COUPLED ISLAND AND DELTA EVOLUTION FROM SATELLITE IMAGERY

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Abstract

The artificial opening and stabilization of the Faro-Olhão inlet around 1950 permanently altered tidal and wave-driven sediment transport in the Ria Formosa Barrier Island system. An example is the accelerated elongation of Culatra Island, located downdrift of the new inlet. Earlier hypotheses attributed this acceleration to the storm-driven collapse of the adjacent ebb-delta, though conclusive evidence is lacking. This study uses shoreline and ebb-delta mapping derived from satellite imagery (1984-2024) to estimate sediment budgets and investigate the growth of the island. Sediment from the ebb-tidal delta could account ~34% of the total growth, while the erosion of the updrift island could contribute ~30%. The remaining volume is likely supplied by additional longshore sediment transport, probably associated with updrift inlet bypassing. These findings highlight the value of monitoring barrier island dynamics with high temporal resolution, which is achievable using freely available satellite imagery.

Introduction

Sandspits follow cyclic development patterns that are still not fully understood. Some studies attributed the onset of this cyclic behaviour to external forces, particularly variation in wave climate (e.g., Allard et al., 2008), while others found sandspit morphodynamics to be self-regulated with wave regime explaining only a small part of their evolution (Taveneau et al., 2024). Here, we analyse the evolution of Culatra Island, a barrier island located in South Portugal, formed by a series of longitudinally attached sandspits that contributed to the elongation of the island (Figure 1). The growth of the island has been linked to the attachment of shoals from an adjacent ebb-delta, through a process of ebb-shoal collapse, driven by moderate to extreme storm events in a context of ebb-tidal current decay (Andrade, 1990; Pacheco et al., 2011). This work aims to explore the process of sandspit formation and elongation through satellite imagery, and the key interactions with the adjacent ebb-delta.

Figure 1. Image of the study site from ESRI world imagery layer.

Study site

The Culatra Island, located in the barrier island system of the Ria Formosa, South Portugal, has been elongating at least since the mid 1800 (Kombiadou et al., 2019), with the formation of a series of sandspits in the backbarrier area (Kombiadou et al., 2023). The Armona inlet functioned as the primary inlet of the Ria Formosa until the opening (1929) and subsequent stabilization (completed in 1955) of the updrift Faro-Olhão inlet. This inlet captured most of the system tidal prism, which led to a reduction in the size of the Armona inlet and ebb-tidal delta. In 1985, Armona inlet accounted for approximately 48% of the Ria Formosa's total spring tidal prism, but this contribution had declined to about 28% by 2010 (Pacheco et al., 2010). The inlet is ebb-dominated and characterised by semi-diurnal tides, with a spring tidal range of 2.8 m, a neap range of 1.3 m, and a maximum tidal range of 3.5 m. The offshore mean significant wave height is about 1 m with an average wave peak period of 8.2 s. Wave energy is predominantly from the W-SW (over 70%), with approximately 20% coming from the E-SE, causing net longshore transport to the east. Culatra Island, located on the eastern flank of the Ria Formosa, is partially sheltered from the dominant W–SW swells.

Methodology

Satellite-derived shorelines and delta mapping

Shorelines derived from satellite imagery spanning April 1984 to February 2024 were extracted using data from Landsat 5, 7, and 8 satellites. The imagery collection was processed using CoastSat, an open-source Python toolkit (Vos et al., 2019). Additionally, annual composite satellite images were processed to identify the seaward edge of the terminal lobe of Armona ebb-tidal delta. Each composite collection was cloud- and shadow-masked, atmospherically corrected and harmonised to common RGB and NIR bands. The composite images were then normalised across all years to ensure spectral consistency. After, the land areas were masked using the Normalised Difference Water Index and a buffered water mask was used to exclude shoreline noise. Image classification was done applying k-means clustering (with two classes) to the normalised bands to separate shallow bedforms (represented by brighter pixels) from deeper waters. The terminal lobe of the ebb-tidal delta was then identified and smoothed to provide a consistent time series of delta edge positions. This enabled the tracking of annual changes in the ebb-tidal delta planform from 1985 to 2024.

Sediment budget estimation

Sediment budgets were calculated using satellite-derived area estimations of Culatra Island and the ebb-tidal delta. These areas were estimated based on delineated shorelines and delta edges, under the assumption of no morphological changes to the back barrier. Sediment volumes were calculated separately for: (1) the main island (i.e. the extent prior to 1984), (2) the new sand spits, and (3) the ebb-tidal delta. This was done by multiplying each morphological feature by an average depth, assumed to represent the active depth of the compartment: 10 m, 4 m and 2 m, respectively.

