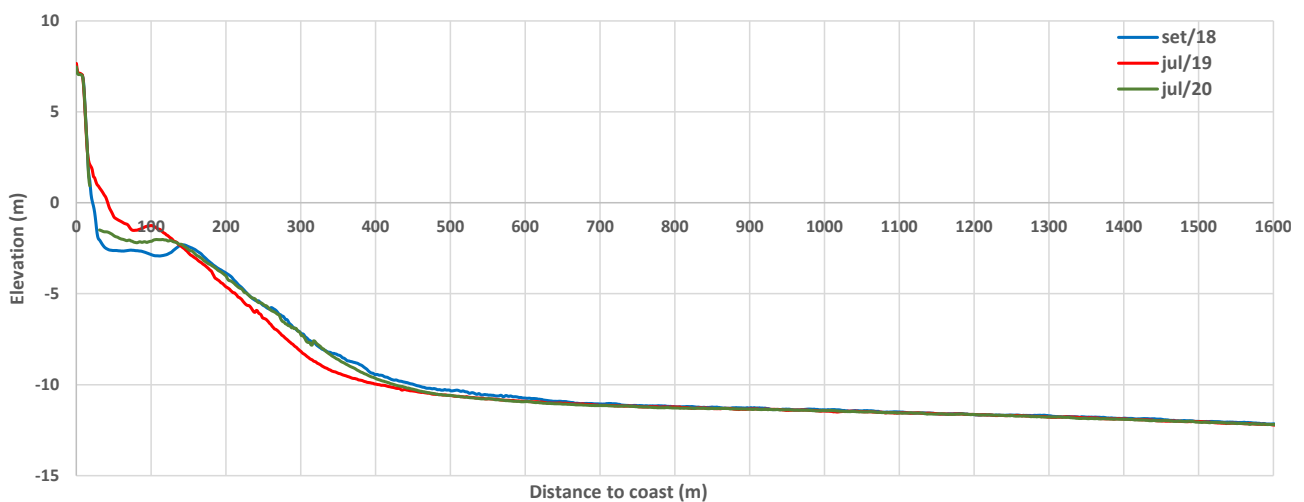


Figure 106 - Longitudinal profile 3 – Furadouro beach.

The fourth cross-section, located at the southernmost extent of the surveyed area, exhibits notable morphological changes over the analysed period. The graph (Figure 107) indicates a progressive reduction in dune height over the years. Between 2018 and 2019, accretion occurred, leading to the formation of a distinct backshore, as evidenced by the well-defined beach berm and beach slope in the July 2019 profile, approximately at 100 meters from the shoreline. Beyond this, the surf zone presents distinct variations across the different profiles. The trough, dislocated to a higher level and migrated closer to shore between 2018 and 2019, and in 2020, the trough shifted slightly seaward and lowered the elevation level, indicating partial morphological adjustment following the pronounced changes observed in the previous year.

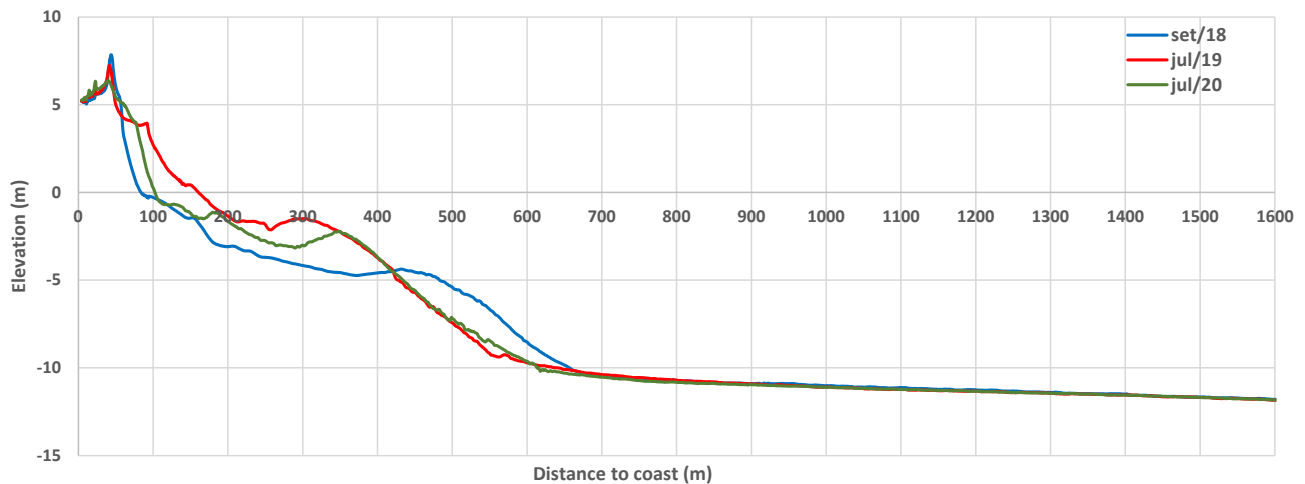


Figure 107 - Longitudinal profile 4 – Furadouro beach.

The most significant morphological variations are observed within approximately 600 m from the shoreline, where wave-driven sediment transport and hydrodynamic forces exert the greatest influence. Beyond this distance, in deeper offshore areas, changes in seabed elevation become less pronounced, indicating a more stable substrate with reduced sediment mobility. A clear pattern of erosion is observed between September 2018 and July 2019, particularly in the nearshore zone and areas adjacent to groin structures. These zones exhibit heightened sensitivity to erosional forces, likely due to the combined effects of wave action, longshore currents, and human interventions. Subsequent monitoring from July 2019 to July 2020 indicates a partial recovery of the coastline, characterized by sediment accretion. However, the extent of recovery varies significantly depending on the specific profile location. This variability may be attributed to differences in local hydrodynamic conditions, sediment supply, and the presence of coastal structures.

5.2.2 DOURO ESTUARY

Separating the COSMO Digital Elevation Model into distinct bathymetric and topographic datasets and computing the difference between the 3 successive survey dates, it is possible to quantify morphological changes. The resulting analysis is presented in Figure 108 and Figure 109, which illustrate the bathymetric and topographic variations observed over two distinct time intervals: a 11-month period (September 2018 to August 2019 to July 2020).

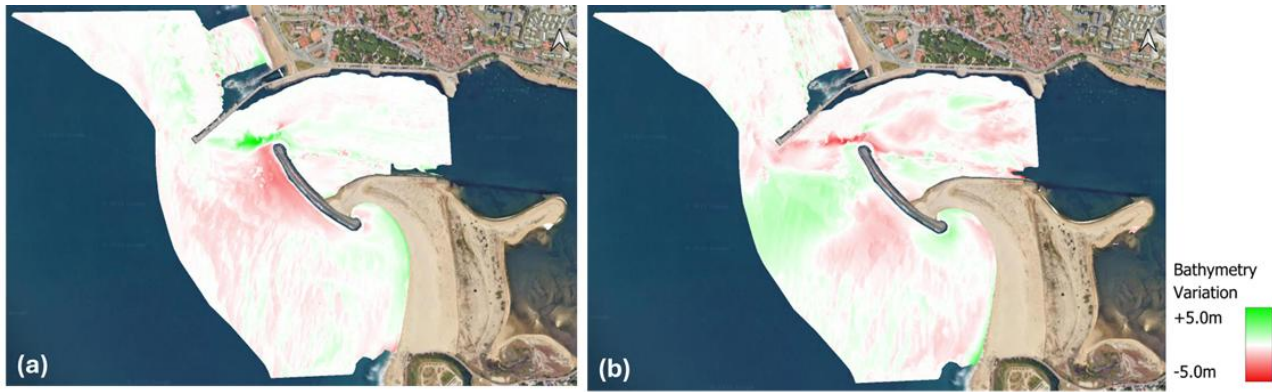


Figure 108 - Map view of bathymetric variation in Douro estuary: (a) Variation between 09/2018 and 07/2019; (b) Variation between 07/2019 and 07/2020.

The bathymetric variation maps (Figure 108) illustrate changes in seabed elevation. The colour scale represents sediment deposition (green, positive values), erosion (red, negative values) and no variation (white, null values). It's possible to identify a noticeable reversal in erosion and accretion patterns between the two periods in some areas. Areas that experienced erosion (red) between 2018 and 2019 appear to have transitioned to accretion (green) in 2019–2020 and vice versa, particularly in the navigational channel and the near the shoreline. From these images its observable any consistent spatial pattern in sediment distribution.

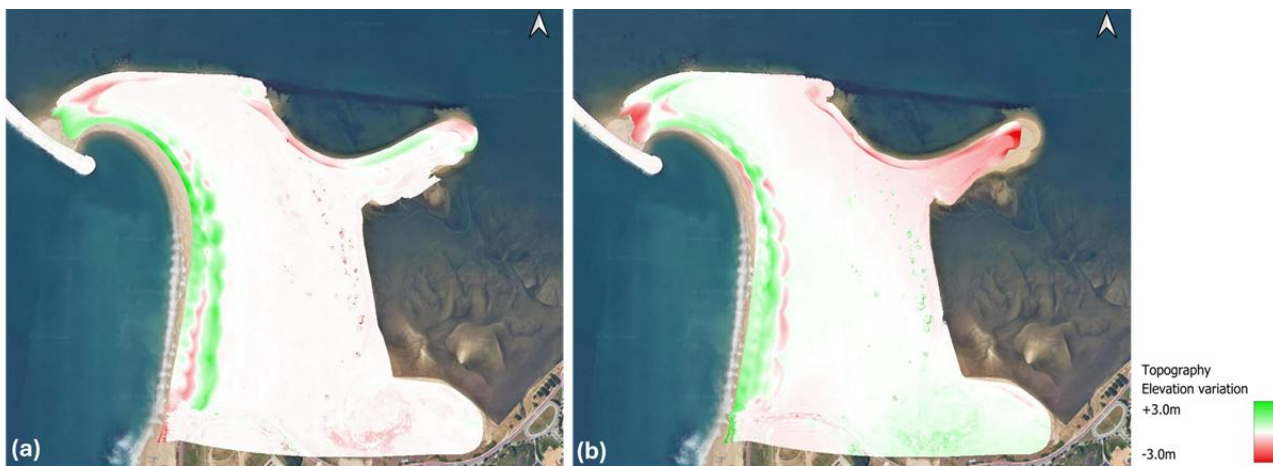


Figure 109 - Map view of topographic variation in Cabedelo beach: (a) Variation between 09/2018 and 08/2019; (b) Variation between 08/2019 and 07/2020.

