ASSESSING THE RESILIENCE OF THE RIA FORMOSA BARRIER ISLAND SYSTEM: PRELIMINARY FINDINGS

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Abstract

The aim of the present paper is to analyse the recent morphological evolution of the sandy barriers of Ria Formosa, a multi-inlet system located in South Portugal, to assess evolution regimes and related controlling factors and to identify resilience mechanisms in response to natural and artificial drivers of change. The data collected comprise aerial photographs and wave buoy and hindcast time-series, covering the period from the 1950s to 2014. The results show that the barriers have either been growing, or remaining stable. The growth patterns were either promoted by natural mechanisms, or triggered by stabilization works and supported by natural factors (e.g. longshore transport, shoal attachment). The presence of a broad marsh platform in the backbarrier was found to promote barrier stability, while the sustainance of transgressive barriers is advocated by frequent overwash, combined with low depths in the backbarrier lagoon and localised replenishment of sand. These long-term evolution regimes and their relation to artificial and natural factors show that the barriers of Ria Formosa have been resilient during the time-frame of the study, either absorbing disturbances (Armona and Tavira), or adapting to change while maintaining their functions (rest of the barriers).

Keywords: Geomorphology, remote sensing, multi-decadal analysis, ecological resilience

1. INTRODUCTION

Ria Formosa is a roughly triangularly-shaped multi-inlet barrier island system (Figure 1) in southern Portugal, with a total extension of around 55 km, and expanding at a maximum distance of 6 km from mainland (at Cape Santa Maria). At present, it consists of two peninsulas and five islands, developed along two flanks, while the connection between the tidal lagoon and the ocean is performed through six tidal inlets. The more energetic western flank is impacted by frequent (71% occurrence) waves originating from W-SW and the longer, eastern, flank is exposed to E-SE waves (23% occurrence) [Costa *et al.*, 2001]. The tidal regime is semi-diurnal, with average amplitudes of 1.3 and 2.8 m for neap and spring tides, respectively, while maximum spring tides can reach 3.5 m. The wave climate is moderate, with average annual offshore significant wave heights of 1.0 m and peak periods of 8.2 s [Costa *et al.*, 2001]. The area, declared a Natural Park, is of high ecological and socio-economic significance [Guimarães *et al.*, 2012]; it is the most important wetland in South Portugal, supporting a variety of diverse habitats and species (e.g. dunes, marshes, seagrasses, etc.), as well as various anthropogenic activities (e.g. fisheries, tourism, bivalve gathering, etc.). Still, the crucial importance of the sandy barriers themselves to the existence and persistence of the entire system and the supported habitats is often overlooked.

The aim of the present paper is to investigate the recent (past 60 years) long-term morphological evolution of the barriers of Ria Formosa in the presence of human interventions and natural processes

(i.e., storms), to identify the main drivers of change for each barrier and, based on those results, to gain insights on the major mechanisms promoting resilience.

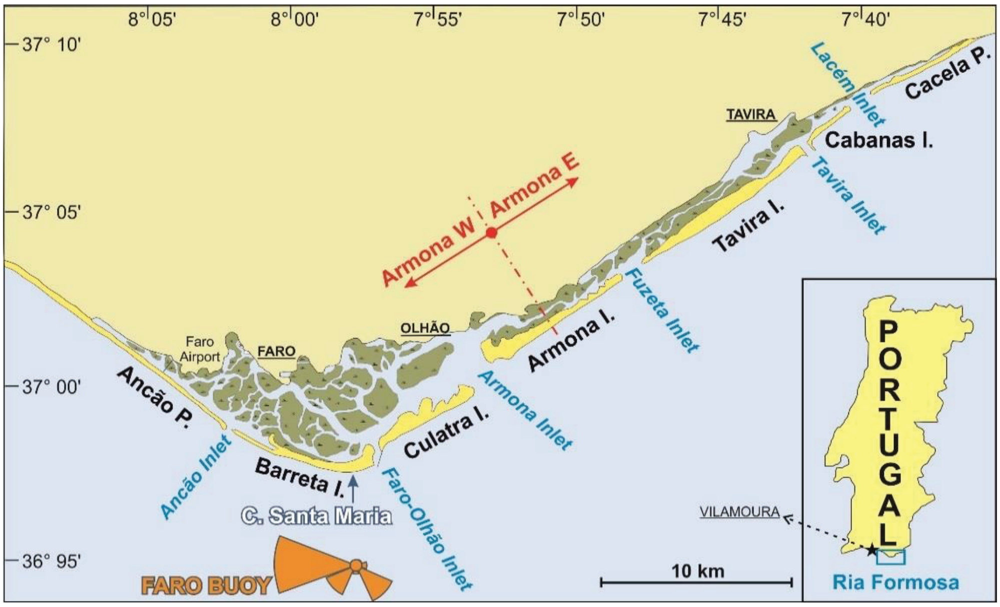

Figure 1: The Ria Formosa barrier island system; the location of the Faro buoy and the Santa Maria Cape are noted on the map, as well as the names of islands, peninsulas, inlets and the division of Armona to W and E.

