remote sensing

Technical Note

Assessing Shoreline Changes in Fringing Salt Marshes from Satellite Remote Sensing Data

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Abstract: Salt marshes are highly important wetlands; however, external pressures are causing their widespread deterioration and loss. Continuous monitoring of their extent is paramount for the preservation and recovery of deteriorated and threatened salt marshes. In general, moderate-resolution satellite remote sensing data allow for the accurate detection of salt marsh shorelines; however, their detection in narrow and fringing salt marshes remains challenging. This study aims to evaluate the ability of Landsat-5 (TM), Landsat-7 (ETM+), and Sentinel-2 (MSI) data to be used to accurately determine the shoreline of narrow and fringing salt marshes, focusing on three regions of the Aveiro lagoon in Mira, Ílhavo and S. Jacinto channels. Shorelines were determined considering the Normalized Difference Vegetation Index (*NDVI*), and the accuracy of this methodology was evaluated against reference shorelines by computing the Root Mean Square Error (*RMSE*). Once validated, the method was used to determine historical salt marsh shorelines, and rates of change between 1984 and 2022 were quantified and analyzed in the three locations. Results evidence that the 30 m resolution Landsat data accurately describe the salt marsh shoreline (*RMSE*~15 m) and that the accuracy is maintained when increasing the spatial resolution through pan-sharpening or when using 10 m resolution Sentinel-2 (MSI) data. These also show that the salt marshes of the Ílhavo and S. Jacinto channels evolved similarly, with salt marsh shoreline stability before 2000 followed by retreats after this year. At the end of the four decades of study, an average retreat of 66.23 ± 1.03 m and 46.62 ± 0.83 m was found, respectively. In contrast to these salt marshes and to the expected evolution, the salt marsh of the Mira Channel showed retreats before 2000, followed by similar progressions after this year, resulting in an average 2.33 ± 1.18 m advance until 2022.

Keywords: vegetation indices; satellite imagery; DSAS; salt marsh dynamics; shoreline erosion

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1. Introduction

Salt marshes are coastal ecosystems colonized with halophyte plants typical of middle and high latitudes, which are commonly distributed in the upper intertidal zone of low-energetic coastal regions [1]. These are considered among the most productive and valuable ecosystems due to the wide range of services they offer, such as nutrient regeneration, water filtration, primary production, habitat for several faunas (e.g., fish, crustaceans, etc.), a refuge for seabirds, as well as breeding sites and food sources for a variety of migratory birds [2,3]. Moreover, salt marshes store large amounts of carbon in their sediments [4,5] (approximately 3900 g C m^{-2} yr^{-1}), making them one of the most efficient carbon sequesters worldwide [2]. The high carbon sequestration capacity of marsh sediments is attributed to low oxygen conditions, which reduce the rate of decomposition and promote carbon retention in the soil [2,4]. Salt marshes also play a crucial role in dissipating wave energy during storms, contributing to coastal protection [1].

Despite the multiple values provided, salt marshes are increasingly degraded [3]. Mariotti [6] summarized three main causes for salt marsh degradation and loss: (1) lateral erosion that occurs at the front of steeply sloping salt marsh platforms when subjected to intense currents or waves; (2) inland waterlogging that occurs when the salt marsh accretion rate is lower than the rate of mean sea level rise. In this situation, the salt marsh does not show effective growth, and the stress caused by tidal flooding induces plant senescence [7,8]; (3) inland lake formation occurs when the sediment subsides in areas where the salt marsh is unable to drain water.

Several studies provide evidence that salt marsh degradation and loss are often related to increased tidal action and reduced sediment supply [3,9,10]. Day et al. [9] associated the salt marsh shoreline retreat in Venice Lagoon (1.2–2.2 m yr^{-1} between 1993 and 1995) with channel deepening, which triggered the tidal prism increase and wind-induced waves. Similarly, Lopes et al. [3,10] identified salt marsh degradation in the Aveiro lagoon and concluded that the deepening of the lagoon channels promoted hydrodynamic changes (increase in tidal currents and frequency of inundation) responsible for the degradation of the local vegetation.

As external pressures are causing their extensive global degradation and loss, the ability to continuously monitor salt marshes and identify drivers of change is essential for their protection and conservation [11]. Salt marsh shoreline can be assessed precisely (with accuracy in the order of centimeters) using RTK-GPS (Real Time Kinematic Global Positioning System); however, this method is expensive, time-consuming, and limited to accessible regions [11]. Contrarily, methods based on remote sensing technologies enable the determination of salt marsh shorelines at low costs, even in inaccessible regions [11,12]. For instance, previous studies proved efficient in evaluating the long-term evolution of salt marsh extent through the processing of moderate-resolution satellite imagery. Blount et al. investigated the shoreline dynamics of Formosa lagoon (Portugal) salt marshes through the visual interpretation of aerial imagery from Landsat archives (Landsat-5 (TM), Landsat-7 (ETM+), and Landsat-8 (OLI)), as well as Sentinel-2 (MSI) data. Sagar et al. [13] and Murray et al. [14] using Landsat archive data, mapped the shoreline evolution of coastal wetlands in Australia and China, respectively, by computing the Normalized Difference Water Index (*NDWI*). Both studies proved that *NDWI* segmentation is effective in determining tidal flat extent at low tide but fails at other tidal stages. Kuleli et al. [15] also applied the segmentation of *NDWI*, using Landsat archive data, to map the wetlands of Turkey by computing an automatic optimal threshold. Laengner et al. [16] with Landsat archive data, developed an unsupervised method to identify salt marsh vegetation across European coastlines by computing the Normalized Difference Vegetation Index (*NDVI*). That study assumed that salt marshes had *NDVI* values higher than 0.3. However, as *NDVI* is sensitive to tidal and seasonal variations, considering a fixed *NDVI* threshold can be inadequate [12]. Indeed, based on Landsat (TM) and ETM+ archives, Lopes et al. [12] proposed a new methodology to map salt marsh extent in estuarine systems by combining *NDWI* and vegetation indices. Accordingly, *NDWI* was used to determine tidal flat area, while vegetation indices were used to identify vegetation over exposed tidal flats. Among the vegetation indices analyzed, *NDVI* was found to be the best index to identify salt marshes [12].

This study builds on these principles and aims to assess the ability to identify salt marsh shorelines by processing data given by remote sensors with different spatial and spectral resolutions. In detail, this study focuses on Aveiro lagoon salt marshes (Portugal) and uses data from Landsat-5 (TM), Landsat-7 (ETM+), and Sentinel-2 (MSI) satellites to compute *NDVI* and identify salt marshes according to NDVI values, following the findings of Lopes et al. [12] and Laengner et al. [16]. The values of *NDVI* best-describing salt marshes were determined by evaluating the shoreline uncertainty, taking into consideration reference shorelines acquired with a GPS-RTK or obtained by visual interpretation of high spatial resolution orthophotomosaics. The NDVI's best-describing salt marsh shorelines were then used to assess historical shorelines.

