SHORELINE DETECTION BY APPLYING SEMIAUTOMATIC ALGORITHMS FOR HYPERSPECTRAL AND MULTISPECTRAL SATELLITE IMAGERY ON THE BEACHES OF THE GULF OF ORISTANO (SARDINIA, ITALY)

Sabrina Terracciano, Juan Montes-Pérez, Riccardo Brunetta, Paulo Cabrita, Enrico Duo, Paolo Ciavola, Clara Armaroli

Abstract: Coastal areas are influenced by natural processes and human activities and require effective monitoring tools to understand their dynamic evolution. This study utilizes satellite imagery and semi-automatic shoreline extraction algorithms (CoastSat and SAET) to assess coastal erosion in the Gulf of Oristano over long-term and short-term periods. The algorithms' performance was validated using PRISMA and Sentinel-2 imagery, alongside RTK-GNSS surveys acquired during ASI OVERSEE project fieldwork. The field site beaches vary in exposure due to their positions, and their morphologies are influenced by the presence of *Posidonia oceanica* banquettes. A one-year analysis focused on Arborea Beach, where periodic Posidonia banquettes affect the accuracy of Satellite-Derived Shorelines (SDSs). The study shows the beach's susceptibility to storm surges, evidenced by significant erosion after a major storm in March. Despite algorithmic limitations, automated shoreline extraction allows efficient temporal analysis. This research evidences the role of advanced algorithms in precise coastal monitoring, offering crucial insights into erosion dynamics and supporting effective mitigation strategies.

Keywords: Coastal dynamics; CoastSat; SAET

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Introduction

The influence of storm events can generate erosion and modify the morphology of beaches, resulting in sediment loss and coastal damage [1]. Anthropogenic impact on coastal areas and the reduction of return periods of extreme events due to climate change, make it necessary to monitor these environments to predict future consequences [2].

Traditional coastal monitoring techniques often have limitations, such as small study areas or low temporal resolution. To address these issues, the use of freely available optical satellite imagery with planetary coverage and high revisit frequency is increasingly being utilized. The development of algorithms for shoreline extraction has significantly enhanced and streamlined the study of coastal systems. These advancements enable automated temporal analysis over periods ranging from a few days to several years [3].

Beach erosion can be classified into two main types. The first type is permanent shoreline retreat, which is driven by factors such as rising mean sea levels and negative coastal sedimentary budgets, leading to the inland migration or submersion of beaches. The second type is temporary erosion, which results from storm surges and wave action. Although this form of erosion may not always cause long lasting shoreline retreat, it can still be highly destructive [4]. Even though some coastal systems adapted to the impact of extreme events without showing chronic retreat, the increasing frequency of storm events continues to pose significant challenges [5].

The aim of this study is to analyse the erosion impact of storms events, evaluate the effectiveness of satellite imagery and shoreline extraction algorithms in monitoring these changes in order to better understand and mitigate the effects of permanent and temporary beach erosion.

Materials and Methods

This study is focused on the Gulf of Oristano, a semi-enclosed embayment located on the western coast of Sardinia, Italy. The Gulf of Oristano covers an area of approximately 150 km^2 with an average depth of about 15 m and with a maximum depth of around 25 meters [6]. The coastline of the Gulf of Oristano is characterized for the presence of long stretches of sandy beaches. The back shore is predominantly occupied by extensive salt-marsh systems and several coastal lagoons (Figure 1).

The meteo-marine conditions in the Gulf of Oristano are influenced by three predominant wind regimes. The northwest winds, known locally as the Mistral, are the most powerful. Additionally, winds from the southwest (Libeccio), and from the southeast (Sirocco), also affect the area. Despite the dynamic wind patterns, the tidal range is limited, approximately 20 cm.