Analysis of the two images reveals (in Figure 109) significant morphological changes in the northeastern inland arm of the sandspit over the study period. Between 2018 and 2019, this feature exhibited growth in height in the riverside. However, from 2019 to 2020, the whole arm experienced a reduction in elevation, particularly at its tip. Closer to the shoreline, an overall trend of accretion is evident, contributing to beach widening. Additionally, dune formations display variations in height along the coast, suggesting localized sediment deposition and redistribution processes shaped by wind and wave action.

The topography of this case study is the Douro estuary's sand spit known as Cabedelo do Douro beach. To facilitate the analysis, the structure is divided into four sections, based on the approach previously adopted by Bastos et al., (2012), as illustrated in Figure 110.



Figure 110 - Sandspit sector division. Coordinates in PT-TM06 ETRS89 (EPSG:3763).

In each sector it is calculated the volume of sediments lost or gained in between surveys. Resulting in the values shown in Table 14.

Table 14 - Cabedelo sandspit volume variation between surveys.

	Topography			
Volume Variation (m³)	NW	NE	SW	SE
2019-2018	+17265.6	-5943.1	+13845.3	-11850.6
2020-2019	+6569.16	-26757.9	+16947.0	+16662.1

The southwest of the beach shows yearly volume growth. The northeast side of the sandspit, on the innerside of the estuary, shows yearly erosion specially suffering in the inland arm, while the NE sector had a significant increase in erosion, highlighting it as a vulnerable area. The SE sector shifted from erosion to strong accretion, suggesting dynamic sediment redistribution.

For the bathymetric volume assessment, it is considered a division in 4 parts (identified in Figure 111 as A, B, C and D) each defined by its specific hydrodynamic and morphological context: the riverside of the estuary (A), the transitional area between the river and the sea (B), seaward side of the estuary (C) and the nearshore area adjacent to the sand spit (D).

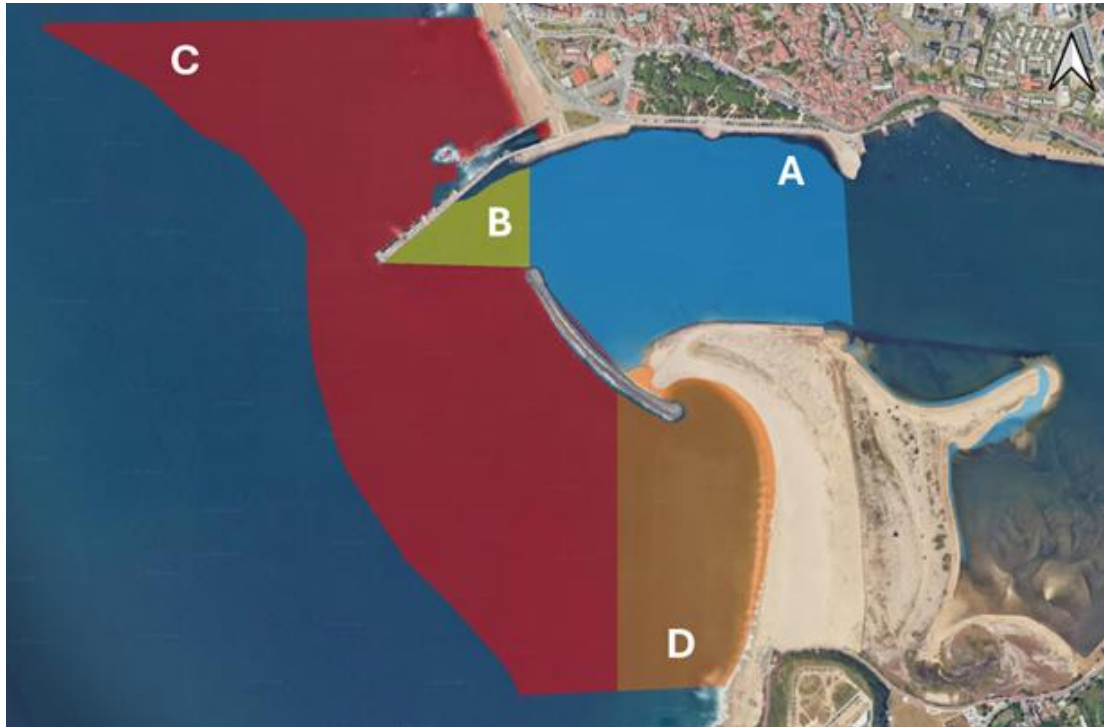


Figure 111 - Bathymetry division.

In each sector it is calculated the volume of sediments lost or gained in between surveys. Resulting in the values shown in Table 15.

Table 15 - Douro estuary bathymetric volume variation between surveys.

	Bathymetry			
Volume Variation (m³)	A	B	C	D
2019-2018	+13460.0	+22015.3	-133303.6	+32754.3
2020-2019	-50751.8	-20993.8	+64009.79	-3494.87

The estuary reveals a highly dynamic sedimentary environment, with all areas alternating between sediment accretion and erosion across the two analysed periods. During the first period (September 2018 to August 2019), the riverside area (Zone A) and the entrance of the navigational channel (Zone B) experienced sediment accretion and in the following period (August 2019 to July 2020), both areas transitioned to erosion. Zone B lost a sediment volume comparable to its previous gain, while Zone A exhibited a much more pronounced sediment loss—over three times greater than its earlier accretion. The marine-facing section (Zone C) displayed the most extreme fluctuations, initially undergoing substantial sediment loss in 2018–2019. However, in 2019–2020, it recovered approximately half of the previously eroded volume. The southernmost sector (Zone D), typically a more sheltered environment where fluvial and tidal wash-over deposits accumulate, also demonstrated a dynamic sediment regime. In the first period, it experienced significant accretion, however, in the second period, it underwent a modest sediment loss (~10% of the previously gained volume), suggesting a partial redistribution rather than an overall erosional trend.

Additionally for a more detailed and direct comparison of vertical elevation changes in the spit it is defined the cross-sections illustrated in Figure 112 for a longitudinal profile analysis.



Figure 112 - Profiles for analysis – Cabedelo Sandspit.

The first cross-section (Figure 113) is oriented perpendicular to the inner side of the breakwater, intersecting the sandspit. Analysis of the elevation profiles reveals a clear trend of accretion between 2018 and 2019, leading to the formation of a surface-level path that temporarily connected the beach to the breakwater. However, between 2019 and 2020, this newly formed feature experienced a subsequent loss in elevation, indicating erosion and redistribution of sediment. This process may have been driven by wave action, changes in hydrodynamic forcing, or seasonal variations in coastal dynamics. In the central portion of this zone, elevation levels remain relatively stable over time, showing minimal variation compared to the more dynamic areas near the breakwater and shoreline. The cross-sections were extracted using X-coordinates referenced to the PT-TM06 ETRS89 projected coordinate system (EPSG:3763), which is the official coordinate system for mainland Portugal.

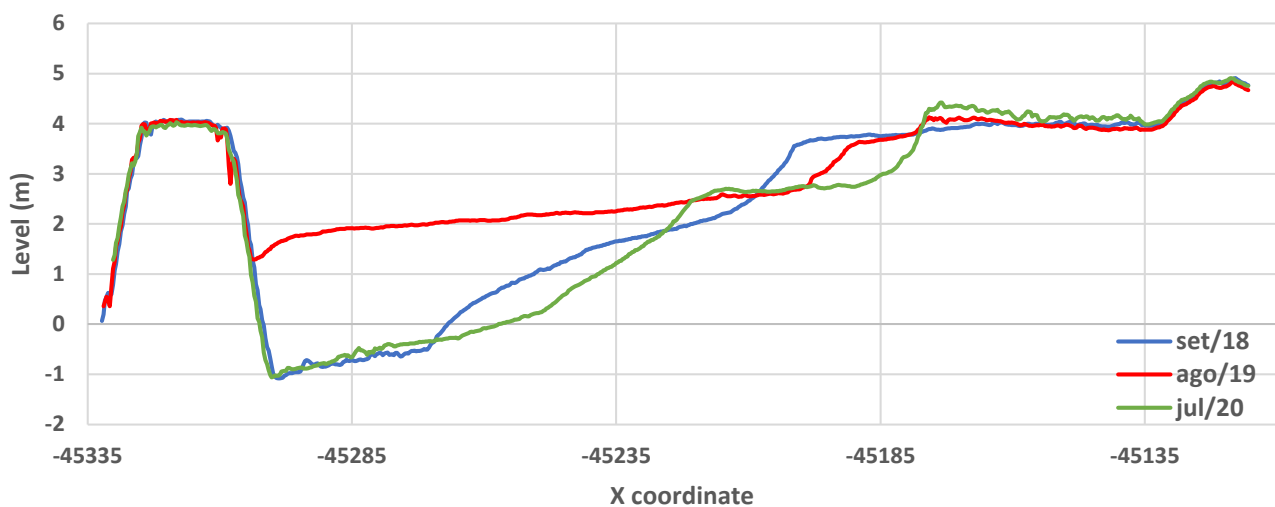


Figure 113 - Longitudinal profile 1 – Cabedelo sandspit. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

The profiles of cross sections 2 (Figure 114), 3 (Figure 115), 5 (Figure 117), 6 (Figure 118) and 7 (Figure 119) represent transverse elevation measurements across the entire sandspit along its longitudinal extent. These cross-sections provide critical insights into the morphological evolution and stability of different sections of the sandspit over the time period. Analysis of the elevation profiles indicates that the central portion and the river-facing side of the sandspit exhibit relatively minor height variations, suggesting greater morphological stability. This stability is likely due to reduced hydrodynamic forcing, as these areas are more sheltered from direct wave energy and experience lower sediment transport rates compared to the more exposed sections. The seaward-facing side of the sandspit displays more pronounced elevation fluctuations, reflecting its greater exposure to wave action, tidal currents, and sediment transport processes. The profiles reveal a recurring pattern of accretion between survey periods, indicating episodic sediment deposition.