2. DATA AND METHODS

The morphological evolution analysis was based on aerial photographic data that cover the period from 1947 to 2014. Aerial photographs were georeferenced using the orthophotography of 2002 (oldest available orthorectified photos) as the basis for a backwards-in-time process. The available flights, related characteristics of the rasters and the RMSE related with the georeferencing process are given in Table 1; the average Residual (Res.) RMSE refers to the error remaining after rectification, while the average Accumulated (Acc.) RMSE refers to the error that can cumulate due to the backwards-in-time georeferencing (assessed comparing each flight with the 2002 orthophotos). The average Res. 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 Acc. RMSE is also low, between 0.6 and 1.1 m for high-resolution flights and reaches 2 m for low-resolution aerial photographs.

To assess the barrier evolution, the wet-dry line was digitised, as a shoreline proxy in the ocean side and the limit of upper-mash vegetation, or the debris line (MHWL) was digitised, as a coastline proxy for the lagoon side. It is noted that the wet-dry line includes a high variability due to the tidal level and swash runup at the time of the flight. 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 were taken equal to the total shoreline position error [Morton *et al.*, 2004], calculated from the rectification and digitizing errors. The former was defined as the total Acc. RMSE for each island and the latter was related to the image cell size [Jabaloy-Sánchez *et al.*, 2014].

In terms of forcing, significant wave heights from the Faro buoy were used; the insitu data cover the period from 1993 to 2014 and was complemented with hindcasting results (SIMAR; Spanish State Port Authority) for the period 1958-1992. The storm thresholds considered are 2.5 m for significant wave height and 6 hours for storm duration [after Oliveira *et al.*, 2018]. Only waves incident to the coast were taken into account for each flank (e.g. for E flank only waves from the SE sector: E to S).

Table 1: List of available rasters, including year, resolution, bands (1: BW, 3: RGB, 4: RGB+NIR), average Residual (Res.) RMSE and Accumulated (Acc.) RMSE. Datasets prior to 2001 are orthoimages.

Year	Resolution	Bands	Res. RMSE (m)	Acc. RMSE (m)	Year	Resolution	Bands	Res. RMSE (m)	Acc. RMSE (m)
2014	0.7m	4	-	-	**1989**	1:8000	3	1.0 ± 1.0	1.4
2009	0.5m	3	-	-	**1986**	1:8000	3	0.7 ± 0.4	1.1
2008	0.7m	4	-	-	**1985**	1:15000	1	1.2 ± 1.6	1.3
2005	3.5m	3	-	-	**1980**	variable	1	1.0 ± 1.9	1.6
2002	3.5m	3	-	-	**1976**	1:30000	1	1.1 ± 1.6	1.8
2001	1:8000	3	0.6 ± 0.2	0.6	**1972**	1:6000	1	0.8 ± 0.5	1.1
2000	1:8000	3	0.7 ± 0.6	0.8	**1969**	1:25000	1	1.1 ± 0.6	1.5
1999	1:8000	3	0.6 ± 0.2	0.8	**1958**	1:26000	1	1.1 ± 0.7	2.1
1996	1:8000	3	0.8 ± 1.0	1.0	**1952**	1:20000	1	1.1 ± 0.6	1.7
1989	1:10000	1	0.7 ± 0.2	1.2	**1947**	unknown	1	1.6 ± 0.6	2.0

3. RESULTS AND DISCUSSION

3.1 Linear regression analysis

The results of the long-term morphological analysis of the barriers are given in Figures 2 and 3 for the western (Ancão Peninsula and Barreta and Culatra Islands) and for the eastern (Armona, Tavira and Cabanas Islands and Cacela Peninsula) part of Ria Formosa, respectively. To show the main evolution patterns and to facilitate interpretation of WLR rates, indicative digitised shorelines (1950s, 1980s and 2014) are also presented. For Cabanas-Cacela 1996 is the last flight examined. Given that natural inlets are highly energetic environments, with temporal scales of change much smaller than the frame of study, the WLR rates presented and discussed focus mainly on the areas of the barrier not the directly affected by inlets.

The evolution of the Ancão Peninsula is dominated by longshore sediment transport and the eastward migration of the Ancão Inlet [Vila-Concejo *et al.*, 2002]. As seen in Figure 2a, the backbarrier is generaly stable, with low rates of -0.2 to +0.4 m/yr, while, in the oceanfront, retreating shoreline tendencies prevail in the western part and accretive in the eastern, ranging within ±0.8 m/yr. In the inlet-affected eastern part of the barrier the variability increases in both margins. In Barreta Island (Figure 2b), the beach is dominated by strong progradation, with rates that reach 6 m/yr in the Santa Maria Cape and range from +2.4 to +3.5 m/yr in the rest of the coast of the western flank. The southward expansion of the island (maximum shoreline progression of 350 m between 1952 and 2014 at the Cape) is due to the stabilisation of the Faro-Olhão (hereafter F-O) Inlet that enabled the entrapment and accumulation of longshore sediment drift. In the vicinity of the F-O Inlet, erosive tendencies that reach -1.0 m/yr are observed, possibly due to local flow conditions near the western