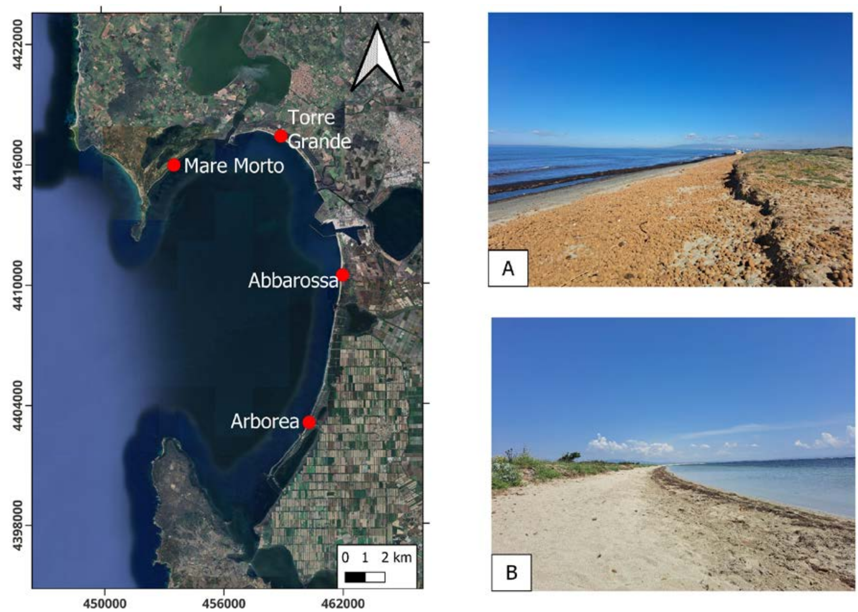

Figure 1 – Study area: A) Arborea beach; B) Mare Morto beach.

An initial 20-year study (2002-2022) was conducted. This study involved extracting the shoreline for the entire Gulf of Oristano using the CoastSat algorithm [7] for multispectral images in order to identify erosional trends. Landsat 7 satellite images were used due to their availability from the 2000s and their spatial resolution of 15 meters. The decision to use the CoastSat algorithm for long-term analysis was based on its ability to perform extensive temporal analyses quickly and automatically. Once the SDS dataset was obtained, a preliminary analysis of the principal trends over 20 years of shoreline data was conducted using CoastSat post-processing tools.

Subsequently, a 3-year study (2022-2024) was conducted and the SDS extraction for the entire Gulf of Oristano was performed using the SAET algorithm [8] with Sentinel-2 satellite imagery. The algorithm is specifically developed for storm events and ensures better accuracy under these conditions.

Once the second SDS dataset was obtained, the Digital Shoreline Analysis System (DSAS) tool in ArcMap was employed to analyse the erosion trends. This tool utilizes multiple statistical methods to establish the relationship between the shorelines and requires certain parameters to be set by the operator [9]. Initially, an offshore baseline was edited parallel to the shorelines. Subsequently, transect perpendicular to the baseline spaced 100 m were generated. Finally, various statistical analyses were applied to the points where the transects intersect the shorelines, following the methodology outlined by Himmelstoss et al. [9]: Net Shoreline Movement (NSM), the Shoreline Change Envelope (SCE), the End Point Rate (EPR) and the Linear Regression Rate (LRR). The NSM corresponds to the distance (m) between the oldest and the most recent shoreline, the SCE represent the value of the distance from the closest intersection from the baseline and the farthest, while EPR is the ratio of the NSM to the time between the oldest and most recent shoreline [10]. Finally, the Linear Regression Rate (LRR) represents the rate of change in meters per year. It is determined by the slope of the regression line, which is calculated based on the intersection points of time and distance from the baseline.

Further analyses on a smaller scale were focused on Arborea beach, located in the southern part of the Gulf of Oristano. This dissipative beach which faces the northwest and is exposed to the storm events driven by the Mistral winds. Its primary characteristic is the presence of *Posidonia oceanica* banquettes, *Posidonia oceanica* is a Mediterranean seagrass, which accumulates naturally on the beach [11] with higher frequency along the shore and in larger quantities in the southern part near the jetty.