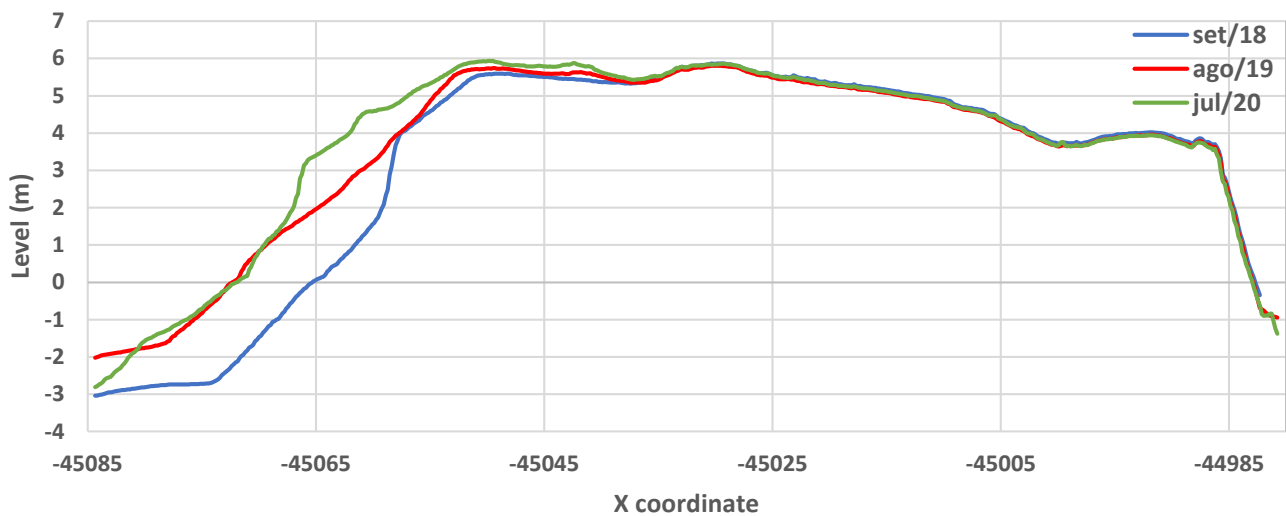


Figure 114 - Longitudinal profile 2 – Cabedelo sandspit. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

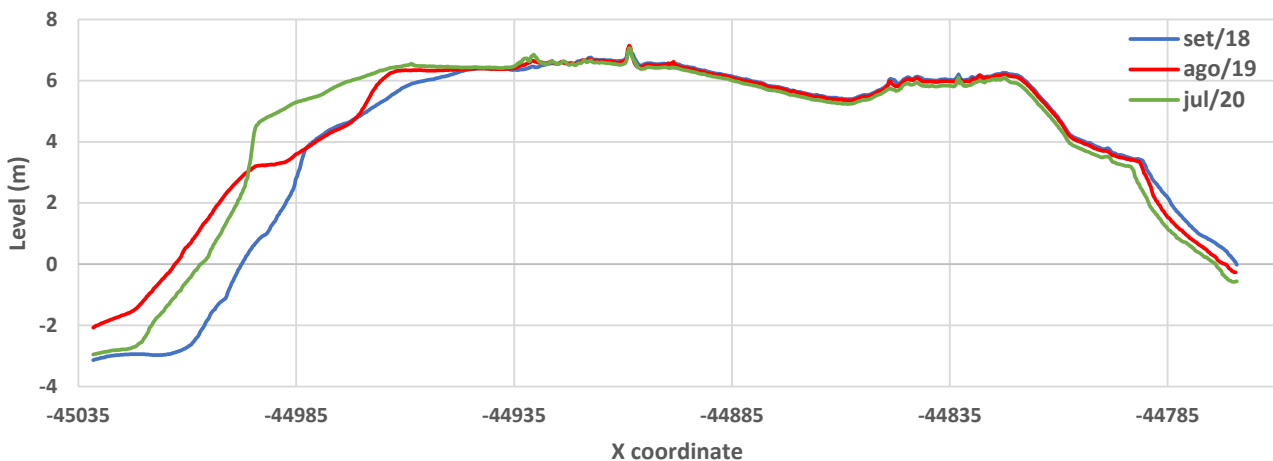


Figure 115 - Longitudinal profile 3 – Cabedelo sandspit. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

Cross-section 4 (Figure 116) represents the longitudinal profile of the inland arm of the sandspit, providing insights into its morphological evolution over the surveyed period. Analysis of the elevation profiles reveals a consistent pattern of erosion throughout the study timeframe, indicating a progressive reduction in sediment volume.

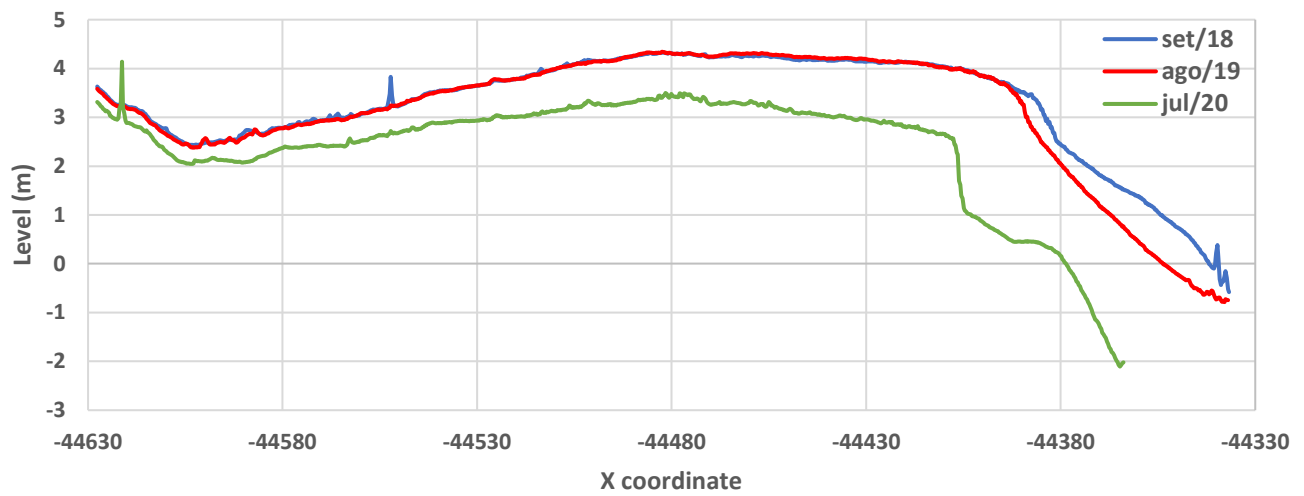


Figure 116 - Longitudinal profile 4 – Cabedelo sandspit. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

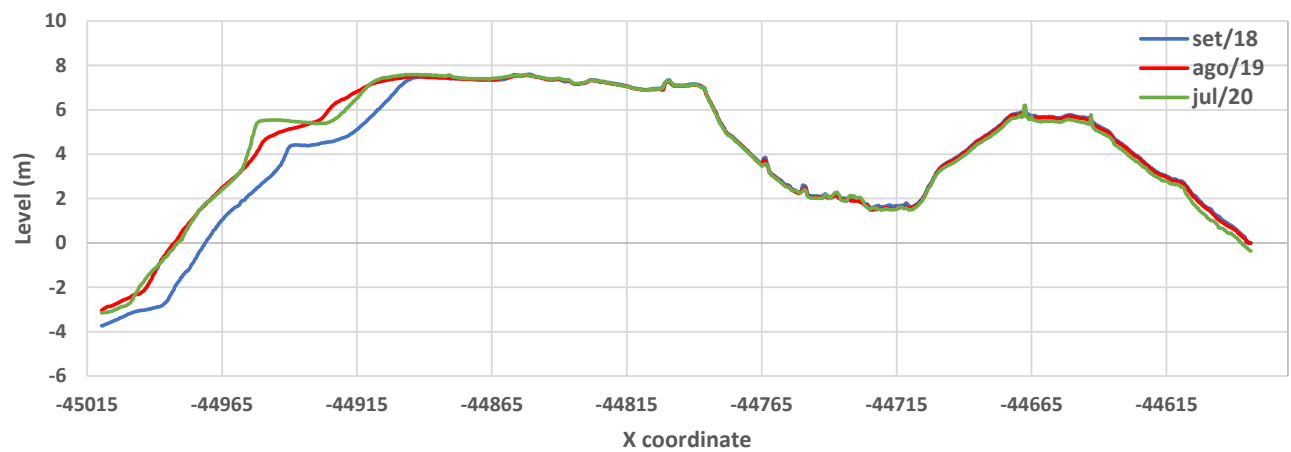


Figure 117 - Longitudinal profile 5 – Cabedelo sandspit. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