jetty. In the leeside, the coast is very stable, with near-zero rates, mainly due to the presence of a broad, mature marsh. The evolution of Culatra Island (Figure 2c) is dominated by the rapid eastward elongation of the island, also initiated by the stabilisation of the F-O Inlet. The stabilisation caused sediment starvation to the western shore, with recession rates of -0.5 to -2.0 m/yr, and a decrease in the tidal prism of the downdrift Armona Inlet [Pacheco *et al.*, 2010] that resulted to the attachment of the ebb delta shoals to Culatra and accretion of the eastern part of the island, with rates that reach 22 m/y. The island tip progressed eastwards by an average of 3.2 km between 1952 and 2014. The backbarrier area of the island is relatively stable, with low rates of ±0.5 m/yr in the western, oldest part and with slighly higher variability and erosive tendencies of, on average, -0.6 m/yr in the eastern, recently formed, part.

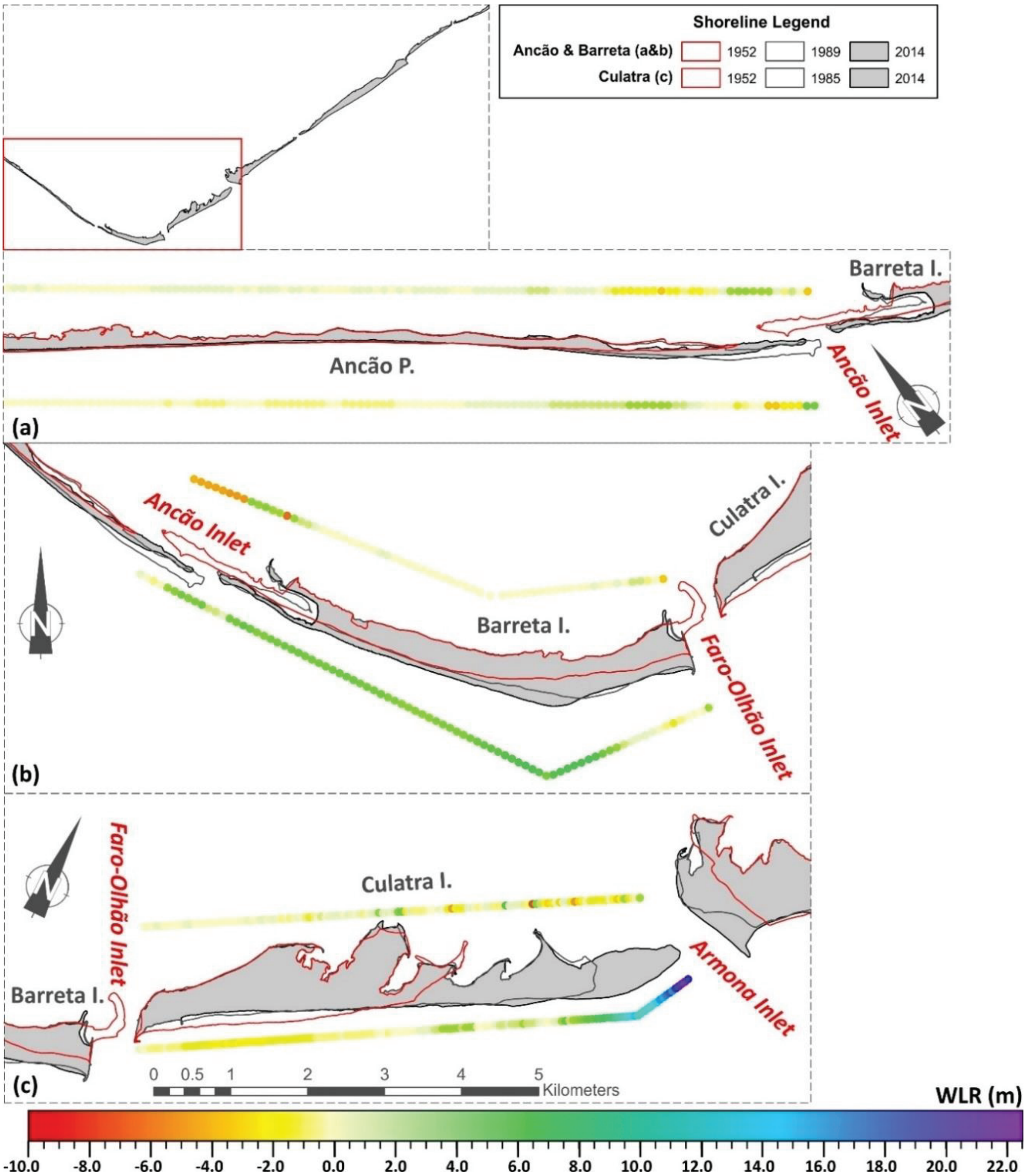

Figure 2: WLR values (in m/yr) for Ancão Peninsula (a) and Barreta (b) and Culatra (c) Islands, presented as coloured dots along the ocean and lagoon-side baselines (erosive rates: red-yellow; accretive rates: green-blue-purple, with reference to the horizontal colour-bar); indicative shorelines are presented and the location of the area is noted on the (top-left) map.