2. Study Area

Aveiro Lagoon (Figure 1) is a shallow coastal system located on the northwest coast of Portugal, connected to the Atlantic Ocean through a single inlet artificially fixed in 1808. The lagoon includes four main channels (Mira, Ílhavo, S. Jacinto e Espinheiro), and receives freshwater from five rivers (Vouga, Antuã, Cáster, Boco, and Ribeira dos Moínhos) (Figure 1). It is approximately 45 km long and 8.5 km wide, and 50 km^2 of its total area corresponds to salt marshes, with the most extensive areas located in the central part of the lagoon and at the extremity of the S. Jacinto Channel [3,17]. The estuarine vegetation includes *Halimione portulacoides* (L.) Aellen, *Sarcocornia perenis* (Mill.) A.J. Scott, *Juncus maritimus* Lam., and *Phragmites australis* (Cav.) Steud. in the upper salt marshes, while *Spartina maritima* (Curtis) Fernald and *Salicornia ramosissima* (Hook.f.) J.Woods colonized the low marsh regions and natural depressions [3,10,18].

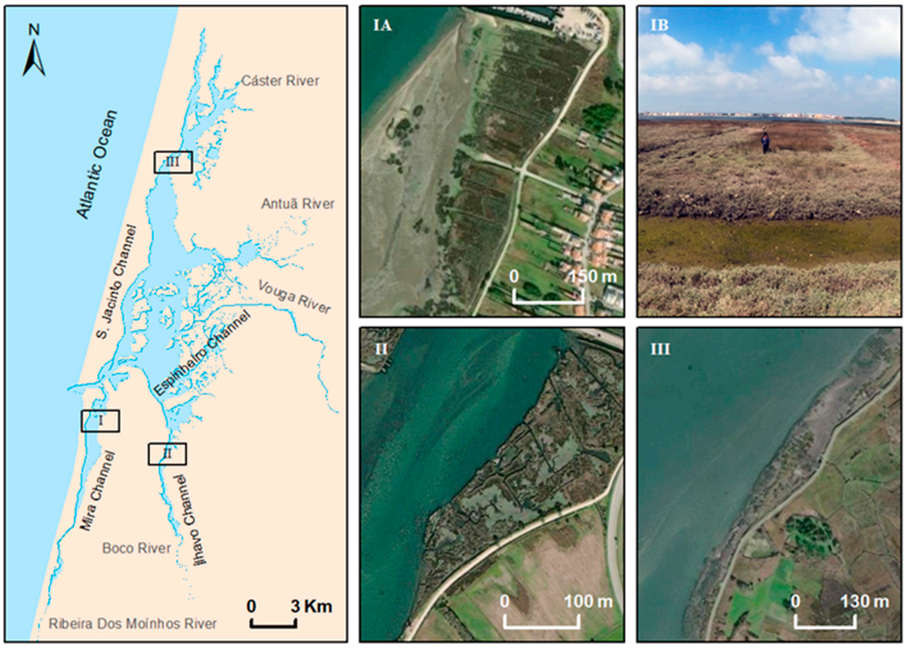

Figure 1. Map of Aveiro lagoon showing the location of main channels and rivers (**left**) Black, numbered polygons represent the locations of the three marshes studied. **I**—Mira's salt marsh (**IA**—aerial photograph; **IB**—panoramic photograph taken during fieldwork). **II**—Aerial photograph of Ílhavo's salt marsh **III**—Aerial photograph of S. Jacinto's salt marsh.

The lagoon circulation is dominated by tidal action, which is semidiurnal [19]. The mean tidal range at the inlet is 2 m; however, it increases to 3.2 m at spring tides and decreases to 0.6 m at neap tides [17]. The tide propagates through the lagoon channels as a damped progressive wave due to the increased effect of bottom friction, observing a decrease in tidal amplitude and an increase in phase towards the end of the channels [17].

During the last three decades, the lagoon channels have become deeper, mainly because of dredging activities carried out at the end of the nineties. The greatest increases in depth occurred in the channel connecting with the inlet (~14 m) and in the lower sections of S. Jacinto and Espinheiro (~8 m) channels. These morphological changes reduced the damping of the tidal wave propagation along the lagoon channels and induced the intensification of tidal currents, changes in inundation patterns, and higher inundation extents [3,10]. Since then, salt marshes have been degraded and lost because the high tidal currents induced edge erosion and the high exposure of plants to flooding caused their senescence. Moreover, the increase in moisture in sediment caused by sea level rise will most likely result in a reduction in the biomass of the pioneer species [3,10,20].

This study intends to investigate in detail the salt marsh degradation in three salt marsh regions (Figure 1I–III), which are on the margins of Mira, Ílhavo, and S. Jacinto channels.

3. Methodology

3.1. Data Collection

The data analyzed in this study includes:

(1) Surface Reflectance (SR) derived from Landsat-5 (TM) and Landsat-7 (ETM+), given by the USGS Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA), and Sentinel-2 (MSI), given by the Centre National d'Etudes Spatiales (CNES) for the Theia data center (Table 1). SR data for 1984, 2000, and 2022 was used to derive salt marsh shorelines based on the values of the *NDVI*. It should be noted that these dates consider three key moments: 1984, the start of Landsat-5 (TM) data collection; 2000, the beginning of salt marsh degradation as shown by Lopes et al. [10]; and 2022, indicative of the present.

(2) Salt marsh shoreline was collected in Mira with a Trimble R8 receiver on 6 April 2022, during low tide to guarantee that the tidal flat was completely exposed. The coordinates of shoreline points were acquired with an accuracy of more than 10 cm using the GPS-RTK method by receiving signals from Global Navigation Satellite Systems (GNSS) and communicating with the reference network ReNEP (Portuguese Network of Permanent GNSS Stations) station closest to the sampling site. Cost and accessibility limitations made it impossible to collect data in the other two salt marshes.

(3) Orthophotomosaics for 2021, made available by the General Directorate of Territory (DGT) (Table 1), were used to delineate reference shorelines for the Ílhavo and S. Jacinto salt marshes.

Table 1. Information regarding the aerial images used in this study Orthophotomosaics, Landsat, and Sentinel images are available at https://www.dgterritorio.gov.pt/ (accessed on 1 September 2022), https://espa.cr.usgs.gov/ (accessed on 1 September 2022), and https://www.theia-land.fr/en/homepage-en/ (accessed on 1 September 2022), respectively.