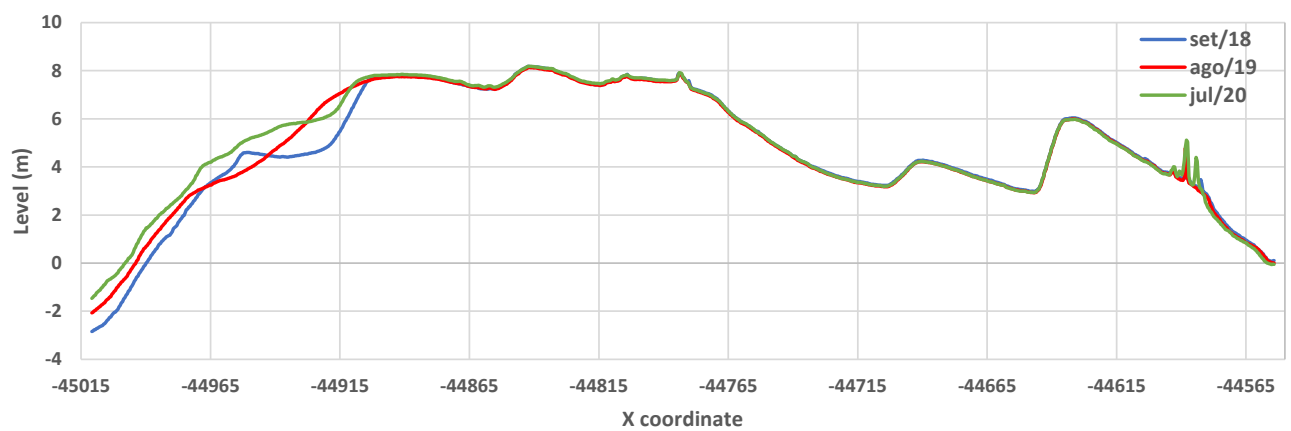


Figure 118 - Longitudinal profile 6 – Cabedelo sandspit. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

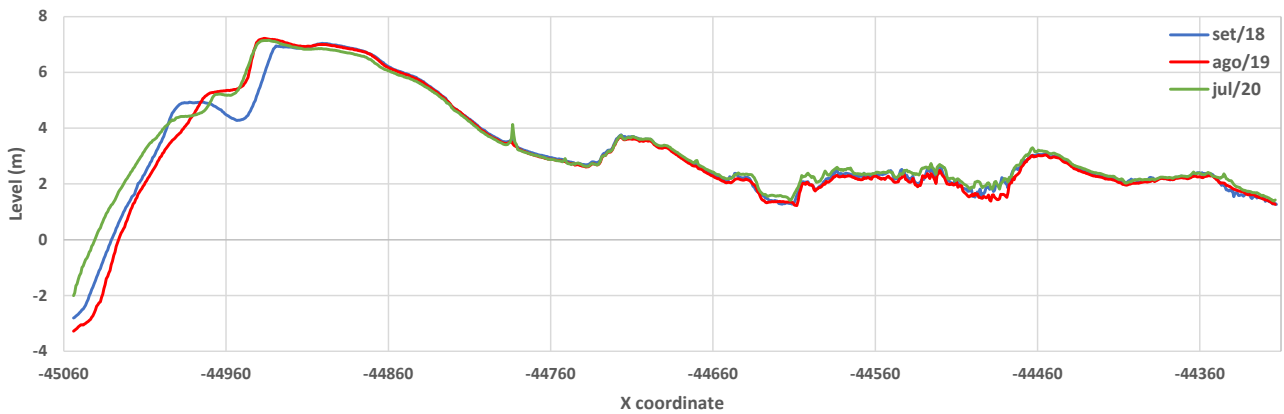


Figure 119 - Longitudinal profile 7 – Cabedelo sandspit. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

For the bathymetric analysis of the Douro Estuary, six profiles were defined to assess the underwater topography and depth variations across the study area. These profiles, as illustrated in Figure 120, were strategically selected to capture key morphological features and hydrodynamic influences within the estuarine system.



Figure 120 - Profiles for analysis – Douro estuary's bathymetry.

The first longitudinal profile (Figure 121), located along the coastal zone of the northern bank of the estuary, reveals minimal seabed variations across the surveyed periods. The bathymetric data indicate a relatively stable underwater morphology, with only minor fluctuations in elevation between surveys. No significant patterns of accretion or erosion are observed, suggesting that this section of the estuary experiences limited sediment transport dynamics or reduced hydrodynamic energy or also that at time the surveys were taken the northern bank is in a state of dynamic equilibrium.

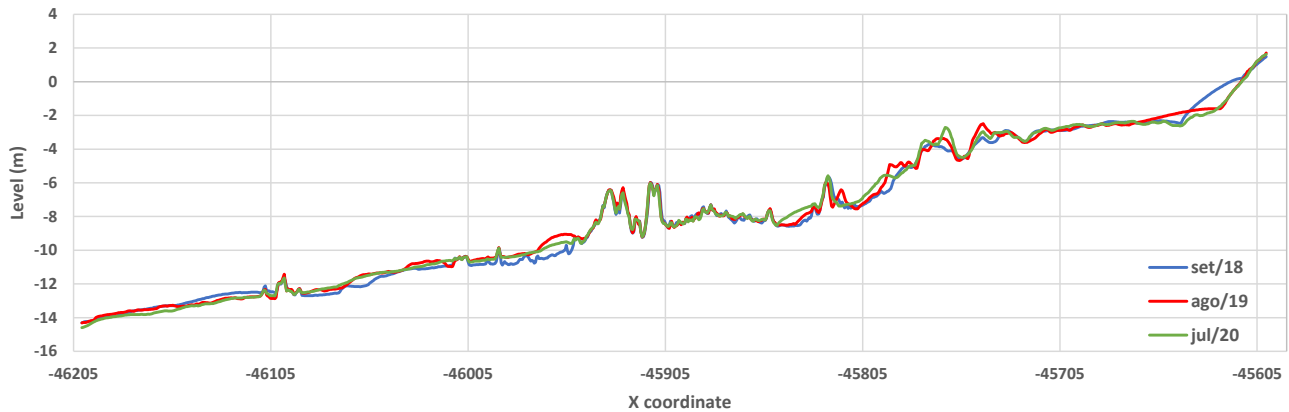


Figure 121 - Longitudinal profile 1 – Douro estuary's bathymetry. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

Longitudinal profile number 2 (Figure 122) corresponds to the cross-section located between the two breakwaters positioned on either side of the estuary inlet. Analysis of the surveyed profiles reveals a general consistency in seabed morphology across different years, with minimal variation in depth. However, a notable deviation is observed in the 2019 profile, where a distinct sediment deposition event is evident. This accumulation is particularly pronounced in a localized area adjacent to the southern breakwater, where a previously defined small underwater valley appears to have been partially infilled. The observed sediment deposition suggests an episodic transport event, potentially influenced by storm-induced wave action, altered tidal dynamics, or changes in sediment supply within the estuarine system.

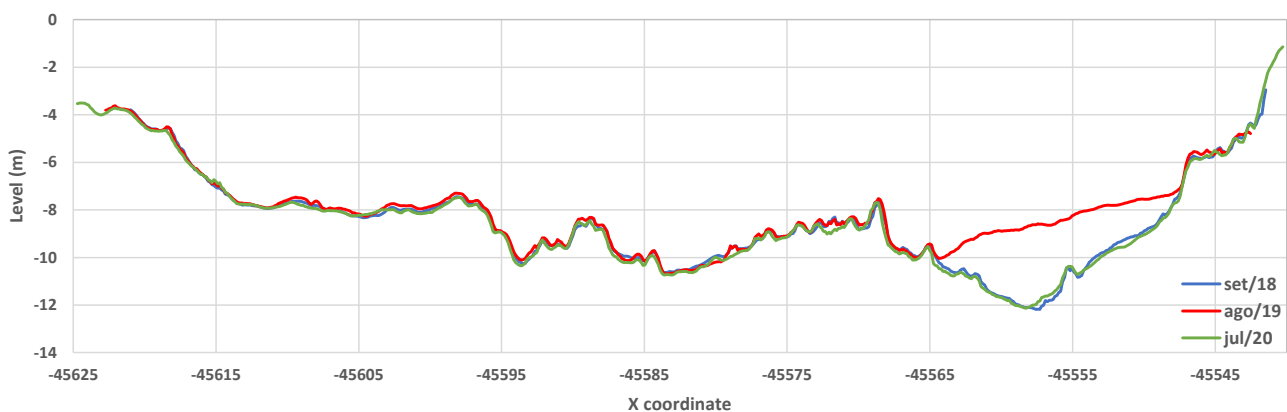


Figure 122 - Longitudinal profile 2 – Douro estuary's bathymetry. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

Profile 3 (Figure 123) corresponds to the navigational channel that extends through the estuary, serving as a critical passage for vessel transit. The analysis of this profile reveals significant depth variations along the channel, indicating a complex and dynamic seabed morphology. Despite these depth variations, the overall seabed slopes along the channel remain relatively consistent across all surveys. This indicates that while short-term

sediment redistribution occurs, the fundamental morphology of the channel remains stable over time. A particularly notable feature within this profile is the presence of two distinct underwater valleys situated between the breakwaters, each exhibiting different depths. The landward valley appears to have remained relatively unchanged throughout the surveyed period. However, the seaward valley underwent a significant transformation in 2019, where sediment deposition partially filled the depression.