Armona Island (Figure 3a), also impacted by the reduction of the tidal prism in the updrift Armona Inlet, grows towards the NW near the inlet, with average shoreline progradation of 470 m during the study period, significantly lower than the one of Culatra. The related rates in the area are of the order of +5.5 to +15.5 m/yr. These accretive tendencies extend along the ocean side until the middle of the island, with decreasing rates towards the east (average of +0.6 m/yr) and turn erosive near the Fuzeta Inlet, ranging from -0.2 to -1.6 m/yr. The island has an extensive backbarrier and the lagoon-side coastline is stable, apart from the areas near the inlets, where rates can reach -6.8 and +9.6 m/yr. Tavira Island also possesses a mature and extensive marsh in the backbarrier and, thus, the rates in the related coastline are near-zero. In the ocean side, the shoreline is accreting near the Tavira Inlet (up to 3 km from the jetty, updrift), on average by 1.5 m/yr and by a maximum of +4.8 m/yr, and retreating in the central part, with an average rate of -0.8 m/yr. For Cabanas Island and Cacela Peninsula, hereafter referred to as C-C for brevity, the analysis extends only up to 1996, due to extensive nourishment in the area, implemented in 1997 (around $48 \cdot 10^4$ m^3) [Vila-Concejo *et al.*, 2002]. Thus, extending the analysis beyond this date would make it impossible to distinguish natural from artificial evolution. As shown in Figure 3c, the entire subsystem presents strong regressive behaviour. Maximum erosion trends are identified in the central part (2.5 to 6.5 km downdrift from the Tavira jetty) and range from -5 to -10 m/yr, with an average of -6.4 m/yr. Coastal retreat decreases towards the SW and NE parts of C-C, due to frequent small scale nourishment with dredged material from the channel (unrecorded) near the Tavira jetty, for the former, and the attachment to the mainland, for the latter. The backbarrier is also migrating landwards by an average of 3.3/yr and local maximum rates of 8.5 m/yr. The low depths of the backbarrier bay have enabled the transgression of C-C, through frequent overwashes [Matias *et al.*, 2008] that move sediment towards the mainland, thus allowing the barriers to shift their position landwards under storm waves.

3.2 Barrier morphological evolution trends

To analyse the evolution of the barriers in relation with the wave activity and human interventions, the total area of the barriers was calculated and is presented in Figure 4 for each flank, as change relative to the first available recording (1952), along with the average annual significant storm wave height and total annual storm duration. Significant interventions in the area are also noted in the timeline, along with breaching events in each flank.

In the west flank (Figure 4a&b), it can be noted that the evolution of Ancão and Barreta is highly interlinked, with the growth of one barrier to be largely followed by a reduction of the other. Ancão presents accretion in the period of 1952 to 1972, related with the eastward migration of the Inlet. In the same period, Barreta is growing southwards due to the stabilization of the downdrift F-O Inlet. The storms of 1973 caused the breaching of a second inlet in the peninsula [Vila-Concejo *et al.*, 2002], initiating losses for Ancão and corresponding gains for Barreta. From 1976, the inlet started an eastward migration cycle, reaching its eastmost position in 1996, which is reflected in the growth of Ancão and the reduction of Barreta barrier areas following 1985. The reduction in Ancão between 1972 and 1985 is attributed to the construction of the Vilamoura jetties, around 10 km west (updrift; location shown in embedded map of Figure 1) from the Peninsula, that reduced the longshore drift reaching Ancão [Ferreira *et al.*, 2006]. In June 1997, extensive coastal management work was performed in Ria Formosa, including the relocation of Ancão Inlet [Vila-Concejo *et al.*, 2002]. This is reflected in the evolution of Ancão and Barreta, with significant drop to the former and related increase to the latter that lasted up to 2002, where the inlet reached its westernmost point. Subsequently, a new eastward migration cycle started, coincident with beach nourishment projects in Ancão ($2.65 \cdot 10^6$ m^3 distributed in Ancão, Armona, Tavira and Cabanas) [Dias *et al.*, 2003] and in the updrift coastal zone (1998, 2004 & 2010) [Oliveira *et al.*, 2008] that increased sediment availability in the area and halted coastal retreat in Ancão. From 2002 onwards, Ancão and Barreta showed only small-scale changes (within ±5%). Taking into account that longshore sediment transport is directed eastwards and assuming that the sediment bypassing the F-O jetties is low, the summation of the area

of the two barriers (dashed blue line in Figure 4a) can reveal the direct impacts of the F-O stabilisation to the sediment balance of the western flank. The curve shows that the accumulation of sand initiated by the F-O jetties was intense up to 1972, reaching 18% in 20 years. The growth was slower up to the early 2000s, with a further increase of around 8% in 30 years, which appears to have stabilised; at present, the width of Barreta has reached the width of the jetty (grey-filled curve in Figure 2b) and accumulation is occurring as submerged sand banks in front of the island [Pacheco *et al.*, 2008].