Importantly, Posidonia deposits are left untouched by human activities, allowing natural processes to occur uninterrupted [12]. This beach has undergone several human-induced changes over the years. A road has been constructed across the dune area and walking paths have been established on the dunes. Additionally, there is a World War II military bunker present on the beach.

The first analysis performed on Arborea beach was the error analysis, through shoreline extraction using three different algorithms: two for multispectral images (CoastSat and SAET) and one for hyperspectral images (HyperSho), employing the profile method as the shoreline extraction technique [13]. To ensure comparable results and highlight the efficacy of SAET algorithm using various water indices, the AWEIsh index was employed in extracting shoreline positions. This index is particularly effective in identifying the sand-water boundary under conditions with dark elements, such as shadows [14]. Additionally, this index has demonstrated good performance and accuracy in the presence of *Posidonia oceanica* on Arborea Beach [15]. The accuracy of the extraction was evaluated through the comparison with in-situ data. Average distances were calculated using ArcGIS tools by measuring the distance from the points of the Satellite-Derived Shorelines (SDS) to the line of in-situ data. The instant shoreline (defined as the boundary between water and sand) was acquired with RTK-GNSS during the campaigns for the OVERSEE project on 18/09/2022, 23/05/2023, and 10/10/2023 by continuous measurement with an acquisition time of 1 second.

Finally, a one-year analysis was conducted on Arborea Beach to examine in detail the impact of storms, as well as erosional and accretional trends. The year analysed was 2023 and to ensure that the analysis was conducted using an initial condition of seasonal stability, the shoreline from 13 September 2022 was chosen as the reference shoreline [3]. SAET algorithm was selected as the preferred extraction method due to its better accuracy revealed in the error analysis. Regarding the HyperSho algorithm for hyperspectral images, although it revealed fairly accurate results, it was not used for short- and long-term analysis due to the limited availability of PRISMA images, compared to the more extensive Sentinel and Landsat collections.

Results

The long-term analysis indicates distinct erosion patterns in the southern region of Arborea Beach, as illustrated in Figure **2**. Over the analysed 20-year period, the northern region showed stability, characterised by alternating phases of accretion and erosion, as evidenced by the data from transect 2 (B) and 5 (C). Notably, Figure 2 highlights that transect 14 (E) demonstrates a gradual erosion trend, which has become more pronounced over the last decade of the analysis.

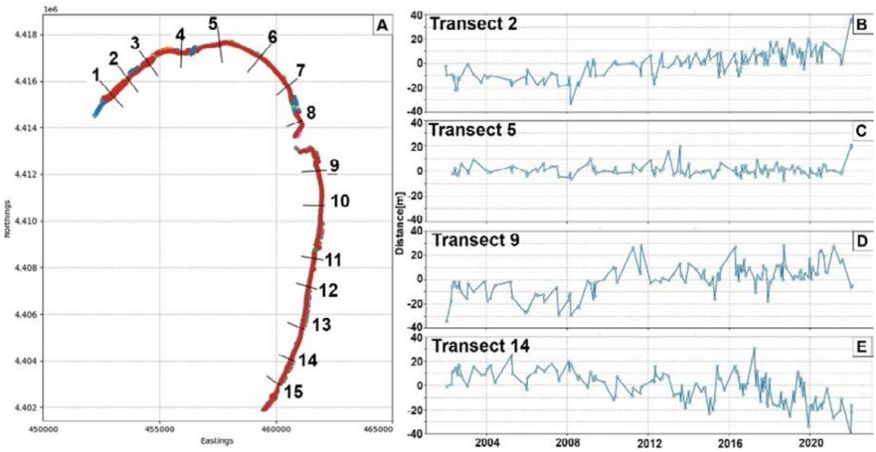

Figure 2 – A) CoastSat shorelines analysis (2002-2022); B), C), D), E) shoreline evolution along transects 2, 5, 9, 14, respectively.