Aerial Images	Dates	Source	Spectral Bands	Spatial Resolution (m)
Orthophotomosaics	2021	DGT (Directorate of Territory)	Red (R), Green (G), and Near Infra Red (NIR)	0.25
Landsat-5 (TM)	17 April 1984	NASA and USGS (National Aeronautics and Space Administration and United States Geological Survey)		30
Landsat-7 (ETM+)	20 March 2000		RG, NIR, and Panchromatic	
	2 April 2022			
Sentinel-2 (MSI)	2 April 2022	ESA (Eros Science Processing Architecture)	RG and NIR	10

3.2. Salt Marsh Shoreline Assessment and Validation

Reference shorelines were constructed for the three salt marshes under study. For the Mira salt marsh, the shoreline monitored with the RTK-GPS was considered, while for Ílhavo and S. Jacinto salt marshes, shorelines were obtained through the visual interpretation of false color composites of orthophotomosaics (see Table 1) to better visualize the boundary between vegetated and non-vegetated tidal flats.

Regarding satellite imagery, salt marsh shorelines for 2022 were determined by computing the *NDVI* [21] from the SR of Sentinel-2 (MSI) and Landsat-7 (ETM+) satellites. In the case of Landsat-7 (ETM+) data, two *NDVI* maps were built, one using the 30 m spatial resolution bands and the other by applying the pan-sharpening technique to increase the spatial resolution of the bands from 30 m to 15 m. In detail, pan-sharpening was conducted using the *Image Analysis* tool within ArcGIS 10.8 and considering the Gram-Schmidt method [22]. Then, reference shorelines were superimposed on the *NDVI* maps, and the range of *NDVI* values that could best fit the reference salt marsh shorelines was identified. Different NDVI values were considered because a preliminary analysis of the NDVI maps revealed that, for the same satellite scene, the range of values that best represented the shoreline in the three salt marshes was different. This process generated various shorelines for each *NDVI* map and for each salt marsh.

After that, the uncertainty of satellite-derived shorelines was estimated through the Root Mean Square Error (*RMSE*):

$$RMSE = \sqrt{\frac{1}{N} \times \sum_{i=1}^{N} \left(Y_{Sat} - Y_{Ref}\right)^2}, \quad (1)$$

where N is the number of transects, and Y_{Sat} and Y_{Ref} are satellite-derived and reference shoreline positions, respectively, of each transect. The difference between shoreline positions ($Y_{Sat} - Y_{Ref}$) was assessed using the Net Shoreline Movement tool of DSAS v5.1 software, operable in ArcMap 10.8. The transects were defined perpendicular to a baseline and intersected the shorelines every 5 m. *RMSE* values were analyzed, and the *NDVI* values best describing salt marsh shorelines were determined. Further analyses were made to investigate these hypotheses: (1) satellite images of the Landsat archive with a spatial resolution of 30 m can be used to accurately determine the shoreline of fringing salt marshes; (2) increasing the spatial resolution of Landsat-7 (ETM+) images to 15 m through pan-sharpening techniques produces more accurate results; and (3) Sentinel-2 (MSI) images with a spatial resolution of 10 m provide better results than those obtained through Landsat images.

3.3. Salt Marsh Shoreline Change

Once validated, the method was used to determine salt marsh shorelines from satellite historical imagery (1984 and 2000), and salt marsh shoreline change rates were computed using the DSAS v5.1 add-in to Esri ArcGIS desktop (10.8) software. The DSAS tool enables the quantification of shoreline changes and related statistics from multiple shorelines. The shoreline change rate was computed considering the *End Point Rate (EPR)* method within DSAS, following the next steps: (1) A reference baseline was created and perpendicular transects were placed every 5 m; (2) the distance between the baseline and shoreline locations was assessed for each transect; (3) *EPR* change rates were calculated for each transect according to:

$$EPR = \frac{\Delta S}{\Delta t}, \quad (2)$$

where:

ΔS—Is the distance between the oldest and most recent shorelines

Δt—Is the time elapsed between the oldest and most recent shorelines

In this work, it was decided to analyze separately the shoreline changes that occurred before and after the year 2000, ($EPR_{1984–2000}$, and $EPR_{2000–2022}$, respectively), because this year marked the end of dredging activities that triggered hydrodynamic changes [3]. In this way, for $EPR_{1984–2000}$, ΔS is the distance between 1984 and 2000 shorelines and Δt was set 16 years, while for $EPR_{2000–2022}$, ΔS represents the distance between 2000 and 2022 shorelines and Δt is 22 years. The rates of shoreline changes ($EPR_{1984–2000}$ and $EPR_{2000–2022}$) were further used to assess the average shoreline change by: (1) summing in each transect the $EPR_{1984–2000}$ and $EPR_{2000–2022}$; (2) calculating the mean and standard deviation of the previous result and multiplying by 38 years.

For each site, maps and graphs were produced using ArcGis 10.8 and MATLAB 2021a, and shoreline changes were analyzed along the salt marshes.

4. Results

4.1. Salt Marsh Shoreline Validation

Table 2 presents the *RMSE* for all satellite-derived salt marsh shorelines for different *NDVI* thresholds for the three study sites. Regarding Landsat, the considered *NDVI* values produced *RMSE* below the spatial resolution of the spectral bands (30 m) for all salt marshes. Despite this, only at the Ílhavo salt marsh did the pan-sharpening techniques result in somewhat smaller errors, with an average difference of 3.57 m. In Mira and S. Jacinto, the differences between *RMSE* obtained considering or discarding pan-sharpening techniques are very small, not exceeding 2 m.

Regarding Sentinel-2 (MSI) imagery, *NDVI* values produced average errors of 35.44, 14.76, and 5.80 m for S. Jacinto, Mira, and Ílhavo salt marshes, respectively. Compared to Landsat-7, S. Jacinto was the only site presenting larger values of *RMSE*, with an average difference of approximately 22 m. In Mira, the performance of Sentinel-2 is similar to that of Landsat, while in the Ílhavo *RMSE* obtained from Sentinel-2 is smaller than those obtained with Landsat (by approximately 6 m).

It is interesting to note that the Ílhavo salt marsh is the only site that showed somewhat better results when increasing the spatial resolution of spectral bands either by using pan-sharpening techniques or Sentinel data.

Table 2. Best-fitting *NDVI* was obtained automatically from Landsat-7 and Sentinel-2 data for each salt marsh and respective *RMSE* (m).