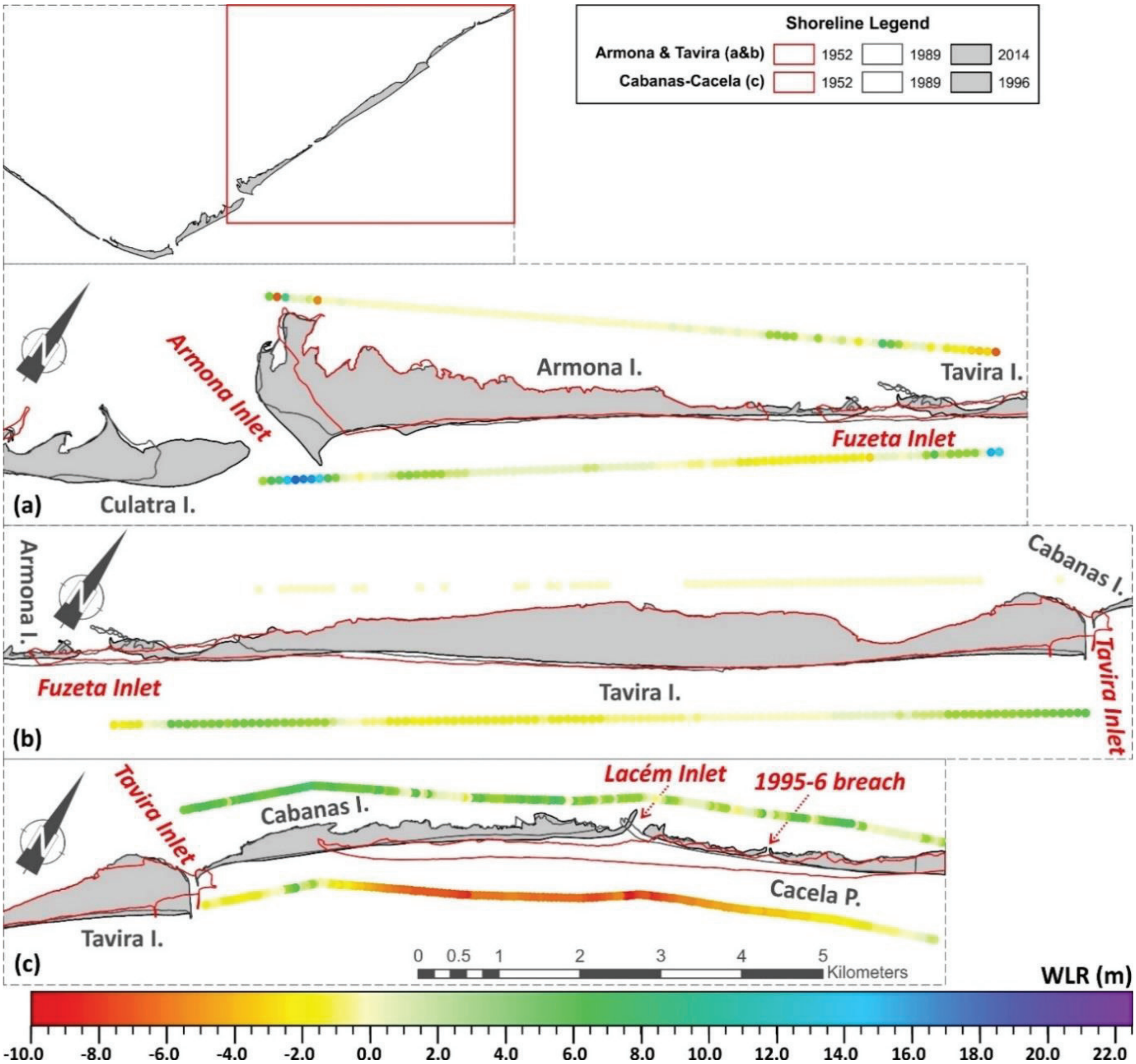

Figure 3: WLR values (in m/yr) for Armona (a) and Tavira (b) Islands and Cabanas Island-Cacela Peninsula (c), presented as coloured dots along the ocean and lagoon-side baselines (erosive rates: red-yellow; accretive rates: green-blue-purple, with reference to the horizontal colour-bar); indicative shorelines are presented and the location of the area is noted on the (top-left) map.