This same trend was also observed in the short-term analysis conducted using the Shoreline Analysis and Extraction Tool (SAET), as depicted in Figure 3. Indeed, the Linear Regression Rate (LRR) values demonstrate predominantly positive values in the northern part of the Gulf of Oristano, indicating areas of accretion. However, there are localized areas within this region where the LRR values are negative which identifies beach erosion. The application of the DSAS tool revealed also significant erosion trends at Arborea Beach. Specifically, the DSAS analysis indicated a high rate of erosion, up to 15 meters per year (Table 1).

Table 1 – DSAS statistic on the beaches of the Gulf of Oristano.

Position	Trend	Name beach	Rate m/y
Area 1	Erosion	Arborea	>15
Area 2	Accretion	Abbarossa	>5
Area 3	Stable	Torre Grande	0
Area 4	Accretion	Mare Morto	>1

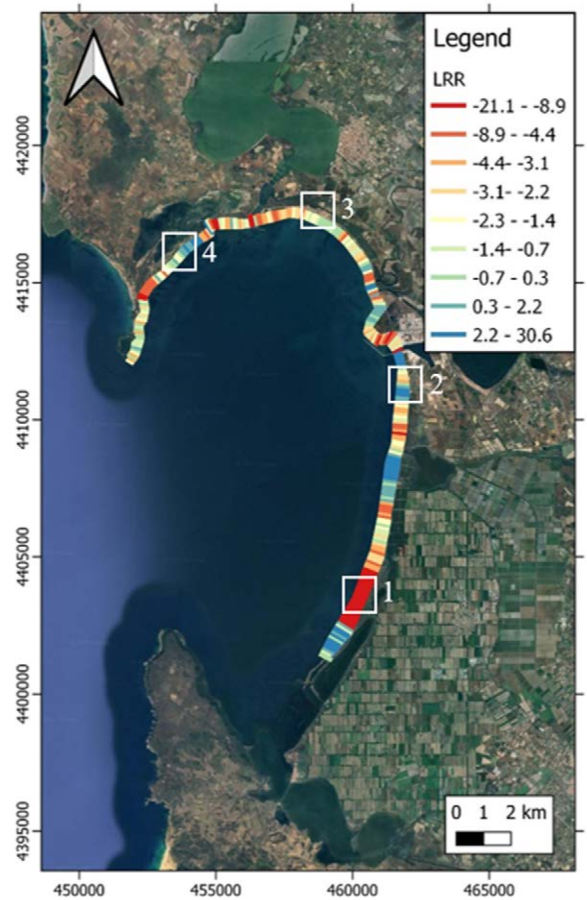

Figure 3 – Short-term shorelines analysis of the Gulf of Oristano from SAET algorithm (2022-2024). DSAS transects and Linear Regression Rate (LRR) statistical analysis (m/y). Area 1 correspond to Arborea beach; Area 2 correspond to Abbarossa beach; Area 3 correspond to Torre Grande beach and Area 4 correspond to Mare Morto beach.

The comparison with RTK-GNSS data is shown in Figure 4, where a notable correlation emerges between the SDS extracted using SAET and the location of the shoreline extracted with CoastSat. This correlation is particularly evident as the shoreline consistently appears shifted towards the sea in all three cases. On the other hand, the shoreline extracted using SAET algorithms seems to follow the path of the GPS shoreline. This is particularly evident in the second image, which correspond to an average distance between the shorelines of less than 1 meter (Table 2). In the first two figures a large amount of *Posidonia oceanica* is visible on the swash area as well as floating on the water while in the third one the Posidonia is absent.

The error analysis revealed that the SAET algorithm exhibited the lowest error, with an average error of approximately 5 meters (Figure 5). Conversely, the CoastSat algorithm demonstrated the highest error, as indicated by its Root Mean Square Error (RMSE) (Table 2).