		NDVI	***RMSE* (m)**
Mira	Landsat-7 (Pan-sharpening)	0.10	16.99
		0.11	13.62 *
		0.12	16.24
	Landsat-7	0.09	17.6
		0.10	15.02 *
		0.11	19.81
	Sentinel-2	0.43	15.28
		0.44	14.39 *
		0.45	14.61
Ílhavo	Landsat-7 (Pan-sharpening)	0.07	7.58
		0.08	6.11 *
		0.09	11.32
	Landsat-7	0.05	12.08
		0.06	10.77 *
		0.07	12.89
	Sentinel-2	−0.01	6.32
		0.00	
		0.01	4.81 *
		0.02	
		0.03	6.27
S. Jacinto	Landsat-7 (Pan-sharpening)	0.04	15.41
		0.05	13.36 *
		0.06	13.5
	Landsat-7	0.04	12.88
		0.05	11.53 *
		0.06	16.4
	Sentinel-2	0.23	40.67
		0.24	31.96 *
		0.25	33.69

* Lower *RMSE* (m) that corresponds to the *NDVI* that best represents the reference shoreline.

4.2. Salt Marsh Shoreline Change

The shoreline of the Mira Channel salt marsh (Figure 2) evidences two distinct parts. In the north of the transect 50, the salt marsh shoreline experienced almost no change between 1984 and 2022, while in the south, the shoreline experienced opposite variations: between 1984 and 2000, the shoreline retreated on average by 0.59 m yr^{-1}, and after 2000, the salt marsh pograded at an average rate of 0.65 m yr^{-1}. As evidenced in Figure 3, the rates of retreat monitored between 1984 and 2000 were similar to the rates of progradation after 2000, and accordingly, the progression of the salt marsh shoreline during the 38 years under study was very small (2.33 ± 1.18 m).

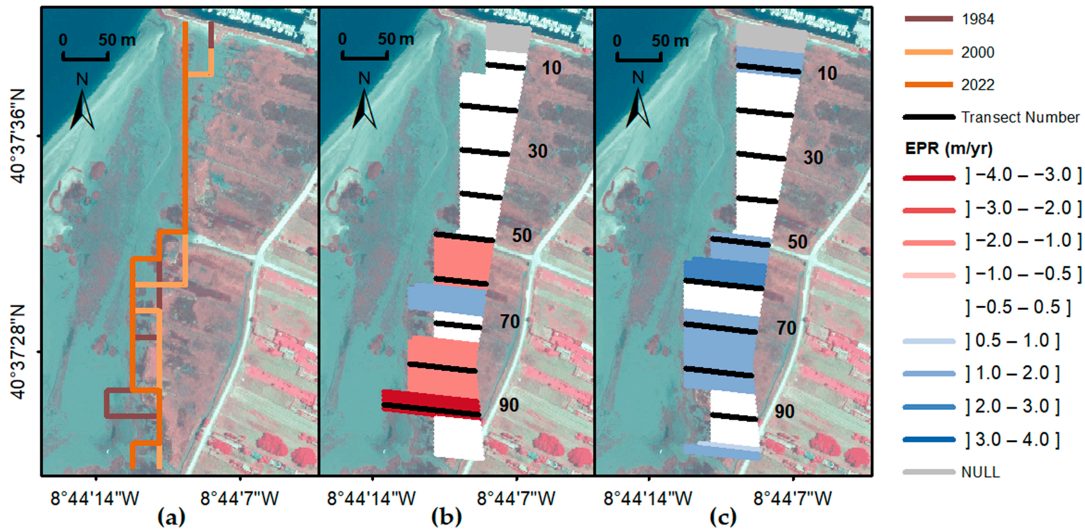

Figure 2. (**a**) Satellite-derived salt marsh shorelines for 1984, 2000, and 2022 for the Mira Channel; perpendicular transects depicting the rates of change for the time interval established: (**b**) before 2000 and (**c**) after 2000. Black lines represent the transect number every 50 m along the salt marsh.

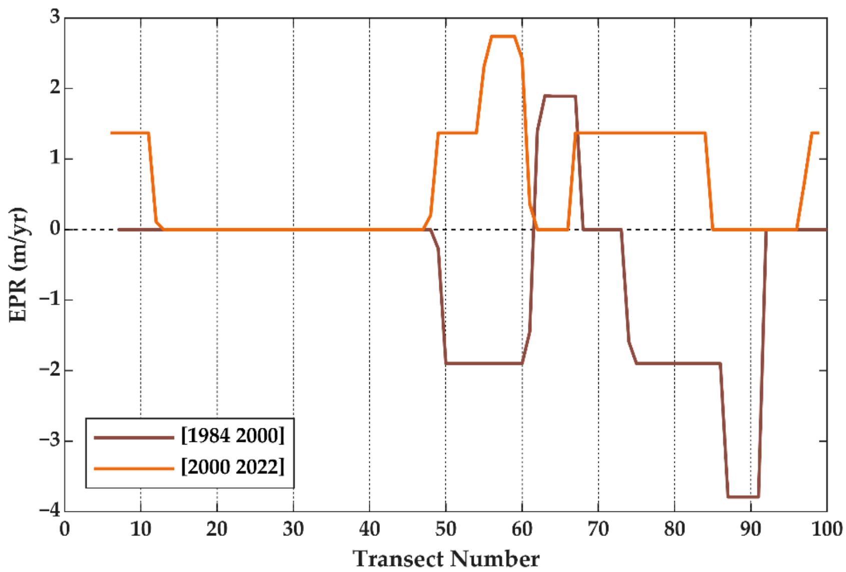

Figure 3. Shoreline variation rates before and after 2000, calculated by the End Point Rate (m yr^{-1}) method along transects in the salt marsh of the Mira Channel.

Regarding the salt marsh located on the margin of the Ílhavo Channel (Figures 4 and 5), the results reveal zero or negative variation rates in both periods under study, which correspond to shoreline retreats. Between 1984 and 2000, the shoreline was almost stable, presenting an average retreat of 0.57 m yr^{-1}, while after 2000, a clear retreat was detected along the whole extension of the marsh, depicting an average retreat of 1.19 m yr^{-1}. On average, the salt marsh shoreline retreated 66.23 ± 1.03 m during the 38 years under observation.