In the eastern flank, Culatra and Armona present a growing tendency almost throughout the study period. This growth is also attributed to the stabilisation of F-O that, as mentioned previously, induced the reduction of the tidal prism of the in-between Armona Inlet. The growth of Armona is also affected by the eastward migration of the Fuzeta Inlet, migration that also impacts the downdrift barrier of Tavira. To elucidate the evolution of the barriers and the 'net' contribution of the stabilisation works (F-O and Tavira jetties), Armona was split in two parts, W and E (see Figure 1 for location), which were added to each neighbouring barrier, assimilating, in this manner, the short-term, strong

morphological changes due to the Fuzeta Inlet movement. Thus, the joined barrier evolution of Culatra and west Armona (Culatra+Armona W in Figure 4c) and of east Armona and Tavira (Armona E+Tavira in Figure 4c) can be studied; given that the margins of these two groups correspond to stabilised inlets (F-O to the W and Tavira to the E), the ocean-side longshore gains and losses of the total area can be omitted. As shown by the evolution of Culatra and Armona W, the area is growing continuously throughout the study period, with a linear trend of $3.1 \cdot 10^4$ m^2/yr (R^2=0.97), reaching an increase of 40% in 2014, compared to 1952. Small-scale shifts to the relative change of the accumulated sand area are attributed to storm events (e.g. trend reduction between 1980-85, due to the intense wave activity of 1983). The evolution of Tavira shows reduction in total area, however, after the addition of Armona E the curve shows low variability, within ±5% (orange solid vs. dashed lines in Figure 4c); it, thus, becomes evident that the reducing trend in the area of Tavira is due to the migration of Fuzeta and not to storm impacts. The extension of the Tavira jetties in 1985 seems to invoke sediment accumulation that lasts up to 1997, after which, slightly decreasing trends are observed, most likely related to the highly energetic storms and to long-lasting events (Figure 4d). The beach nourishment of 1999-2000 in Tavira and Armona [Dias *et al.*, 2003] caused limited changes in the barrier area evolution. The C-C barriers present relative stability in total area, with the values to fluctuate between -10 and +7%, mainly due to storms and overwash events. The average roll-over of the system between 1947 and 1996 is of the order of 150 to 200 m in the west-central part and reduces to 80 m in the eastern part (east from the 1995-6 breach, see Figure 3).

3.3 Evolution regimes and resilience mechanisms

The main long-term barrier evolution trends for the period of 1952-1996 for C-C and 1952-2014 for the other barriers, identified in Ria Formosa, are summed-up in Figure 5 and the related major evolution regimes and corresponding drivers of change (artificial triggers and natural mechanisms that sustain these regimes) are summarised in Table 2. Human pressures such as intense occupation (e.g. Ancão and Culatra) and frequent dredging of backbarrier channels (e.g. Ancão and Tavira) to ensure navigability are not considered in the analysis, since they generate changes at shorter spatial-temporal scales and can be omitted for the ones considered in the study.

Apart from the presence of the Vilamoura jetties, inlet relocations and beach-dune nourishments that are the main artificial factors in the area, the evolution of the Ancão Peninsula is largely dominated by longshore sediment transport, promoting its elongation and the eastward migration of the Ancão Inlet. The stabilisation of F-O Inlet played a decisive role to the evolution of Barreta, Culatra and Armona W, generally promoting growth in all cases (apart from localised erosion in Culatra directly downdrift from the jetty). For Barreta, it caused strong southward accretion by trapping sediments from longshore drift and by changing local circulation patterns around the western jetty. For Culatra and Armona W, the mechanism boosting this growth (and the narrowing of the in-between inlet) was the increase of the tidal flow through F-O and the corresponding loss of hydraulic efficiency in Armona after the stabilisation. Excluding the changes due to the eastward migration of Fuzeta, Armona E and Tavira W are relatively stable, supported by broad backbarrier zones. The stabilisation of the Tavira Inlet induced accumulation immediately updrift (east Tavira) and lack of sediment to the downdrift Cabanas Island, contributing to the generic erosive trend at C-C. Losses in W Cabanas are replenished using dredged matter (unrecorded), sustaining a ‘forced’ stability of the area. C-C are at a transgressive state, fed by frequent overwash and the shallow depths of the backbarrier lagoon, while largely retaining the total barrier area.