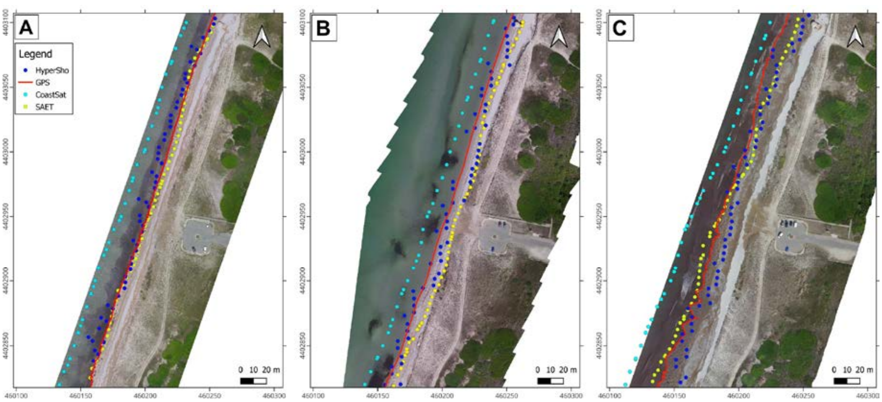

Figure 4 – Maps of shoreline extractions: A) SDSs and drone flight basemap of 18 September 2022; B) SDSs and drone flight basemap of 23 May 2023; C) SDSs and drone flight basemap of 10 October 2023.

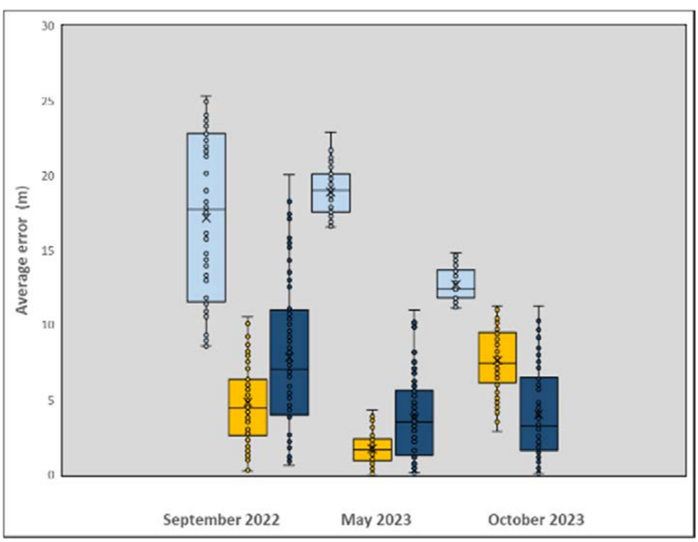

Figure 5 – Boxplot of the error analysis. In yellow SAET algorithm, in clear blue CoastSat algorithm and in dark blue HyperSho algorithm.

Furthermore, the error tends to be higher for CoastSat in cases with more Posidonia and lower with less Posidonia.

Regarding HyperSho, the error is comparable to that found by SAET, and the results do not appear to be affected by the presence or absence of Posidonia.

Table 2 – Error analysis of the SDSs.

Algorithm	RMSE of the algorithm	Date	Error	Value (m)
CoastSat	< 10 m	September 2022	Average	17.14
			St.dev	5.63
		May 2023	Average	18.88
			St.dev	1.54
		October 2023	Average	12.70
			St.dev	1.16
SAET	> 3 m	September 2022	Average	4.81
			St.dev	3.04
		May 2023	Average	1.72
			St.dev	1.06
		October 2023	Average	7.62
			St.dev	2.14
HyperSho	> 6 m	September 2022	Average	7.81
			St.dev	5.11
		May 2023	Average	3.76
			St.dev	2.67
		October 2023	Average	4.01
			St.dev	2.95

The one-year analysis revealed an erosional state throughout the beach, with only a few episodes of accretion of up to 10 meters (Figure 6). The accretion is mainly observed on the southern part (transect 10) adjacent to a pier.

