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# Towards Assessing the Resilience of Complex Coastal Systems: Examples from Ria Formosa (South Portugal)

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**ABSTRACT**

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The present paper contributes to assessing the resilience of a complex barrier island environment, namely of the Ria Formosa multi-inlet system in southern Portugal. The long-term morphologic evolution of four study areas during the last 60 years (1947 to 2014) is analysed based on aerial photographs, including the environments of oceanic and backbarrier beaches, dunes and salt marshes. The results show that each study area responded to external drivers (inlet stabilisation works, storms, etc.) differently, evolving in distinct patterns during the study period. All four study areas appear resilient to external pressures and/or forcing conditions, since they are either transforming (Barreta and Culatra islands), or adapting (Cabanas island and Cacela peninsula) or remaining stable at a near-equilibrium state (Tavira island). Based on the analysis of the multi-decadal evolution of the sites, four resilient barrier states are identified, related to the *maturity* and *growth* of the barrier. In the next stages, the research will focus on the relation between medium to short-term changes, aiming at understanding the response and feedbacks of the environments to specific drivers of change and relating them to resilience indicators.

**ADDITIONAL INDEX WORDS:** *Barrier islands, long-term evolution, remote sensing.*

## INTRODUCTION

The Ria Formosa barrier island system (Figure 1) in southern Portugal is an extensively studied coastal system, however a dedicated analysis and assessment of its resilience is yet to be performed. Resilience is defined here as the capacity of a system to absorb disturbances or shocks, re-organize and adapt to change, while retaining its structure, identity and feedbacks (Folke, 2006). The assessment of the eco-geomorphological resilience of a barrier island system is a challenging task, not only due to its complexity, but also due to the presence of distinct environments that interact with each other at different spatio-temporal scales (Stallins, 2005). This resilience assessment is the main objective of the EVREST (Evolution and Resilience of Barrier Island Systems) project, namely to develop resilience conceptual schemes and indexes for Ria Formosa that can afterwards be used or adapted to any barrier system. The analysis covers medium to long-term eco-morphologic evolution (year to multi-decadal) for four study areas (Figure 1): 1) Barreta island, 2) Culatra island, 3) Tavira island and 4) Cacela peninsula and Cabanas island. For each area, the evolution of the barrier itself and of distinct environments (marsh and foredune) are analysed. The main aim of the present paper is to determine the long-term morphological evolution and trends of the four study areas and, based on those results, to discuss and gain insights on the resilience of the environments that constitute this barrier island system.

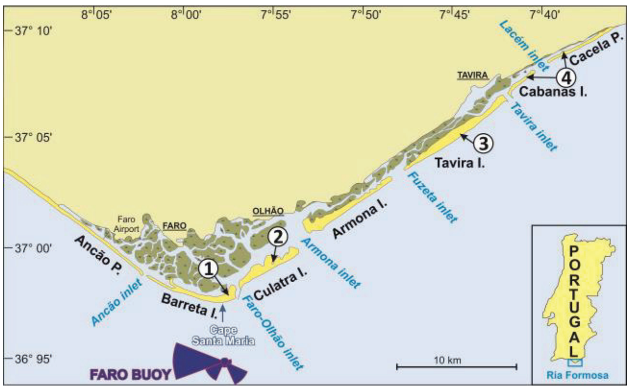


Figure 1. The Ria Formosa barrier island system; the four study areas are noted on the map.

## METHODS

The analysis is based on aerial photographic data that were collected and included in a comprehensive geodatabase. These raster datasets cover the period from ca. 1950 to present (1947, 1952, 1958, 1969, 1972, 1976, 1980, 1985, 1986, 1989, 1996,

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1999, 2000, 2001, 2002, 2005, 2008, 2009 and 2014). The most recent datasets (2002-14) are orthoimages. Aerial photographs were georeferenced using the orthophotography of 2002 (oldest available orthorectified map) as the basis for a backwards-in-time process. The average georeferencing residual RMSE ranges from 0.6±0.2 m for the most recent, high-resolution, flights, to 1.6±0.6 m for the oldest ones. The RMSE that could accumulate due to the backwards-in-time processing was also assessed, comparing each flight with the 2002 orthophotos. The results showed that the average accumulated error is low, between 0.7 and 1.1 m for high-resolution flights and reaches 2 m for low-resolution aerial photographs.