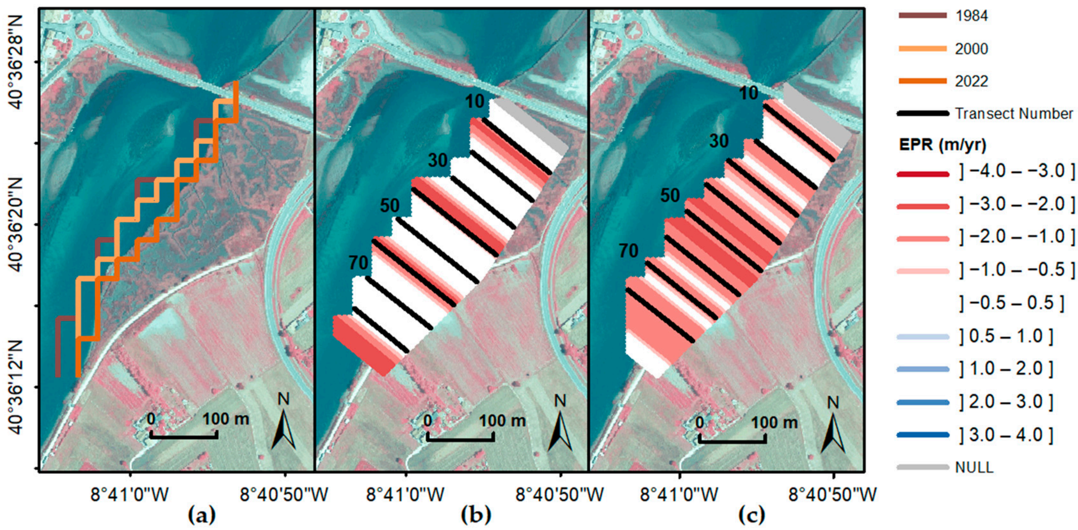

Figure 4. (**a**) Satellite-derived salt marsh shorelines for 1984, 2000, and 2022 for the Ílhavo Channel; perpendicular transects depicting the rates of change for the time interval established: (**b**) before 2000 and (**c**) after 2000. Black lines represent the transect number every 50 m along the salt marsh.

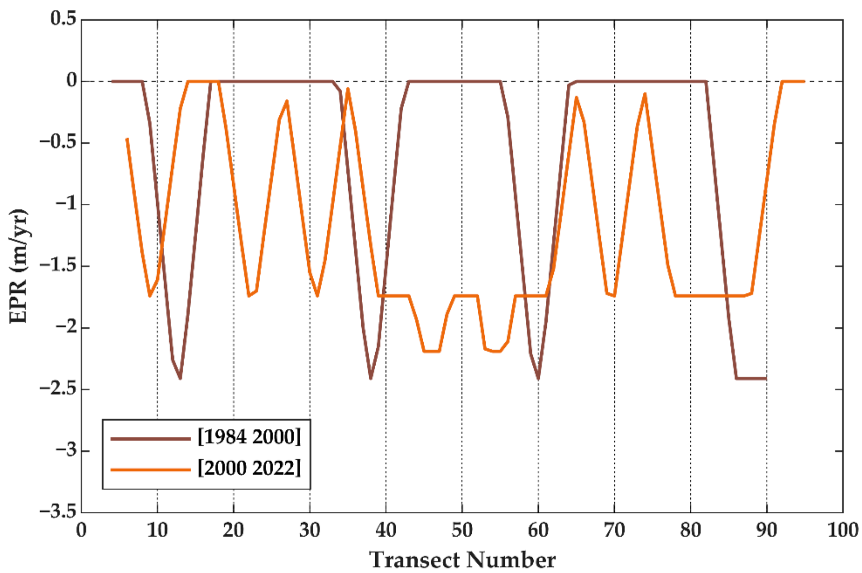

Figure 5. Shoreline variation rates before and after 2000, calculated by the End Point Rate (m yr^{-1}) method along transects in the salt marsh of the Ílhavo Channel.

Similar to the Ílhavo Channel, in S. Jacinto (Figures 6 and 7), the salt marsh shoreline remained stable over the whole extension between 1984 and 2000, and exhibited a clear retreat after 2000, exhibiting a mean retreat rate of 1.23 m yr^{-1}. On average, after the 38 years under study, the salt marsh shoreline retreated by 46.62 ± 0.83 m.

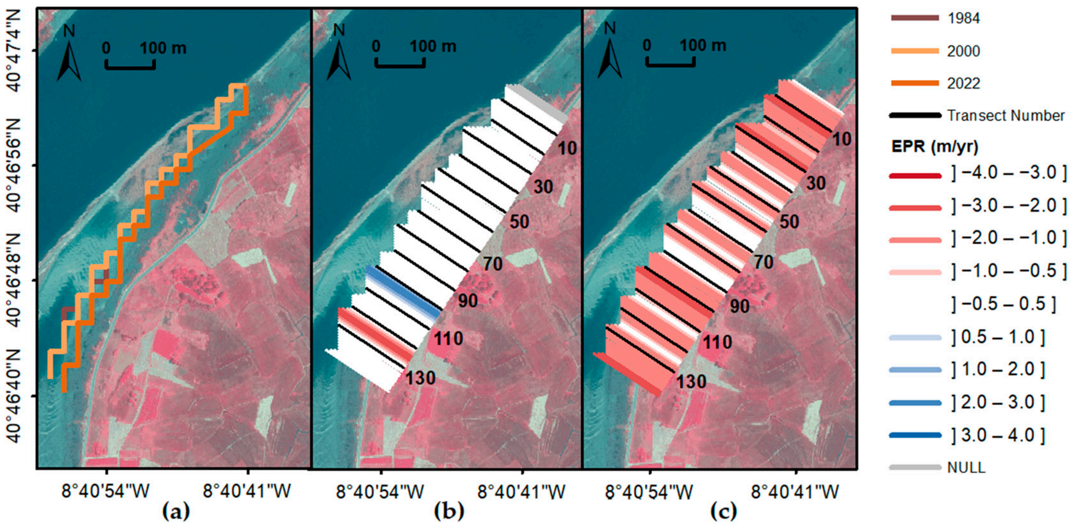

Figure 6. (**a**) Satellite-derived salt marsh shorelines for 1984, 2000, and 2022 for the S. Jacinto Channel; Perpendicular transects depicting the rates of change for the time interval established: (**b**) before 2000, and (**c**) after 2000. Black lines represent the transect number every 50 m along the salt marsh.