Results

Since 1993, there has been a long-term trend of sediment volume loss of approximately -2,900 m^3/yr on the main island (pre-1984 extent), accounting for a total of ~900,000 m^3 (Figure 2a). In contrast, the new sandspit (post-1984 extent) has gained approximately 3,000,000 m^3 of sediment since 1984, with two varying trends (Figure 2b). Before 2007, the sandspit accreted at an average rate of 110,000 m^3/yr, which declined to 32,000 m^3/yr between 2007 and 2024. At the same time, the terminal lobe of the ebb-tidal delta has exhibited a long-term retreating trend with two distinct phases that match the spit growth pattern (Figure 2c). Until 2007, the delta edge retreated at an annual rate of -3.7 m, followed by a reduced retreat rate of -0.75 m/yr. This equates to a total sediment loss of ~1,020,000 m³ from the ebb-tidal delta. Combined, the erosion of the main island (30%) and the ebb-tidal delta (34%) account for approximately 64% of the total growth of the new sandspit.

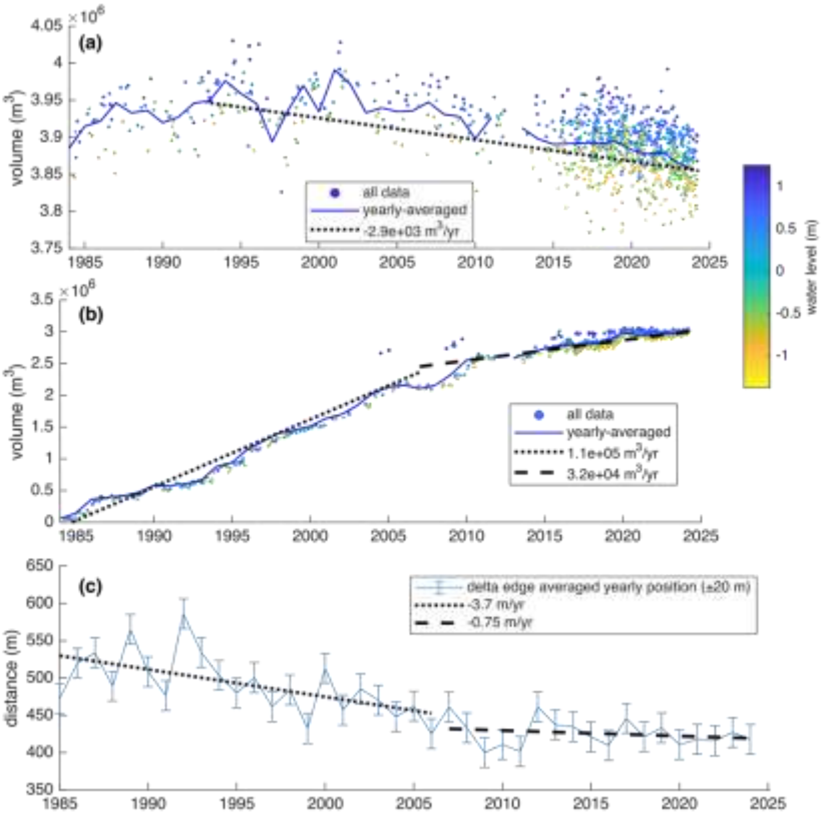

Figure 2. Sediment volumes for (a) the main Island (pre-1984 extent) and (b) the new sandspits. (c) Annual and spatial averaged terminal lobe position of the ebb-tidal delta.

Discussion and Conclusion

Culatra Island has elongated almost linearly during the period of analysis with similar rates to those documented in previous studies using vertical aerial photographs and orthophographs, covering the period 1956-2014 (Kombiadou et al., 2019). The sediment contributing to the elongation of the island has been assumed to originate predominantly from the ebb-tidal delta through shoal attachment (Andrade, 1990), as well as from updrift island erosion. This is partly supported by current findings indicating that 34% and 30% of the sediment for the new sand spits can be attributed to sediment loss from the ebb-tidal delta and the pre-1984 island extent, respectively. However, sediment loss from the delta and updrift island erosion, as identified in this study, could only account for 64% of the sediment volume accreted in the new sandspits. This suggests that a further sediment source contributing ~1,000,000 m³ (or ~26,000 m³/yr) is needed to account for the elongation of the island. Such a source is also necessary to explain the relatively low erosion rate of the former island, given that the net littoral drift along the study area is estimated to be ~100,000 m³/year (e.g., Pacheco et al., 2011), which is three times higher than the erosion rate of the pre-1984 Culatra Island sector (32,000 m³/year). While it has been demonstrated that the Faro-Olhão inlet has prevented sediment bypassing since its stabilisation in the 1950s (Pacheco et al., 2008, 2011), we hypothesise that this could be the most plausible source of the missing sediment to the new sandspit. This hypothesis could also help to explain the stability of the former island, which only displays clear signs of erosion within the vicinity of Faro-Olhão downdrift jetty (Kombiadou et al, 2019).

The new insights into Culatra Island's elongation and sediment volumes derived from satellite imagery demonstrate the potential of remote sensing techniques for monitoring morphological changes along the coast. Although the uncertainties of the satellite-derived sediment volumes remain to be estimated, a preliminary comparison with surveyed topo-bathymetric data shows that the order of magnitude appears to be correct. This emphasises the importance of satellite imagery for improving our understanding of, and ability to monitor, coastal changes. Both of these are essential for planning coastal adaptation measures.

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