Different coast/shorelines were digitized in the ocean and lagoon side for all flights; seawards, the wet-dry line and the foredune foot were taken as proxies, while for the lagoon side, the backbarrier coastline (limit of upper-mash vegetation, or debris line; ca. MHWL) and the edge of the marsh (subtidal-intertidal vegetation boundary; ca. MWL) were digitised. Weighted Linear Regression (WLR) analysis was performed on the entire dataset, using the Digital Shoreline Analysis Tool (Thieler *et al.*, 2009). The uncertainty values, used for the WLR, were taken equal to the total shoreline position error (Morton, Miller and Moore, 2004), calculated as the square root of the sum of squares of the rectification error and the digitizing error. The former was defined as the total accumulated digitization RMSE for each island and the latter was related to the image cell size (Jabaloy-Sánchez *et al.*, 2014).

## RESULTS

The results presented refer to long-term morphological changes in the four study areas, based on WLR analysis, performed on the entire dataset. For clarity reasons, only the oldest and the most recent coastlines are presented, while WLR rates are shown in a common graph for ocean-side coastlines (lower panel) and for lagoon-side coastlines (upper panel). The WLR rates integrate all available information and, therefore, a direct, visual comparison of the WLR values with the presented coastlines is not feasible.

The morphological evolution of Barreta Island is shown in Figure 2. Strong progradation, of the order of 5 m/yr, is evidenced in most of the oceanfront and is attributed to the stabilization of the Faro-Olhão inlet and consequent sand retention from updrift (west). Near the Santa Maria Cape (southernmost point of Ria Formosa), these rates reach 7 m/yr. Localized erosion rates are present in the western area, under the influence of the westward migration of the Ancão inlet (Vila-Concejo *et al.*, 2006) and (more recently) at the eastern edge, due to local flow conditions near the inlet. In the inland border, the backbarrier presents strong stability, apart from the east and west extremities, the former due to frequent dredging to ensure navigability of the channel and the latter affected by the Ancão inlet migration/closure. The marsh is either stable, or growing with rates of 0.5 m/yr that can locally reach 1-5 m/yr.

The evolution of Culatra and the related WLR rates are given in Figure 3. Eroding trends exist in the ocean shore of the western part of the island, up to a distance of 3-3.5 km westwards (downdrift) of the Faro-Olhão inlet; from there on, the rates become positive with increasing values towards the Armona inlet (~10-20 m/yr). These trends are directly related to the artificial stabilization of the Faro-Olhão inlet that produced sediment starvation in the western part, decrease in the tidal prism of the Armona inlet and accretion of recurved spits in the eastern part (Ferreira, Matias and Pacheco, 2016). The results show that there is an apparent clockwise shift of around 5º in the orientation of the island during the study period (the coastline angle was around N 57º E in the 1950's and in the 2010's it reached N 62º E).