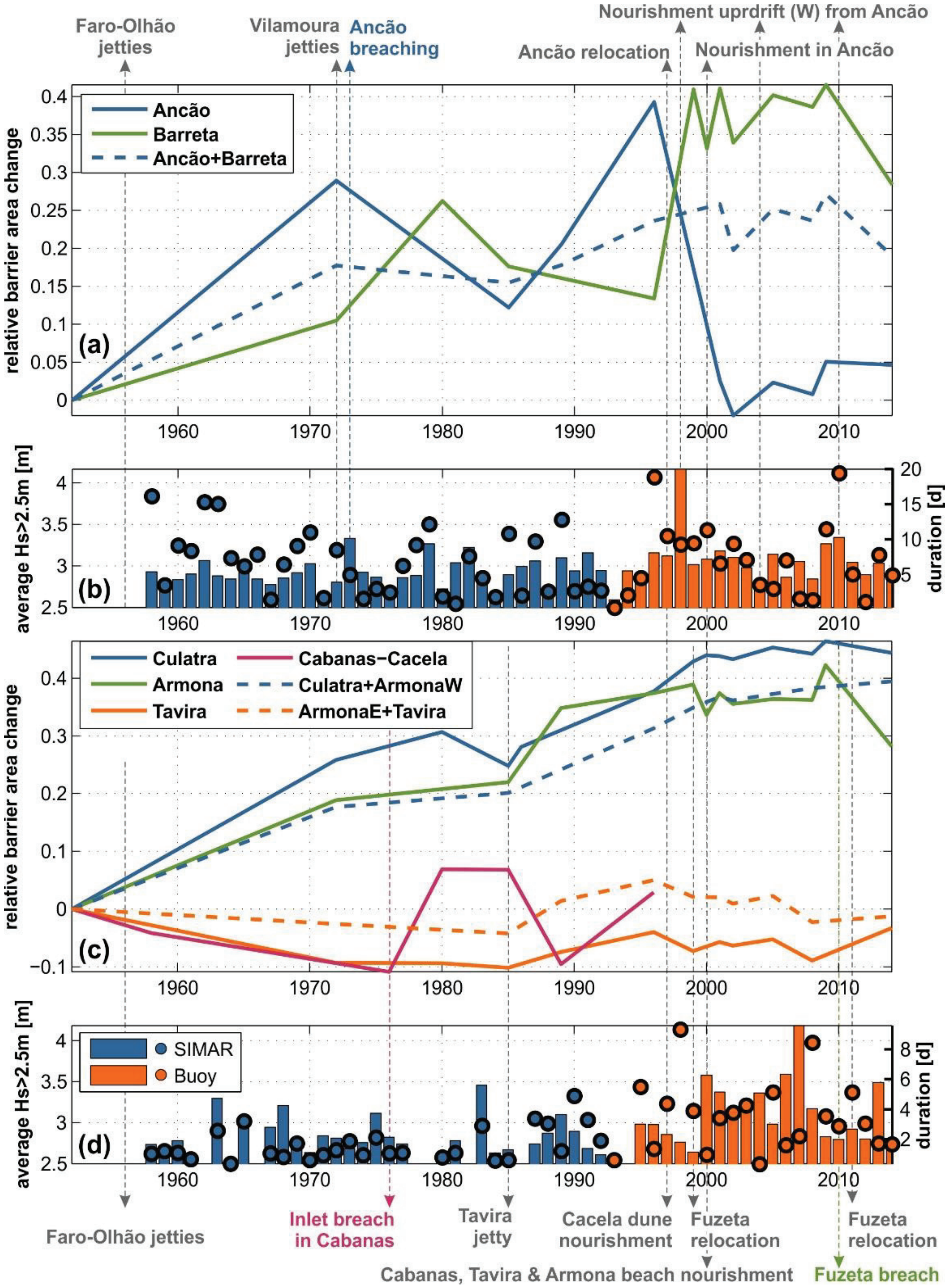

Figure 4: Evolution of total barrier area, relative to 1952, and average storm significant wave height for the western (a, b) and eastern flank (c, d). Wave data include average significant storm wave heights (bars, with reference to the left axis) and total annual storm duration (scatter-points, with reference to the right axis) at the location of the Faro buoy (Figure 1); data after 1993 are buoy records and older ones are SIMAR hindcasting data (Spanish State Port Authority). Human interventions (grey and black arrows: W from the area) and Inlet breaching events (arrows coloured as the related island) are noted.