In addition, a major storm event occurred in March 2023 with a peak of wave height of 3.96 m (Fig. 7), which allow us to analyse its effects on the beach (Fig. 6).

Figure 6 illustrates erosion and accretion events, especially along transects 10 to 20.

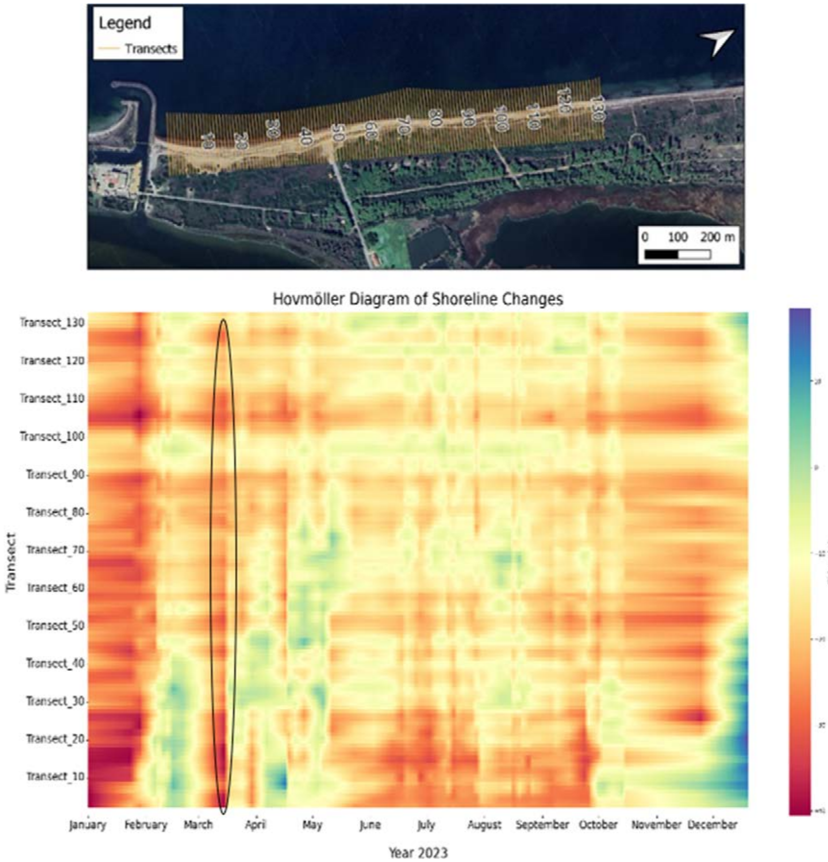

Figure 6 – Hovmöller diagram of shoreline changes on Arborea beach. The event occurred in March 2023 is highlighted.

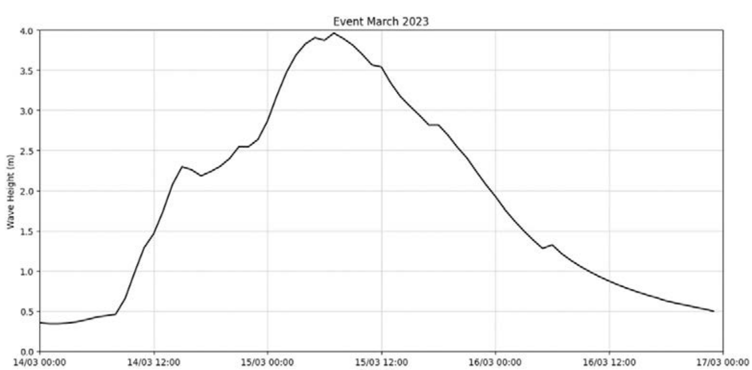

Figure 7 – Significant wave height during the event of March 2023. The data was obtained from the Copernicus Marine Environment Monitoring Services (CMEMS); the selected point was located in the entrance of the Gulf of Oristano (coordinate point: 8.4139.81).