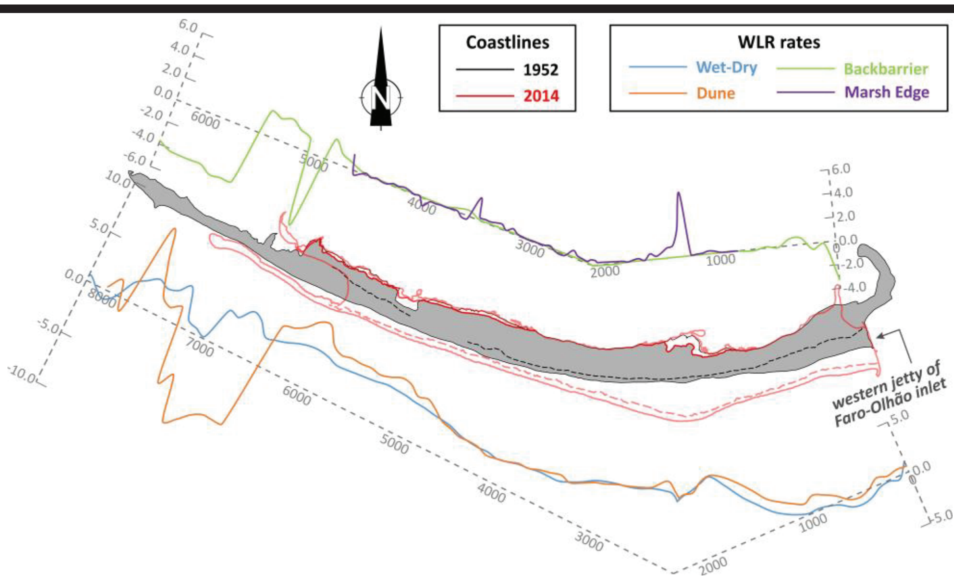


Figure 2. Results from the shoreline analysis in Barreta Island: Only the oldest (1952; black line) and the most recent (2014; red line) coastlines are presented in the plot, while dashed lines denote the corresponding dune lines. The wet-dry (blue line) and the dune (orange line) WLR rates (m/yr) are presented in the lower graph and the backbarrier (green) and marsh edge (purple) are shown at the top graph. Negative values denote erosion/shoreline retreat while positive ones denote accretion/shoreline advance.

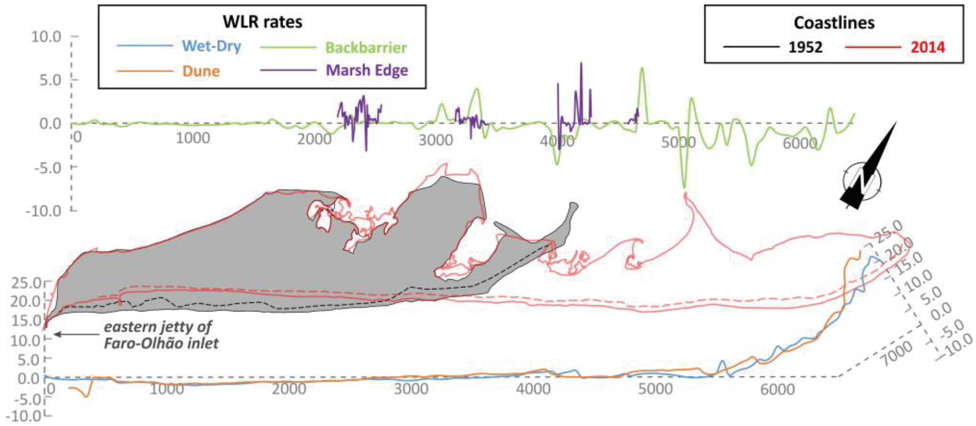


Figure 3. Results from the shoreline analysis in Culatra Island: The colour coding is the same as in Figure 2.

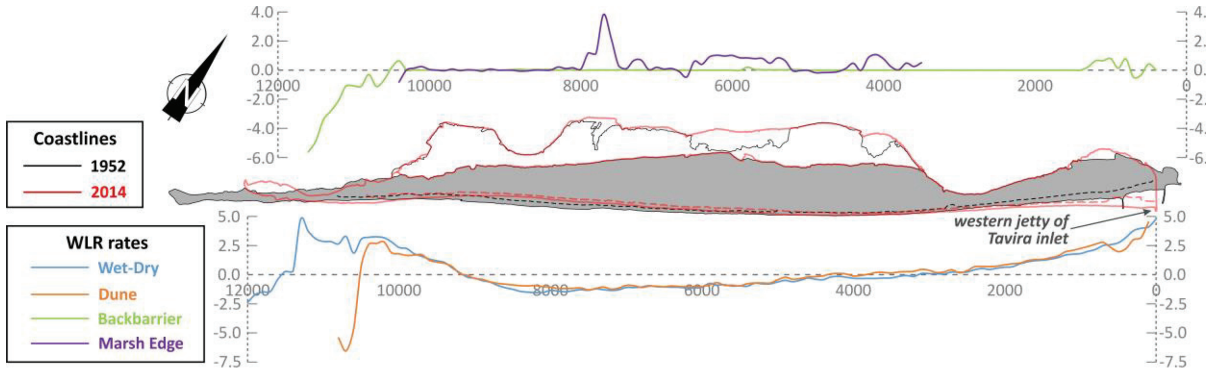


Figure 4. Results from the shoreline analysis in the Tavira Island: The colour coding is the same as in previous plots.