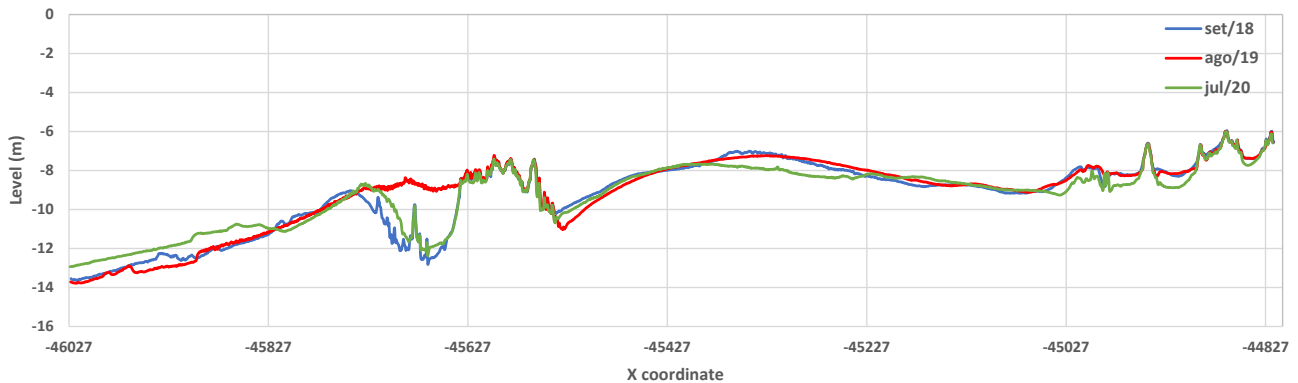


Figure 123 - Longitudinal profile 3 – Douro estuary's bathymetry. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

Profile 4 (Figure 124) extends from the northern coast of the sandspit to the north bank, traversing the inner river side of the southern breakwater and capturing a cross-sectional view of the estuary. The bathymetric analysis indicates that the seabed morphology remains relatively stable over time, with minimal variations in depth across different survey periods. However, certain localized areas exhibit deviations, particularly in the 2019 profile, where the seabed appears to be elevated by a few meters compared to the other surveyed years.

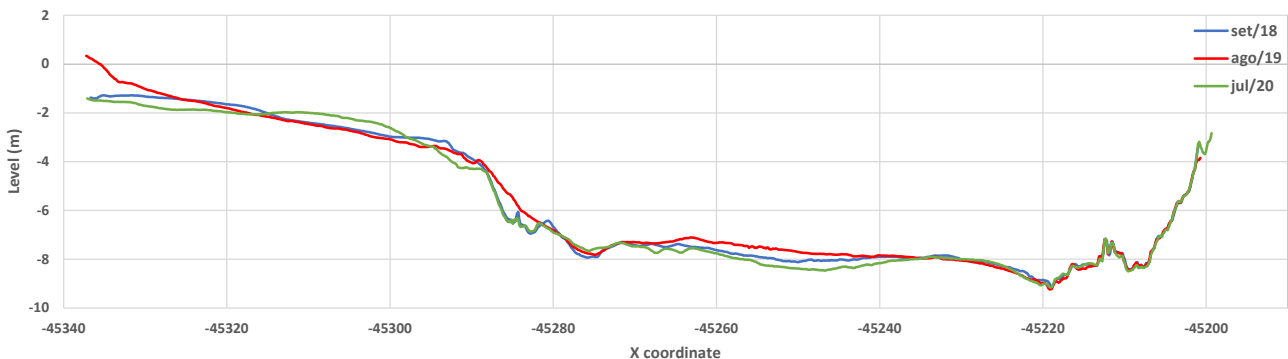


Figure 124 - Longitudinal profile 4 – Douro estuary's bathymetry. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

Profiles 5 (Figure 125) and 6 (Figure 126) capture the bathymetric variations on the seaward side of the estuary, with Profile 5 extending from the southern groin and Profile 6 originating from the sandspit coast. The analysis of Profile 5 reveals significant erosion in the August 2019 survey. Conversely, Profile 6 exhibits a relatively stable seabed morphology across all three surveys. Notably, in the nearshore region adjacent to the sandspit, a pattern of accretion is observed between the 2018 and 2019 surveys, indicating a net sediment gain during this

period. This accumulation appears to have persisted through 2020, suggesting that sediment deposition processes have been dominant in this area.

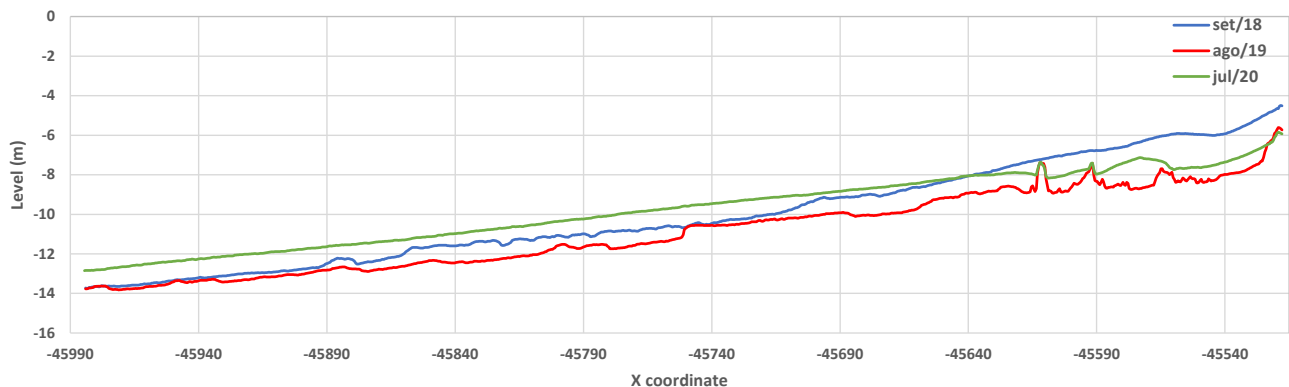


Figure 125 - Longitudinal profile 5 – Douro estuary's bathymetry. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

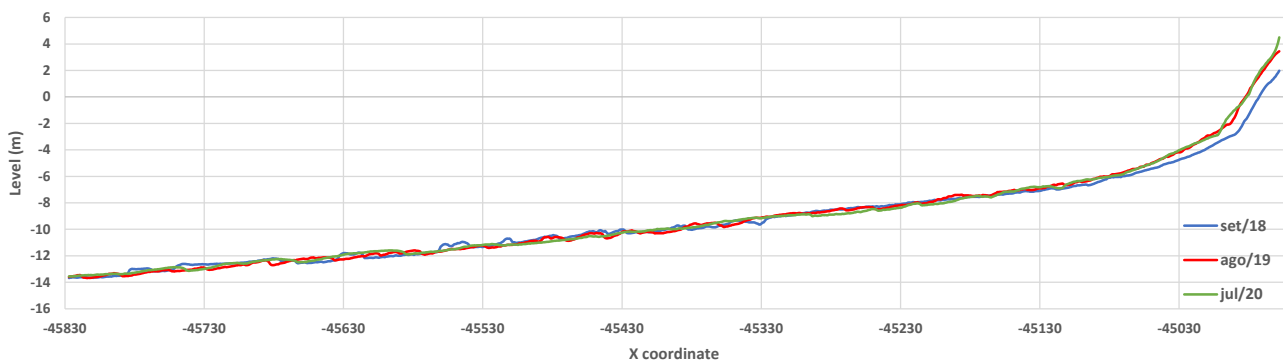


Figure 126 - Longitudinal profile 6 – Douro estuary's bathymetry. X-coordinates in PT-TM06 ETRS89 (EPSG:3763).

5.2.3 ANALYSIS OF RESULTS

This section evaluates sediment transport patterns, erosion, and accretion trends within the study period, considering the role of significant wave events.

For both case studies, the morphology of the coast evolved through winter months, characterized by high-energy wave conditions, followed by calmer periods that likely contributed to sediment recovery. However, the rate and extent of this natural recovery remain uncertain. The primary objective of this analysis is to determine the extent to which intense storm activity during winter months altered the coastal morphology and how the subsequent lower-energy conditions influenced potential recovery.

A comparative analysis of the surveys at Furadouro Beach revealed opposite patterns of accretion and erosion between the two periods, suggesting dynamic sediment redistribution. The 2019 bathymetric survey exhibited clear evidence of rip current-induced erosion, which may have contributed to localized sediment removal and offshore transport. Despite similar wave conditions across both periods, the differences in morphological evolution may indicate that wave intensity alone does not fully explain the observed changes. The longer post-storm recovery period in 2019–2020, four months compared to two months in 2018–2019, may have allowed for a more stable sediment redistribution, enabling the coastal profiles to reach a more balanced dynamic state. This highlights the importance of considering not only the intensity of storm events but also their timing relative to the survey dates, as the duration between high-energy conditions and subsequent measurements may influence

whether erosion or accretion is more dominant. Further analysis incorporating post-storm recovery rates and sediment transport mechanisms could enhance the understanding of Furadouro Beach's response to wave forcing.