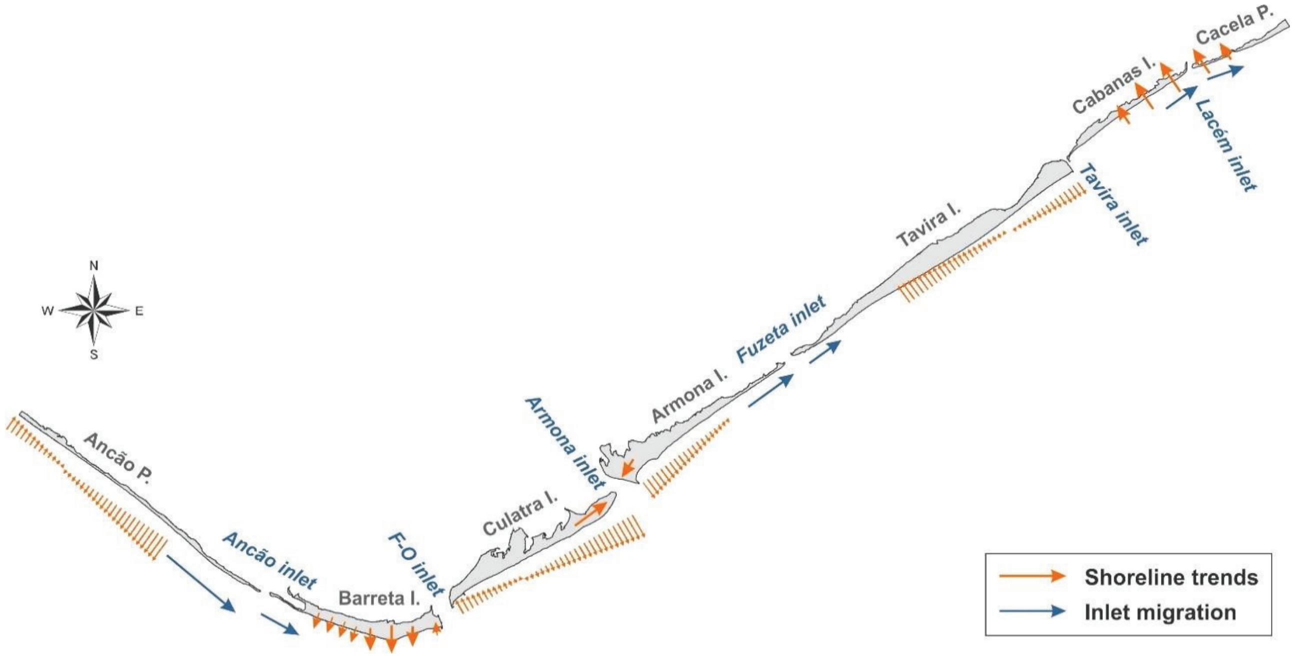

Figure 5: Schematic representation of the multi-decadal morphological response of the barriers of Ria Formosa. The major trends are noted as arrows (orange for shoreline and blue for Inlets) on the 2014 map.

The evolution regimes identified (Table 2) include: a) natural growth, limited by artificial factors (Ancão), b) artificially triggered growth, promoted by natural factors (Barreta, Culatra and Armona W), c) stability, promoted by natural (Armona E) and artificial factors (Tavira) and d) transgression triggered by artificial factors and supported by natural and artificial factors (C-C). Therefore, accepting the definition of ecological resilience 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], it can be deduced that the barriers of Ria Formosa appear resilient to natural (i.e., storms) and human disturbances. The barriers have either absorbed disturbances, remaining practically unchanged (Armona and Tavira), or adapted to the changing conditions while maintaining their main functions (rest of the barriers).

Table 2: Morphological evolution of barriers, related main artificial and natural drivers of change, triggering and/or supporting evolution, and resilience mechanisms (NR: Nourishment; LST: Longshore Sediment Transport; SBL: Shallow Backbarrier Lagoon).

Barrier		Evolution Regime		Limiting/Promoting Factors		Resilience Mechanism
		Growth	Position	Artificial	Natural	
Ancão		growing (SE)	stable	Vilamoura jetties, NR	LST	adaptation
Barreta		growing (S)	stable	F-O jetties	LST	adaptation
Culatra		growing (NE)	stable	F-O jetties	Armona ebb shoals	adaptation
Armona	**W**	growing (SW)	stable	F-O jetties	Armona ebb shoals	adaptation
	E	stable	stable	-	broad backbarrier	absorption
Tavira		stable	stable	Tavira jetties	broad backbarrier	absorption
C-C		stable	retreating	Tavira jetties, NR	SBL, overwashes	adaptation

4. CONCLUSIONS

Raster datasets from the last 60 years (1947-2014) were used to define ocean and lagoon-side coastlines and to analyse the multi-decadal morphodynamic changes of the Ria Formosa barriers. With the exception of Cabanas-Cacela, the analysis showed overall low rates in the backbarrier coasts. In the ocean side, the shoreline in the Ancão Peninsula presents erosive tendencies in the west

part that turn accretive towards the east (-0.8 to +0.8 m/yr). In Barreta, there is a generalised tendency for shoreline progradation that peaks in the Santa Maria Cape (+6 m/yr) and extends to the rest of the west flank (+2.4 to +3.5 m/yr), while localised erosion is identified near the Faro-Olhão jetty. In Culatra, the shore downdrift from the jetty (up to 3.5 km from it) is receding (-0.5 to -2 m/yr), while strong accretion rates prevail in the rest of the island (maximum: +22 m/yr). The shoreline in Armona is accreting in the west part, with highest rates near the inlet (+5.5 to +15.5 m/yr), and showing limited erosive tendencies in the east part (-0.2 to -1.6 m/yr). The shore in east Tavira, and up to 3 km west from the jetty, is prograding (on average by +1.5 m/yr) and turns retreating in the central-western part (on average by -0.8 m/yr). In Cabanas-Cacela, both barriers are migrating landwards, with peak rates in the central part (ocean-side: -5 to -10 m/yr; lagoon-side: -3.3 to -8.5 m/yr).

Regarding existing morphological evolution regimes, the related promoting factors and the resilience of the barriers of Ria Formosa, the investigation showed:

1. The existence of two main barrier evolution patterns in the area: growth and stability.
2. The decisive contribution of jetty construction to the recent evolution of the majority of the barriers; barrier growth has been largely triggered by such interventions and, consequently, fuelled by natural processes (e.g. longshore sediment transport). For example, the stabilisation of the Faro-Olhão Inlet resulted to an increase in total barrier area of the west flank by 25% and of the affected barriers of the east flank by 40% (corresponding to an overall increase of the entire east flank by 8%), between 1952 and 2014.
3. The long-term resilience of the barriers to artificial (stabilisation works) and natural (storms) stressors is demonstrated through two main mechanisms: adapting to change (either growing, or transgressing landwards), or absorbing shocks while remaining stable in terms of position and area (observed in barriers with broad salt marsh platforms in the backbarrier).

The assessment of resilience indicators and the evaluation of future scenarios for barrier island evolution will be the next steps of the research.

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