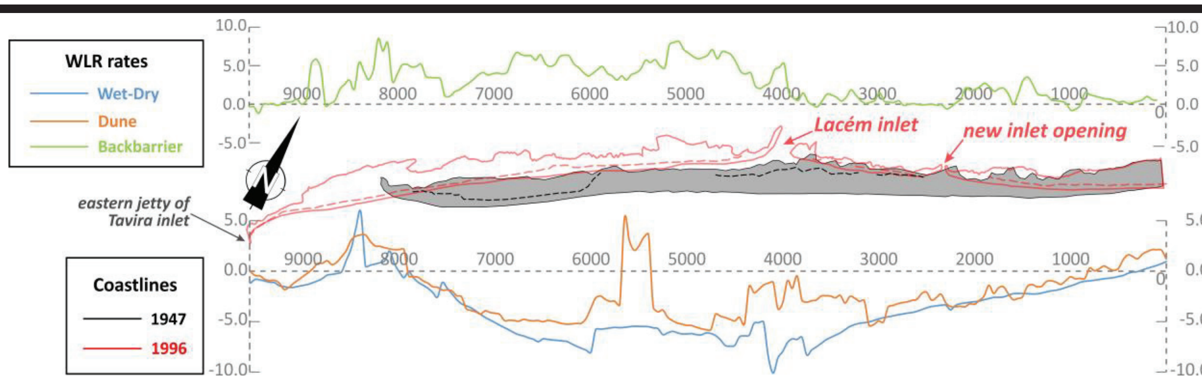


Figure 5. Results from the shoreline analysis in Cabanas-Cacela subsystem: The colour coding is the same as in previous plots, with the exception of marshes that do not develop in the area during the study period.

Regarding the evolution in the lagoon side, the backbarrier rates are low in the western, older part of the island (up to 3 km from the inlet), ranging from -1 to +1 m/yr. Eastwards, the values become increasingly variable, ranging from -7.4 to +6.4 m/yr, with an overall average retreat rate of -0.8 m/yr. This variability and dominant retreat tendency is most likely due to the elongation of the island itself, combined with the ebb dominance at the Armona inlet (Ferreira, Matias and Pacheco, 2016). Regarding marsh evolution in Culatra, the WLR rates show that the marsh of the west-most, oldest, embayment has been growing since the 1950's, with an average rate of +1.0 m/yr. Localised erosive tendencies (-0.6 to -3 m/yr) are most likely due to human pressures (i.e. navigation, shellfish gathering, etc.), since geometrical patterns appear in the marsh vegetation of these areas after marsh-loss. Similar conditions, with marsh development

rates around 0.5 to 1.3 m/yr and low, localised marsh-loss trends, are also observed in the remaining three embayments of the island.

The WLR rates of Tavira (Figure 4) show that the island presents remarkable stability in the lagoon side during the last 70 years, especially for the backbarrier line (non-zero values near the edges are due to inlet dynamics). The marsh area shows accreting trends, around +0.6 m/yr in the eastern-central part, while for the western part the values are near-zero. In the oceanfront, both proxies present the same behaviour, with retreat tendencies in the western-central part and progradation trends near the Tavira inlet that are related with the longshore sediment accumulation against the jetty. As in the case of Culatra, Tavira also shows a clockwise shift in main shoreline orientation during the study period, though significantly lower, of the order of 2º (the coastline angle changed from around N 54º E to N 56º E between 1952 and 2014).