In the Douro Estuary sandspit, the morphodynamic evolution between 2018 and 2019 was likely influenced by the absence of major river discharge events, which may have allowed for sediment deposition along the riverside, particularly in deeper estuarine areas such as the section between the breakwaters. Regular high-energy winter waves likely induced erosion along the seaward side of the southern breakwater while promoting accretion near the shoreline of the sandspit. The observed patterns suggest that longshore sediment transport played a role in redistributing eroded material from the southern breakwater toward the sandspit shoreline.

Between 2019 and 2020, extreme morphodynamic forcing occurred in December 2019, with significant wave heights exceeding 5m, wave power surpassing 250 kW/m, and high river discharge from Crestuma Dam. These events occurred almost simultaneously in late December 2019, making it difficult to isolate their individual effects on estuarine morphology. The increased river flow likely eroded the deeper riverbed areas, particularly in the section between the breakwaters. The resulting sediment was likely transported downstream, where it encountered high-energy marine waves that contributed to deposition seaward of the southern breakwater.

The higher wave power and increased storm frequency likely caused additional erosion along the seaward side of the sandspit and along the north bank beach. The period following these extreme events was characterized by four months of relatively low wave energy, with significant wave heights below 3m and wave power under 100 kW/m, which may have facilitated sediment stabilization and redistribution, attenuating some of the deposition patterns caused by the preceding high-energy conditions.

The findings suggest that while high-energy wave events and river discharge play a crucial role in shaping estuarine and coastal morphology, the post-storm recovery period is equally significant in determining whether erosion persists or sediment redistribution allows for partial accretion. The interplay between longshore sediment transport, tidal dynamics, and river inflows must be further analysed to refine predictions of morphodynamic evolution in both case study areas. It is important to acknowledge that the interpretations presented here are based on available survey data and observed trends, but a more comprehensive understanding of these morphodynamic processes would require a higher temporal resolution of bathymetric monitoring. Ideally, this analysis would have been complemented by monthly and post-storm SDB measurements conducted between the *in-situ* surveys. Such an approach would allow for a more continuous assessment of sediment transport dynamics, providing better insight into the chronological patterns of erosion and accretion and improving our ability to understand the complex evolution of the case study areas.

6

CONCLUSIONS AND FUTURE WORKS

6.1. CONCLUSIONS

The dissertation aimed to advance present understanding of coastal morphodynamics by integrating traditional topo-hydrographic survey methods with novel satellite-derived approaches. Focusing on two distinct coastal environments along Portugal's northwestern coast—Furadouro beach, characterized by high erosion rates, and the Douro estuary sandspit, an essential natural coastal defence—this research sought to evaluate whether the Satellite to Shores (S2Shores) methodology could reliably support monthly-scale monitoring.

The work began by establishing a robust theoretical framework that reviewed the fundamental forces driving coastal morphodynamics, including hydrodynamic processes (waves, tides, and currents), sediment transport mechanisms, geological and biological factors, as well as the impacts of anthropogenic activities. This interdisciplinary perspective was essential in setting the stage for detailed case study analyses, ensuring that all natural and human-induced variables influencing coastal change were considered.

The COSMO program's traditional topo-hydrographic surveys provided a high-resolution view of the spatial and annual changes at both study sites. These surveys yielded critical insights into annual sediment budgets, shoreline dynamics and beach profile variations. The analysis emphasized that accurate *in-situ* measurements remain indispensable; however, for a more comprehensive understanding of complex morphodynamic behaviors, higher-frequency monitoring is beneficial. More frequent data acquisition, such as monthly or post-storm surveys, would allow for a better capture of short-term variations in sediment transport and morphological adjustments, improving the ability to assess the response of coastal environments to hydrodynamic forcing.

A significant innovation of this dissertation was the attempt to validate and implement the S2Shores tool for achieving continuous and cost-effective coastal monitoring. The primary objective was to assess whether S2Shores-derived bathymetric outputs could provide reliable depth estimates, enabling higher-frequency monitoring to complement the *in-situ* COSMO surveys.

The S2Shores algorithm faced significant challenges in accurately estimating bathymetry near the shoreline. The outputs exhibited gaps, inconsistencies, and unrealistic water depth variations. Significant fluctuations in depth estimates, combined with missing data points, hindered the full validation of Satellite-Derived Bathymetry (SDB) for this study. While the method performed slightly more consistently at Furadouro Beach than in the Douro Estuary due to the estuary's more complex hydrodynamic conditions, the overall bathymetric contours remained unreliable, limiting its applicability for precise coastal monitoring. Therefore, it was concluded that SDB, in its current state, is not yet a reliable method for bathymetric assessment in the studied locations, particularly beyond 2 km from the coast.

Although the potential for high-frequency monitoring was a promising concept, the research revealed that environmental challenges—such as cloud cover, and the inherent wave non-linearities of nearshore zones—significantly hindered the ability to extract reliable bathymetric information from satellite imagery. These limitations ultimately prevented the validation of S2Shores for the conditions encountered, leading to the decision to renounce the planned monthly-scale bathymetric assessment.

Satellite-derived approaches remain a promising tool for cost-effective, high-frequency monitoring, further refinement is necessary before they can reliably complement traditional survey methods in highly dynamic coastal settings. Its current accuracy constraints in highly dynamic nearshore environments highlight the need for further refinements in data processing, calibration techniques, and integration with *in-situ* measurements. Future research should explore improvements in SDB algorithms, combined with higher-frequency validation surveys, to enhance the reliability of satellite-derived depth estimates for coastal monitoring applications.

6.2. Future Works

The study also highlights the importance of higher-frequency bathymetric monitoring to better capture short-term morphological changes and improve coastal management strategies. Future research should focus on refining the SDB methodologies, eventually integrating numerical modelling approaches, and expanding the use of remote sensing technologies to enhance the monitoring and prediction capabilities of coastal morphodynamics on shallow waters, in order to overcome the present limitations of the S2Shores tool.

It is also of interest to systematically validate the methodology in other challenging locations (such as the ones that were considered in the Portuguese coast), in order to improve confidence in the reliability and accuracy of the algorithms.

BIBLIOGRAPHIC REFERENCES

- Almar, Rafael; Bergsma, Erwin W.J.; Thoumyre, Grégoire; Solange, Lemai-Chenevier; Loyer, Sophie; Artigues, Stephanie; Salles, Grégoire; Garlan, Thierry; Lifermann, Anne (2024) *Satellite-derived bathymetry from correlation of Sentinel-2 spectral bands to derive wave kinematics: Qualification of Sentinel-2 S2Shores estimates with hydrographic standards*. Coastal Engineering. ISSN 03783839. 189:2024). doi: 10.1016/j.coastaleng.2024.104458.
- Almeida, João. (2013) *Modelação da hidrodinâmica e dinâmica sedimentar do estuário do rio Douro*. Dissertação de Mestrado, Universidade do Porto.
- Alongi, Daniel M. (2008) *Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change*. Estuarine, Coastal and Shelf Science. ISSN 02727714. 76:1 (2008) 1–13. doi: 10.1016/j.ecss.2007.08.024.
- Andrade, César; Taborda, Rui; Freitas, Maria Conceição. (2007) *Projecting future changes in wave climate and coastal response in Portugal by the end of the 21st Century*. Journal of Coastal Research SI. 50. 263-257.
- Assunção, Maria Da; Tel, Araújo. (1999) *The Coastal Zone Of Portugal*. Porto : Associação Eurocoast-Portugal.
- Avilez-Valente, P.; Veloso-Gomes, Fernando; Pinho, J. L.; A., Bio; Melo, W.; Vieira, J. M.; Bastos, L. (2020) *Modelos morfodinâmicos para simulação de estuários em cenários ambientais futuros*.
- B-13 Edition 1.0.0 (2024) *Guidance to Satellite-Derived Bathymetry*. International Hydrographic Organization
- Barbier, Edward B; Hacker, Sally D.; Kennedy, Chris; Koch, Evamaria W.; Stier, Adrian C.; Silliman, Brian R. (2011) *The value of estuarine and coastal ecosystem services*. Ecological Monographs. ISSN 00129615. doi: 10.1890/10-1510.1.
- Bastos, L.; Bio, A.; Pinho, J. L.S.; Jorge da Silva, A. (2012) *Dynamics of the Douro estuary sand spit before and after breakwater construction*. Estuarine, Coastal and Shelf Science. ISSN 02727714. doi:10.1016/j.ecss.2012.05.017.
- Bastos, Rosário, Dias, Joao. (2015). *Em tempo de temporais: o caso do Furadouro (NW de Portugal) como exemplo de (in)gestão do litoral*. Conference: Capítulo do Livro ressacas do Mar/Temporais e gestão costeira. At: ISBN 978-85-7924-440-7.
- Bergsma, E. W. J.; Almar, R.; Maisongrande, P. (2019) *Radon-augmentation of Sentinel-II imagery to enhance resolution and visibility of (nearshore) ocean-wave patterns*. IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium. ISBN 2153-7003
- Bergsma, Erwin W. J; Almar, Rafael; Giros, Alain; Solange, Lemai-Chenevier; Thoumyre, Grégoire; Artigues, Stephanie; Garlan, Thierry; Degoul, Romain. (2023) *S2shores: A Python Library For Estimating Coastal Bathymetry*. Coastal Engineering Proceedings. Doi: 10.9753/Icce.V37.Sediment.36.
- Bergsma, Erwin W. J.; Almar, Rafael; Rolland, Amandine; Binet, Renaud; Brodie, Katherine L.; Brodie, Katherine L.; Bak, A. Spicer. (2021) *Coastal morphology from space: A showcase of monitoring the topography-bathymetry continuum*. Remote Sensing of Environment. ISSN 00344257. 261:2021). doi: 10.1016/j.rse.2021.112469.
- Bergsma, Erwin W. J.; Almar, Rafael; Maisongrande, Philippe (2019a) *Radon-Augmented Sentinel-2 Satellite Imagery to Derive Wave-Patterns and Regional Bathymetry*. Remote Sensing. ISSN 2072-4292. 11:16 doi: 10.3390/rs11161918.
- Bio, A.; Bastos, L.; Granja, H.; Pinho, J. L.S.; Goncalves, J. A.; Henriques, R.; Madeira, S.; Magalhaes, A.; Rodrigues, D. (2015) *Methods for coastal monitoring and erosion risk assessment: Two Portuguese case studies*. Journal of Integrated Coastal Zone Management. ISSN 16468872. 15:147–63. doi: 10.5894/rgci490.