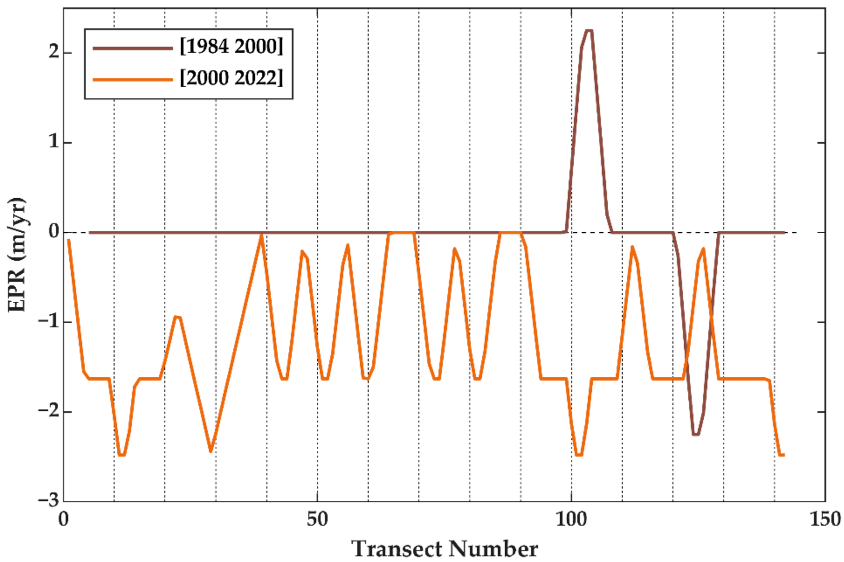

Figure 7. Shoreline variation rates before and after 2000, calculated by the End Point Rate (m yr^{-1}) method along transects in the salt marsh of the S. Jacinto Channel.

5. Discussion

5.1. Salt Marsh Shoreline Validation

Historical satellite images from the Landsat archive enable the characterization of the long-term evolution of ecosystems, such as salt marshes, while allowing the identification of mechanisms underlying modifications and giving insights about future threats, which is fundamental for assisting management options capable of protecting these systems [11–16]. However, the 30 m spatial resolution of Landsat-5 (TM) imagery may be insufficient to accurately monitor shoreline changes in fringing salt marshes. In this study, it was investigated if satellite images from the Landsat archive with a spatial resolution of 30 m can be used to accurately determine the shoreline position for three salt marshes located within the Aveiro lagoon. The *RMSE* obtained when using Landsat-7 (ETM+) data with 30 m of spatial resolution does not exceed 15 m, which is very good given the 30 m spatial resolution of spectral bands. The results further evidence that *RMSE* is generally remarkably similar when increasing the spatial resolution through pan-sharpening techniques. The only exception was observed for the Ílhavo salt marsh, where pan-sharpening improved shoreline accuracy. This fact may seem surprising; however, previous studies also found that increasing the spatial resolution by pan-sharpening does not always yield better image classifications, in part because pan-sharpening may introduce spectral and spatial distortion [23–27]. Moreover, the panchromatic band used in the pan-sharpening process is a level-1 product, which could be an additional source of error, as pointed out by Blount et al. [11].

This study further investigated the accuracy of salt marsh shoreline detection using Sentinel-2 imagery, given the higher spatial resolution and shorter review time offered when compared with operational Landsat missions. Similar to the results obtained for the Landsat-7 pan-sharpening, more accurate results were obtained only at the Ílhavo salt marsh, while at Mira and S. Jacinto, the shoreline accuracy maintained and decreased, respectively.

It is worth noting that shoreline accuracy depends not only on satellite-derived shorelines but also on the precision of reference shorelines that should be ideally monitored in situ with high-precision methods. However, as monitoring salt marshes in situ is challenging, quite complex, and expansive, available ground truth data is often limited and difficult to obtain. In the scope of this work, it was only possible to survey the shoreline in one of the marshes with a GNSS receiver, while in the other two, the reference shorelines were obtained by visual interpretation of ortophotomosaics, adding additional sources of uncertainty. Therefore, and despite the constraints posed by in situ monitoring, future works would benefit from the topographic survey of salt marshes. This data would not only increase the accuracy of shoreline detection but would also make it possible to generate Digital Elevation Models (DEMs), which are considered essential for evaluating salt marsh shoreline changes under rising sea levels [28,29]. It is interesting to note that *NDVI* thresholds best describing salt marsh shorelines varied between salt marshes, suggesting that local factors should be affecting the reflectance of the red and NIR bands and consequently the accuracy of the satellite-derived salt marsh shorelines. In fact, despite the three salt marshes being located within the Aveiro lagoon, they present distinct morphological features and are subject to slightly different tidal conditions during satellite acquisitions. Indeed, the S. Jacinto salt marsh is further distant from the lagoon's entrance than the Mira and Ílhavo salt marshes, and therefore the extension of the tidal flooding may be slightly different at the three locations at the time of the satellite pass. Given that *NDVI* is highly sensitive to soil reflectance and that soil reflectance depends on water content, the existence of tidal flats and their water content can explain the higher performance of shoreline detection in Ílhavo compared with Mira and S. Jacinto salt marshes. Indeed, Ílhavo is a high marsh with steep edges bounded by ditches and channels, while Mira and S. Jacinto salt marshes present a soft slope and adjacent uncolonized mudflats [18]. Consequently, the Ílhavo salt marsh shoreline separates the salt marsh from a water channel, contrary to the other salt marshes, where shorelines separate uncolonized from colonized mudflats (salt marshes). Therefore, the effect of soil brightness is more evident in the latter marshes, hindering the identification of salt marsh shorelines. It is noteworthy that this explanation agrees with the study of Lopes et al. [12], which concluded that salt marsh detection is more accurate when tidal flats are flooded because in this situation the soil brightness effect is reduced.

5.2. Salt Marsh Shoreline Change

Based on studies centered on a review of the main hydrodynamic and geomorphologic characteristics of the Aveiro lagoon and the analysis of possible tidal changes and the geomorphology of this lagoon, as well as the possible causes and consequences of these changes, it was possible to understand the results obtained regarding the salt marsh shoreline changes.

The natural tendency of the lower lagoon, where the three marshes studied are located, favors sediment transport to the open ocean, thus contributing to the deepening of the entrance of the Aveiro lagoon and the channels located in this region [17,30]. However, these natural sedimentary processes alone cannot explain the magnitude of changes observed in the morphology and hydrodynamics of the Aveiro lagoon [1]. Dredging activities carried out in the four main channels in the late 1990s to improve navigation conditions were the major contributors to increasing the lagoon mean depth [3]. Because of this deepening, a reduction of the frictional stress caused by the water flowing over the bottom occurred, which resulted in tidal propagation with lower energy dissipation, a faster speed, and a greater amplitude. This increase in amplitude also resulted in an increase in tidal prism and asymmetry, current velocity, and flood extent, as well as an intensification of the ebb tide dominance associated with erosion processes at the entrance of the Aveiro lagoon [17,31–33].