The evolution of the Cabanas Island and Cacela Peninsula subsystem is shown in Figure 5 for the period 1947-1996. More recent flights were not used in the shoreline analysis, given that extensive engineering works took place in the area in 1997 (Matias *et al.*, 2008), involving beach and dune nourishment and artificial closing of a new inlet that breached the peninsula during the storm events of 1995-96 (see Figure 5 for location of the breach). Marshes are not included in the analysis, since breaching and overwash events in the area prevented their development. The results show an overall tendency of oceanfront coastline retreat that is more intense in the central part of the subsystem and diminishes near the margins, the eastern being the attachment of the Cacela Peninsula to mainland and the western (W. Cabanas) being artificially stabilised with jetties in 1977-1986 to cease the infilling of the Tavira inlet (Vila-Concejo *et al.*, 2002). The maximum erosion rates in the coastal zone are of the order of -5 to -10 m/yr, while the dune line presents lower rates and, in some cases prograding trends, especially near the centre. This is related to berm development along a former breached/inlet area being responsible for washover cessation, resulting in low foredune development with rapid vertical accretion (Matias *et al.*, 2008). At the same time, the backbarrier line is prograding inland at rates of 0.5 to 5 m/yr in Cacela and significantly higher ones (1 to 8.5 m/yr) in Cabanas. As for the oceanfront, the rates diminish at the western and eastern, stable, margins. Generally, the results show that the entire subsystem presents a tendency for landward migration throughout the study period.

To analyse the findings on a broader scale, the temporal evolution of total barrier and marsh areas are given in Figure 6 (a and b, respectively). Barreta shows an overall accreting behaviour, which, excluding the western inlet-impacted area (see dashed line in Figure 6a), shows a strong linear trend of $11\cdot10^3$ m$^2$/yr. The marshes in the barrier grow by about 700 m$^2$/yr until 2001 (Figure 6b), rate that drops to 270 m$^2$/yr from 2001 onwards. Culatra Island has been growing throughout the study period, but at two distinct rates (Figure 6a): $22\cdot10^3$ m$^2$/yr up to 2001 and $10^3$ m$^2$/yr after 2001. The marshes show similar evolution, increasing by $2\cdot10^3$ m$^2$/yr up to 1996 and by reduced rates of around 700 m$^2$/yr thereafter. Tavira has remained at a stable state for the greater part of the study period (since the 1970's), both in terms of sandy and marsh areas; the fluctuation in sandy surface is mainly due to changes in the Fuzeta inlet position (see dashed line in Figure 6a). Regarding Cabanas-Cacela (Figure 6a), the subsystem presents some variability in total barrier area, nevertheless the values only change slightly (±10%), while frequent breaching and overwash incidents do not allow marsh establishment in the area.

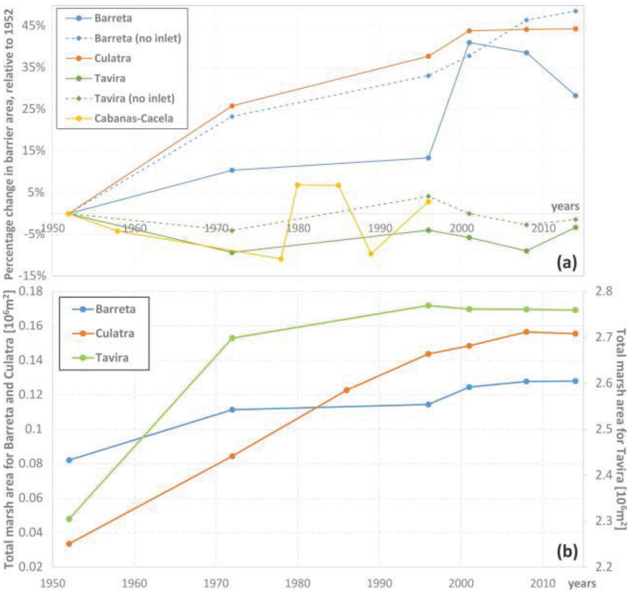


Figure 6. Evolution of: (a) the percentage of area change per study site and (b) total marsh area (in $10^6$ m$^2$), with respect to 1952. In (a) the total island areas excluding the inlet-adjacent zones are also presented for Barreta and Tavira (dashed line, denoted as 'no inlet') and in (b) the curve of Tavira refers to the right vertical axis.