- Boer, Eva Louise Den; Suntoyo; Oele, A. C. (2018) *Determination Of Shoreline Change Along The East-Java coast, using Digital Shoreline Analysis System*. MATEC Web of Conferences. EDP Sciences, 4 Jul. 2018.
- Bosboom, J.; Stive, M. J. F. (2023) *Coastal Dynamics*. Version 1.2 Ed.: Tu Delft Open, 2023. Isbn 978-94-6366-370-0.
- C-55 (2025) *Status of Hydrographic Surveying and Charting Worldwide*. International Hydrographic Organization.
- Caballero, Isabel; Stumpf, Richard P. (2023) *Confronting Turbidity, The Major Challenge For Satellite-Derived coastal bathymetry*. Science of The Total Environment. ISSN 0048-9697. 870:161898. doi: <https://doi.org/10.1016/j.scitotenv.2023.161898>.
- Cesbron, Guillaume; Melet, Angélique; Almar, Rafael; Lifermann, Anne; Tullot, Damien; Crosnier, Laurence. (2021) *Pan-European Satellite-Derived Coastal Bathymetry—Review, User Needs and Future Services*. Frontiers in Marine Science. ISSN 2296-7745. doi: 10.3389/fmars.2021.740830.
- Chen, Yifu; Wu, Lin; Le, Yuan; Zhao, Qian; Zhang, Dongfang; Qiu, Zhenge. (2024) *High-Accuracy bathymetric method fusing ICESAT-2 datasets and the two-media photogrammetry model*. International Journal of Applied Earth Observation and Geoinformation. ISSN 1872826X. doi: 10.1016/j.jag.2024.104179.
- Chowdhury, Piyali; Lakku, Naresh Kumar Goud; Lincoln, Susana; Seelam, Jaya Kumar; Behera, Manasa Ranjan. (2023) *Climate change and coastal morphodynamics: Interactions on regional scales*. Science of The Total Environment. Doi: <https://doi.org/10.1016/j.scitotenv.2023.166432>.
- Coelho, Carlos; Conceição, Tony; Ribeiro, Bruno. () *Coastal Erosion Due to Anthropogenic Impacts on Sediment Transport in Douro River – Portugal*. Proceedings of Coastal Dynamics. Doi: 10.1142/9789814282475_0074
- Coimbra, João. (2023) *Projetar a frente marítima do Furadouro*. Dissertação de Mestrado, Universidade do Minho.
- Cowell, P. J.; Thom, B. G. (1995) *Late Quaternary Shoreline Morphodynamics*. Eds.:Carter, R. W. G.; Woodroffe, C. D. Cambridge University Press. ISBN 9780521598903.
- Dalrymple, Robert; Zaitlin, Brian; Boyd, R. (1992) *Estuarine Facies Models: Conceptual Basis And stratigraphic implications*. Journal of Sedimentary Research. Doi: 10.1306/D4267A69-2B26-11D7-8648000102C1865D.
- Daly, Christopher; Baba, Wassim; Bergsma, Erwin; Thoumyre, Gregoire; Almar, Rafael; Garlan, Thierry. (2022) *The new era of regional coastal bathymetry from space: A showcase for West Africa using optical Sentinel-2 imagery*. Remote Sensing of Environment. ISSN 00344257. Doi: 10.1016/j.rse.2022.113084.
- Davidson-Arnott, Robin; Bauer, Bernard; Houser, Chris (2019) *Introduction to Coastal Processes and Geomorphology*. Cambridge University Press. ISBN 9781108424271.
- Dierssen, Heidi M.; Theberge, Albert E. (2020) *Bathymetry: Assessment*. Coastal and Marine Environments. CRC Press.
- Ferreira, Italo Oliveira; de Andrade, Laura Coelho; Teixeira, Victoria Gibrim; Santos, Felipe Catão Mesquita. (2022) *State of art of bathymetric surveys*. Boletim de Ciencias Geodesicas. ISSN 19822170. Doi: 10.1590/s1982-21702022000100002.
- Freitas, Joana Gaspar De; Dias, João Alveirinho. (2015) *Erosão Costeira: Percepções, Impactes E Estratégias De Proteção. Os Casos Históricos De Espinho E Do Furadouro (Portugal)*. Doi:10.13140/RG.2.1.2133.5760
- Garrison, Tom (2005) *Oceanography: An Invitation to Marine Science*. Ed:Thomson Brooks/Cole. ISBN 9780534408909.

- Gedan, Keryn B.; Kirwan, Matthew L.; Wolanski, Eric; Barbier, Edward B.; Silliman, Brian R. (2011) *The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm*. Climatic Change. ISSN 01650009. Doi: 10.1007/s10584-010-0003-7.
- Global environment outlook 4 : environment for development (2009) United Nations Environment Programme, 2009. ISBN 9789280728361.
- Gomes Da Silva, Paula; Jara, Martínez Sánchez; Medina, Raúl; Beck, Anne Laure; Taji, Mohamed Amine. (2024) *On the use of satellite information to detect coastal change: Demonstration case on the coast of Spain*. Coastal Engineering. ISSN 03783839. doi: 10.1016/j.coastaleng.2024.104517.
- Gonçalves, Francisca. (2022) *Efeito Das Alterações Climáticas Na Dinâmica Sedimentar Da Restinga Do Rio Douro*. Dissertação de mestrado, Universidade do Porto.
- Grabowski, Jonathan H.; Brumbaugh, Robert D.; Conrad, Robert F.; Keeler, Andrew G.; Opaluch, James J.; Peterson, Charles H.; Piehler, Michael F.; Powers, Sean P.; Smyth, Ashley R. (2012) *Economic valuation of ecosystem services provided by oyster reefs*. BioScience. ISSN 00063568. Doi: 10.1525/bio.2012.62.10.10.
- He, Jinchen; Zhang, Shuhang; Cui, Xiaodong; Feng, Wei. (2014) *Remote sensing for shallow bathymetry: A systematic review*. Earth-Science Reviews. ISSN: 0012-8252. doi: 10.1016/j.earscirev.2024.104957
- Hogrefe, Kyle R.; Wright, Dawn J.; Hochberg, Eric J. (2008) *Derivation And Integration Of Shallow-Water bathymetry: Implications for coastal terrain modeling and subsequent analyses*. Marine Geodesy. ISSN: 01490419. Doi: 10.1080/01490410802466710
- Iglesias, Isabel; Pinho, José Luís; Venâncio, Stênio; Avilez-Valente, Paulo; Peixoto, Raquel; Vieira, José Manuel. (2018) *Simulação de níveis de cheia no estuário do rio Douro, antes e após a construção dos molhes*. Revista Recursos Hídricos. ISSN 08701741. doi: 10.5894/rh39n1-cti1.
- Jawak, Shridhar D.; Vadlamani, Somashekhar S.; Luis, Alvarinho J. (2015) *A Synoptic Review on Deriving Bathymetry Information Using Remote Sensing Technologies: Models, Methods and Comparisons*. Advances in Remote Sensing. ISSN 2169-267X. doi: 10.4236/ars.2015.42013.
- Kamphuis, J. William (2000) *Introduction to Coastal Engineering and Management*. Hardcover ed. : World Scientific Publishing Company. ISBN 981-02-3830-4.
- Kras, Etienne; Luijendijk, Arjen; Donchyts, Gennadii; Santinelli, Giorgio; Langemeijer, Jaap; Gwee, Robyn; Moreno-Rodenas, Antonio. (2023) *Satellite Derived Bathymetry For Monitoring Nearshore Dynamics*. Coastal Engineering Proceedings. Doi: 10.9753/Icce.V37.Sediment.46.
- Lekkerkerk, Huibert-Jan. (2020) *State of the art in multibeam echosounders The evolution of a bathymetric workhorse*. Hydro International.
- Li, Zhuoxiao; Peng, Zitian; Zhang, Zheng; Chu, Yijie; Xu, Chenhang; Yao, Shanliang; García-Fernández, Ángel F.; Zhu, Xiaohui; Yue, Yong; Levers, Andrew; Zhang, Jie; Ma, Jieming. (2023) *Exploring modern bathymetry: A comprehensive review of data acquisition devices, model accuracy, and interpolation techniques for enhanced underwater mapping*. Frontiers in Marine Science. ISSN 2296-7745.
- Lima, M., Coelho, C., Jesus, A., Alves, F., Marto, M. (2021). Base de Dados #5 - Eventos de Dano devidos à Ação Marítima - Caso de Estudo (Ovar), Projeto INCCA - Adaptação Integrada às Alterações Climáticas para Comunidades Resilientes (POCI-01-0145-FEDER-030842), Universidade de Aveiro.
- Lima, Márcia; Alves, Filipe; Marto, Marco; Coelho, Carlos. (2021) *Medidas de mitigação e adaptação à erosão costeira e aos efeitos das alterações climáticas*. Revista Recursos Hídricos. ISSN 08701741. doi: 10.5894/rh42n1-cti7.