The salt marsh shorelines obtained and analyzed in this study enabled, for the first time, the quantification of the changes that occurred between 1984 and 2000 (before dredging) and between 2000 and 2022 (after dredging). In the four decades of study, the Ílhavo and S. Jacinto Channel salt marshes showed similar patterns of shoreline changes. Both showed negligible variations before 2000, followed by a clear retreat after this year. For these channels, the results obtained agree with the finding of Lopes et al. [3], who did not point out variations in the estuarine vegetation before 1999 but found a decline after this year.

The S. Jacinto Channel presented the highest modifications of the tidal characteristics, namely greater increases in the tidal prism, resulting in a larger flood area, and greater intensification in tidal currents [17], factors that contributed to the later erosion verified in the salt marsh under study.

The Ílhavo Channel salt marsh was the one that exhibited the greatest total retreat. In addition to changes in the hydrodynamics of this channel, factors such as the size of the marsh and its location in the lagoon may also be related to the observed changes. Indeed, this is a mature salt marsh whose margins present an accentuated slope and are therefore susceptible to erosion triggered by local currents, as described in Mariotti [6]. Occupying a smaller area compared to the other salt marshes, this one becomes more susceptible to hydromorphological changes that occur in the lagoon, namely, the increase in ebb dominance, which is responsible for intensifying the erosion processes.

Contrasting with these two salt marshes, the shoreline of the Mira Channel salt marsh showed the predominance of progression processes [17]. With this, it was noticeable that in 2022, the salt marsh had a larger area than in 2000. This advance and increase in the area may have originated from the construction of the Marina Clube da Gafanha (see Figure 8). As depicted in Figure 8b,c), the northern part of the marsh is bounded by the Marina, which did not exist in 1995 (see Figure 8). Indeed, in 1995, part of the area occupied by the Marina was colonized by vegetation. Siemes et al. [34], through the application of a morphological model, showed that artificial structures can be used to steer the morphological development of salt marshes. By creating an area sheltered from high energy conditions, certain infrastructures can improve the potential for vegetation establishment and stimulate salt marsh growth.

The advance may also be the result of the completion of contract work to improve maritime accessibility in 2013 [35]. In 1998, APA, S.A., initiated a set of investments to provide the Port of Aveiro with infrastructure to adapt to the size of the ships that sought this port. To achieve this, the following works were carried out within 200 m of the harbor dock: dredging operations to lower the navigability quota to 13.20 m. The execution of these works could be the origin of the small shoreline retreats observed. The proximity of Mira's salt marsh to the entrance of the Aveiro lagoon and the main channel, compared to the location of the other two salt marshes, makes it even more susceptible to the deepening of these areas, which, as already discussed, may contribute to the observed changes.

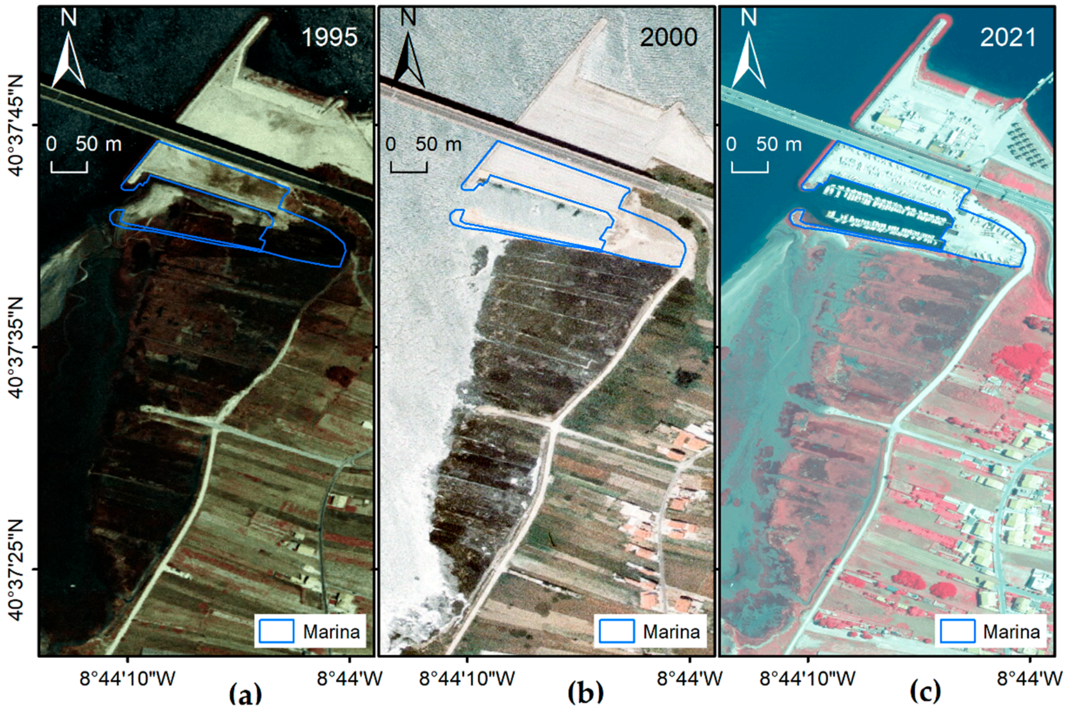

Figure 8. Aerial images of the salt marsh located in the margins of the Mira channel in (**a**) 1995, (**b**) 2000, and (**c**) 2022 The blue lines represent the area occupied by the Marina.

5.3. Potential Impacts of Salt Marsh Shoreline Changes and Recommendations

The results obtained in this study support the idea that the shoreline of the Aveiro Lagoon salt marshes have been retreating, mainly since the 2000s, resulting in a reduction in their extent given that the inland boundary was maintained (the three salt marshes are bounded by roads) (Figure 9). Salt marshes are coastal ecosystems that provide a wide range of ecosystem services, and therefore the shoreline retreat detected can pose serious threats to ecosystem services, namely habitat loss, reduced protection against storm surges, water quality degradation, and a decrease in the capacity to sequester blue carbon [36–39] (Figure 9). Indeed, as salt marshes retreat, the feeding, sheltering, and nesting areas for many species of fauna decrease, which can dramatically alter the lagoon's food web [40]. Also, the protective buffer that salt marshes offer against storm surges [41–43] decreases as they retreat, making adjacent communities more exposed to flooding and the adverse impacts of mean sea level rise. Additionally, the capacity to retain pollutants and excess nutrients may also have decreased as salt marshes retreated [44,45], potentially contributing to the degradation of the lagoon's water quality. Salt marshes are further known for efficiently sequestering atmospheric carbon dioxide and storing carbon in their soils [46–48]. As salt marshes retreat, their carbon storage potential is reduced, contributing to climate change [49].