## DISCUSSION

The results presented provide understanding of the long-term morphological evolution of the four study areas from 1947 to 2014. In Barreta these changes were generated by the construction of the Faro-Olhão jetties downdrift from the island that induced shore and dune progradation, while allowing for a stable backbarrier area and marsh growth and maturation (Figure 2). These jetties also impacted the island of Culatra (Figure 3), causing sediment starvation that resulted to erosion at the zone immediately downdrift from the jetties, shift in island position, and, at the same time, accretion in the form of recurved spits in the eastern part of the island due to attachment of the ebb shoals from the former inlet ebb delta (Ferreira, Matias and Pacheco, 2016). The reduction in barrier growth rates after 2001 (Figure 6a) is an indication that the island could be reaching some sort of morphodynamic stability. This growth pattern also allowed for the development of new marshes in the lagoon side of Culatra. These marshes are in backbarrier growth conditions, while the reduction of growth rates could signify that they are passing on to mature conditions and more complex marsh succession (Carrasco *et al.*, 2008). Changes in Tavira, both in terms of sandy and marsh areas (Figure 6), especially after 1972, are very small, indicating the stability and maturity of the island. Even though Cabanas and Cacela have undergone strong disruptive processes (overwash, breaching and inlet opening) during the study period (Matias *et al.*, 2008), the bulk amount of sediment remained as part of the subsystem, mainly transporting landwards (Figure 5).

Assuming the general definition of social-ecological resilience as the transformability and adaptive capacity of the system (Folke, 2006), the long-term evolution presented shows that all four study areas appear resilient, even though showing distinct responses and evolution patterns. Tavira is the example of a barrier island that appears to be fully developed and very stable throughout the last 40 years, both in the shorefront and in the backbarrier (Figure 4). On the other hand, Culatra and Barreta islands are in conditions of growth, the former in the longshore direction and the latter in the crosshore direction. Culatra is evolving, adjusting its shape to the coastal dynamics, both in the shorefront and in the backbarrier areas, while vigorously developing new marsh ecosystems (Figure 3). Barreta combines a stable backbarrier and marsh environment with a prograding shoreline and foredune (Figure 2). Finally, Cabanas and Cacela have been adapting to the hydrodynamic conditions with a landward rollover (Figure 5), while largely maintaining their initial size. Considering the presence of mature marshes (i.e. near-zero slope in recent marsh evolution) and stable backbarrier area as prerequisites for a barrier island to be characterised as *mature* and relating the evolution patterns of the study areas to their *maturity* and *growth*, the four barrier states of Table 1 are drawn.

Table 1. *Evolution phases of the study-sites.*

| | | Maturity stage | |
|---|---|---|---|
| | | Immature | Mature |
| Growth stage | Growing | *immature - growing (Culatra)* | *mature - growing (Barreta)* |
| | Not Growing | *immature-not growing (Cabanas-Cacela)* | *mature-not growing (Tavira)* |

## CONCLUSIONS

The results on the multidecadal (1947-2014) evolution of the four study areas show different evolution patterns, which were related to coastal processes identified previously in the area. Inlet stabilisation works (Faro-Olhão and Tavira), implemented during the study period, affected local sediment dynamics, causing sediment starvation in some of the islands and promoting accumulation in others. These human interventions, combined with forcing conditions and island morphology, caused the areas to evolve in distinct manners. Tavira appears stable, especially in the backshore area, with a small clockwise shift in shoreline orientation. Barreta has maintained a stable backshore, while prograding seawards. Culatra has been growing in the longshore direction, with reduced rates in the last decade and gradually rotating its orientation in the clockwise direction. Cabanas and Cacela show clear transgressive behaviour, however, largely retaining the total surface of the subsystem in the process. These results show that, even though the morphological response of each barrier is distinct, all of the sites appear resilient, since they are: a) transforming, like Culatra and Barreta, b) adapting, like Cabanas and Cacela, or c) maintaining stable at a near-equilibrium state, like Tavira. Based on these patterns, four resilient barrier island states are identified: *immature and growing*, *mature and growing*, *immature and not growing* and *mature and not growing*. The next steps on this research topic will be to analyse the medium to short-term morphological variability of the areas and of the distinct eco-geomorphologic environments, with relation to the hydrodynamic conditions (waves and sea levels). This will allow the assessment of the barrier islands' response to distinct drivers of change, of positive and negative feedbacks between environments under conditions of change and relating them to resilience indicators.

## ACKNOWLEDGMENTS

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