Discussion

The results of the analyses showed how the evolution of the beaches of the Gulf of Oristano appear to reflect the dominant marine processes. In particular, the dynamics in the northern part of the gulf appear to be quite stable. In contrast, significant erosion is observed at Arborea beach in the southern part. Conversely, accretion occurs at Abbarossa beach, likely due to the presence of the harbour jetty acting as a sediment trap [16]. However, this accretion does not seem to match the rate of erosion occurring further south.

Consequently, there appears to be an overall loss of sediment in the region. Several hypotheses could explain this trend. The analysis conducted in 2023 highlighted the occurrence of significant storm surge events throughout the year. These events were confirmed through the examination of satellite images and were noted to occur even during the summer months, albeit with varying intensities. This erosional trend may be caused by the greater influence of extreme events on the most exposed area, specifically Arborea Beach. This discussion aligns with the research conducted by [16]. In the 2D simulation of water circulation in the Gulf of Oristano, the central area, including Arborea Beach, was shown to experience the highest retreat rates under both Mistral and southwestern wind conditions. Additionally, sediment trapping zones were identified in the southern portion of the gulf, near Capo Frasca, which could explain the loss of sediment in the system.

Another hypothesis suggests that erosion may be linked to the reduced sediment supply from the River Tirso and the presence of jetties, which could obstruct sediment circulation [17]. Consequently, this may increase the area's susceptibility to erosion driven by storm events. These aspects should therefore be investigated further through a historical analysis of the shoreline in the entire Gulf of Oristano.

The results also showed that detailed error analysis, comparing SDS with RTK GPS surveys, as in the study conducted for Arborea Beach, confirms the robustness of the method for temporal analysis with greater accuracy than traditional validation methods using orthophotos, which are subject to operator-dependent errors [18].

In addition, the results were found to be in agreement with the error calculated by the authors for the respective algorithms, remaining about 3 meters for SAET [8], sometimes even reaching lower values of 2 meters, and 6-7 meters for HyperSho [13]. In contrast, the CoastSat [7] algorithm produced a larger error, approximately 17 meters compared to less than 10 meters reported by the authors, likely attributable to specific beach conditions. This issue warrants further investigation in future studies, including an assessment of the influence of *Posidonia oceanica* debris on shoreline detection.

This detailed approach enabled the selection of the algorithm that operates most effectively within that specific context and under site-specific conditions, such as the presence of *Posidonia oceanica*.

The long-term temporal analysis enabled the identification of erosion and accretion trends that occurred over time, as well as the events that may have caused fluctuations in these trends [19]. These insights will serve as important elements for analysis in future studies, contributing to a deeper understanding of the coastal dynamics at the Gulf of Oristano.

The implementation of automatic shoreline extraction from optical satellite images supported the temporal analysis, including the evaluation of the errors inherent to the extraction process due to the limitations of the respective algorithms. For instance, while CoastSat provides the capability to perform an automatic temporal analysis, it shows limitations when extracting coastlines for extensive areas, leading to outliers and large errors.

Conversely, SAET is more effective for large areas; however, the process of shoreline extraction from a substantial number of images is less automated and more time-consuming.

Conclusions

The analysis showed erosive trends observed in both the short-term and long-term periods on sandy beaches located in the Gulf of Oristano. This has made it possible to investigate in detail the potential causes of erosion/accretion trends and has the potential to reconstruct historical records of extreme and non-extreme storm events. Such insights provide a clearer understanding of the extent to which these events have influenced the evolution of the coastal environment.

The results obtained from this work represent a useful methodological approach to monitor the shorelines with high frequency information and the related morphological changes, by using multispectral satellite imagery with relatively short revisit time and a large availability of images.

Finally, the semi-automatic procedures represent a way to facilitate the shoreline detection and to minimise the subjectivity due to human intervention.

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