The potential loss of ecosystem services triggered by the loss of salt marsh areas demands the rapid development of strategies that contribute to the effective protection and conservation of these valuable ecosystems. The implementation of actions that prevent erosion of the marsh shorelines and at the same time promote sediment retention must be a priority because, as discussed above, there is no space available for inland salt marsh progression (Figure 9). The placement of wood fences along the shorelines can be a good option, given their successful implementation in the Venice Lagoon salt marshes [50,51]. Because dredging activities contributed to the salt marsh shoreline retreat and consequent loss of ecosystem services, it is recommended that further dredging activities be avoided in the future. Even when new dredging is considered necessary, it is imperative to use dredged sediments to benefit salt marshes. This has already been done successfully in worldwide estuarine systems [52–56]. Finally, it is of paramount importance to promote actions that raise awareness among the local communities and alert people to the critical role salt marshes play in the ecology and economy of local human communities. Education programs with consistent communication, engagement, and collaboration with various stakeholders would effectively convey the importance of salt marshes and inspire action for their protection and conservation. It is noteworthy that these actions have become even more important in the current context of rising sea levels. Indeed, salt marshes exhibit inland migration as a natural response to mean sea level rise [57]. However, in the case of most salt marshes of the Aveiro lagoon, such migration is almost impossible given the presence of communities.

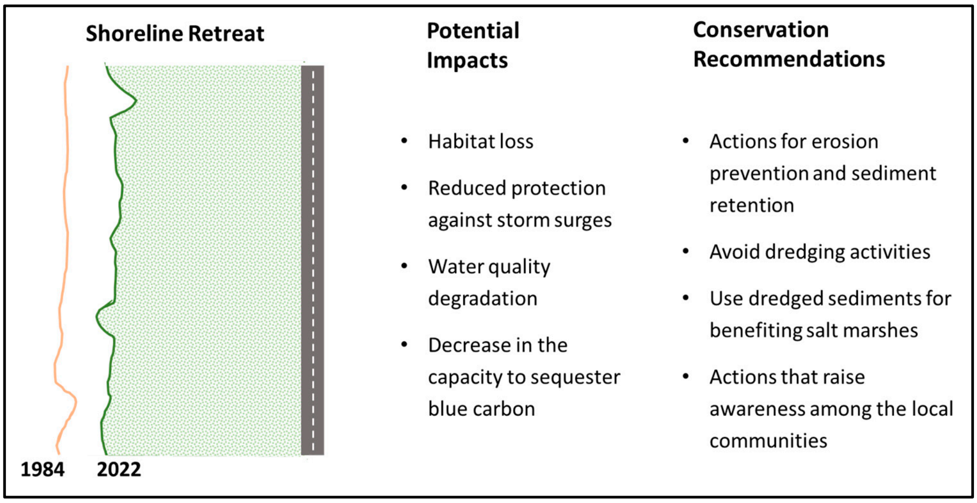

Figure 9. Illustration of salt marsh shoreline changes, potential impacts, and conservation recommendations.

5.4. Limitations

This study used NIR and visible SR from Landsat and Sentinel-2 missions to detect the shoreline of fringing salt marshes. Despite the acceptable accuracy obtained, using 10 m or 30 m spatial resolution data comes with certain limitations given the difficulty in detecting small-scale features with these spatial resolutions. Obviously, this study would benefit from higher spatial resolution data; however, spatial resolution is not the only conditioning factor, and other factors such as costs, temporal coverage, and spectral range must be considered when choosing the sources of satellite remote sensing data. Commercial satellites such as IKONOS, GeoEye, or WorldView collect multispectral data at very high spatial resolution; however, the data is not freely available, and the continuous monitoring of salt marsh shorelines can be quite expensive. Alternatively, Google Earth Pro provides very high-resolution RGB imagery for free; however, distinguishing salt marshes from water and unvegetated tidal flats can be very difficult by visually interpreting RBG imagery. Indeed, the interaction of sun light with vegetation and water has some similarities, since both water and vegetation highly absorb visible radiation and consequently have low reflectance in this region of the spectrum. In contrast, in the NIR region, water and vegetation behave very differently: while plants highly reflect NIR radiation, water bodies present very low reflectance [21,58–61]. This way, spectral vegetation indices, like *NDVI*, have been used to efficiently capture salt marsh shorelines [12,61–63]. In addition, the RGB imagery of Google Earth Pro proved inadequate for this study since there were no images available for the Aveiro lagoon in the year 2000.

Monitoring salt marsh shoreline changes through satellite remote sensing methods involves choosing databases and processing methods appropriate to the monitoring purpose. It is unquestionable that satellite remote sensing provides fundamental data for the scientific community assessing changes in salt marsh ecosystems; however, it is important to highlight that the data features and processing methods used affect the quality of the inferred results.

Satellite remote sensing offers historical, repeatable, and standardized data, allowing scientists to address issues unreachable through in situ observations alone [64]. Despite all the constraints related to satellite data (temporal coverage, availability, costs, spatial and spectral resolutions), the availability of ground-truth data, and accessibility limitations for in situ sampling, it was possible to adequately characterize the variations of salt marsh shorelines of the Aveiro lagoon, infer about the potential impacts of such changes on the ecosystem, and formulate recommendations for salt marsh protection and conservation.

6. Conclusions

This study determines the ability to identify salt marsh shorelines and study their changes by processing data given by remote sensors with different spatial and spectral resolutions for three salt marshes in the Aveiro lagoon from 1984 to 2022.

In response to the hypotheses raised for this study, it is possible to draw the following conclusions: (1) Landsat images can indeed be used to accurately determine salt marsh shorelines and their changes; (2) despite providing higher spatial resolutions, pan-sharpening techniques do not produce consistent results given that lower errors are only produced in some cases and are not significant; and (3) much like pan-sharpening techniques, Sentinel archives also don't produce consistent results, with one instance yielding results that were noticeably poorer than those produced by satellite images from the Landsat archive with a spatial resolution of 30 m.

As a final conclusion, this study proves the accuracy and consistency of the results provided by the processing of satellite data from the Landsat archive with a spatial resolution of 30 m, which was not attainable from Sentinel archives or resolution-increasing techniques, meaning that an increase in resolution does not imply a better identification of shorelines.

The present study provides crucial information to assist in the understanding of the dynamics of salt marshes. To complement this study, future work would involve trying different pan-sharpening approaches and delineating a greater number of salt marsh shorelines both in the field and with Sentinel data. Also, considering that dredging and sediment deposition operations were recently carried out in the lagoon main channels under the scope of the Transposition of Sediments for Optimization of the Hydrodynamic Balance in the Aveiro Lagoon project [35,65], the continuous monitoring of these systems is imperative to understand their evolution mechanisms and apply them to future conservation measures and predictive models considering new human interventions.

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