- Manuel, Diamantino; Pereira, Insua; Jorge, Paulo; Pereira, Silva; José, Leonardo; Santos, Cordeiro; Manoel, Julio; Da Silva, França. (2014) *Unidades Geomorfológicas De Portugal Continental*. Revista Brasileira de Geomorfologia. ISSN 2236-5664.
- Marques, Maria. (2021) *Avaliação De Soluções Para Redução Do Risco De Galgamento Em Frentes Costeiras Urbanizadas Para Diferentes Cenários De Alterações Climáticas*. Dissertação de Mestrado, Universidade do Porto.
- Masselink, Gerd; Hughes, Michael; Knight, Jasper. (2011) *Introduction to coastal processes and geomorphology*. Edition: 2. Editor: Routledge. ISBN 9781444122404.
- Mesuras; Tiago. (2018) *Estratégia de Adaptação de frentes urbanas ao risco de galgamentos e inundações costeiras-O Caso de Estudo do Furadouro (Ovar)*. Dissertação de Mestrado, Universidade Nova de Lisboa.
- Narra, Pedro; Coelho, Carlos; Sancho, Francisco; Palalane, Jaime. (2017) *CERA: An open-source tool for coastal erosion risk assessment*. Ocean and Coastal Management. ISSN 09645691. Doi: 10.1016/j.ocecoaman.2017.03.013.
- Santos, Fábio; Pais-Barbosa, Joaquim; Teodoroa, Ana C.; Gonçalves, Hernâni; Baptista, Paulo; Moreira, António; Veloso-Gomes, Fernando; Taveira-Pinto, Francisco; Gomes-Costa, Paulo; Lopes, Vítor; Neves-Santos, Filipe. (2015) *Coastal Morphodynamic Features/Patterns Analysis Through A Video Based System And Image Processing*. Doi: 10.13140/RG.2.1.3774.4480
- Santos, Filipe; Lopes, António; Moniz, Gabriela; Ramos, Laudemira; Taborda, Rui. (2014) *Desafio Da Mudança Gestão Da Zona Costeira* Relatório de Grupo de Trabalho do Litoral. ISBN 9789899996212.
- Ormond, Maarten; Nederhoff, Kees; Dongeren, Ap Van. (2020) *Delft Dashboard: a quick set-up tool for hydrodynamic models*. Journal of Hydroinformatics. doi: 10.2166/hydro.2020.092.
- Pereira, Carla; Coelho, Carlos (2013) *Mapas de Risco das Zonas Costeiras por Efeito da Ação Energética do Mar*. Revista de Gestão Costeira Integrada. Doi: 10.5894/rgci325.
- Pinto, Celso Aleixo; Silveira, Tanya Mendes; Teixeira, Sebastião Braz (2020) *Beach nourishment practice in mainland Portugal (1950–2017): Overview and retrospective*. Ocean and Coastal Management. ISSN 09645691. doi: 10.1016/j.ocecoaman.2020.105211.
- Pinto, Celso Aleixo; Penacho, Nuno; Pires, Bruno. (2021) Portuguese Coastal Monitoring Program (COSMO): From Design To Implementation.
- Pinto, Inês. (2022) *Galgamentos e Inundações Costeiras na Frente Urbana do Furadouro-Concelho de Ovar*. Dissertação de Mestrado, Universidade do Porto.
- Polcyn, Fabian C.; Brown, William L.; Sattinger, Irvin J. (1970) *The Measurement of Water Depth by Remote Sensing Techniques*.
- Ponte Lira, Cristina; Silva, Ana Nobre; Taborda, Rui; De Andrade, Cesar Freire; (2016) *Coastline evolution of Portuguese low-lying sandy coast in the last 50 years: An integrated approach*. Earth System Science Data. ISSN: 18663516. Doi: 10.5194/essd-8-265-2016.
- Portela, Luís Ivens (2008) *Sediment transport and morphodynamics of the Douro River estuary*. Geo-Marine Letters. ISSN 02760460. doi: 10.1007/s00367-007-0091-1.
- Ramos, Victor; Giannini, Gianmaria; Calheiros-Cabral, Tomás; Rosa-Santos, Paulo; Taveira-Pinto, Francisco. (2022) *An Integrated Approach to Assessing the Wave Potential for the Energy Supply of Ports: A Case Study*. Journal of Marine Science and Engineering. ISSN 2077-1312. doi: 10.3390/jmse10121989.

- Roebeling, P. C.; Costa, L. ; Magalhães-Filho, L. ; Tekken, V. (2013) *Ecosystem service value losses from coastal erosion in Europe: Historical trends and future projections*. Journal of Coastal Conservation. ISSN 14000350. doi: 10.1007/s11852-013-0235-6.
- Salameh, E., Frappart, F., Almar, R., Baptista, P., Heygster, G., Lubac, B., Raucoules, D., Almeida, L. P., Bergsma, E. W. J., Capo, S., De Michele, M., Idier, D., Li, Z., Marieu, V., Poupardin, A., Silva, P. A., Turki, I., & Laignel, B. (2019) *Monitoring Beach Topography and Nearshore Bathymetry Using Spaceborne Remote Sensing: A Review*. Remote Sensing. ISSN 2072-4292. doi: 10.3390/rs11192212.
- Santos, Inês; Teodoro, A. C.; Taveira-Pinto, Francisco. (2011) *Análise Da Evolução Morfológica Da Restinga Do Rio Douro*. 5as Jornadas De Hidráulica, Recursos Hídricos e Ambiente.
- Santos, Filipe; Lopes, António; Moniz, Gabriela; Ramos, Laudemira; Taborda, Rui. (2014) *Desafio Da Mudança Gestão Da Zona Costeira* Relatório de Grupo de Trabalho do Litoral. ISBN 9789899996212.
- Santos, Sara. (2016) *Aplicação de Tecnologias de Informação Geográfica à monitorização das dunas primárias - Subsídios para a prevenção do risco de galgamento na praia do Furadouro*. Dissertação de Mestrado, Universidade de Coimbra.
- Short, Andrew D. (1999) *Handbook of beach and shoreface morphodynamics*. Ed: John Wiley & Sons. ISBN 9780471965701.
- Sigismondi, Costantino (2008) *Long waves perturbations to astronomical tides in Adriatic and Tyrrhenian sea*. AIP Conference Proceedings. ISBN 9780735404830
- Stive, Marcel J. F.; Aarninkhof, Stefan G.J.; Hammb, Luc; Hansonc, Hans; Larsonc, Magnus; Wijnbergd, Kathelijne M.; Nicholls, Robert J.; Capobianco, Michele. (2002) *Variability Of Shore And Shoreline Evolution*.
- Taveira-Pinto, Francisco; Henriques, Renato; Rosa-Santos, Paulo; Fazeres-Ferradosa, Tiago; Neves, Luciana; Taveira Pinto, Francisco V. C.; Sarmento, Maria Francisca. (2022) *Hazard Mapping Based On Observed Coastal Erosion Rates And Definition Of Set-Back Lines To Support coastal management plans in the north coast of Portugal*. Revista de Gestão Costeira Integrada. doi: 10.5894/rgci-n546.
- Taveira-Pinto, Francisco; Silva, Raquel; Pais-Barbosa, Joaquim (2011) *Coastal Erosion Along the Portuguese Northwest Coast Due to Changing Sediment Discharges from Rivers and Climate Change*. Coastal Research Library.
- Teodoro, A. C.; Pais-Barbosa, J. ; Gonçalves, H.; Veloso-Gomes, F.; Taveira-Pinto, F.(2015) *Extraction of Cabedelo sand spit area (Douro estuary) from satellite images through image processing techniques*. Journal of Coastal Research, Special Issue. ISSN 0749-0208.
- Teodoro, A. C.; Taveira-Pinto, F.; Santos, I. (2014) *Morphological and statistical analysis of the impact of breakwaters under construction on a sand spit area (Douro River estuary)*. Journal of Coastal Conservation. ISSN 14000350. doi: 10.1007/s11852-014-0306-3.
- Turner, Ian L.; Harley, Mitchell D.; Almar, Rafael; Bergsma, Erwin W.J. (2021) *Satellite optical imagery in Coastal Engineering*. Coastal Engineering. ISSN 03783839. 167:2021). doi: 10.1016/j.coastaleng.2021.103919.
- Uzakara, Hakan; Demir, Nusret; Karakiş, Serkan (2024) *Satellite-based Bathymetry Supported by Extracted Coastlines*. PFG - Journal of Photogrammetry, Remote Sensing and Geoinformation Science. ISSN 25122819. doi: 10.1007/s41064-024-00298-8.
- Veloso Gomes, Fernando (2023) *Estruturas de defesa costeira e ordenamento no concelho de Ovar Esmoriz, Cortegaça, Furadouro (Portugal) 1993-2015*. Faculdade de Engenharia da Universidade do Porto (FEUP), U.Porto Press, 2023. ISBN 978-989-746-350-1.

Veloso Gomes, Fernando. (2014) *Os Molhes do Estuário do Douro. Uma primeira avaliação*. PORTUS: the online magazine of RETE.

Viaña-Borja, S. P.; González-Villanueva, R.; Alejo, I.; Stumpf, R. P.; Navarro, G.; Caballero, I. (2025) *Satellite-derived bathymetry using Sentinel-2 in mesotidal coasts*. Coastal Engineering. ISSN 03783839. doi: 10.1016/j.coastaleng.2024.104644.

Wright, L. D.; Thom, B. G. (1977) *Coastal depositional landforms: a morphodynamic approach*. Progress in Physical Geography: Earth and Environment. ISSN 0309-1333. doi: 10.1177/030913337700100302.