Cuadernos de Investigación Geográfica *Geographical Research Letters*	2022	Nº 48	pp. 293-307	EISSN 1697-9540

http://doi.org/10.18172/cig.5220

HISTORICAL MORPHOLOGICAL CHANGES (1956-2017) AND FUTURE TRENDS AT THE MOUTH OF THE EBRO RIVER DELTA (NE SPAIN)

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ABSTRACT. The present work focuses on the recent morphological changes recorded in the Ebro River delta, by using aerial photographs in the last six decades and by analyzing changes in the main constitutive features through geomorphological maps. Geomorphological maps of the years 1956 and 2017 are here presented. The results obtained give very valuable clues about the recent trends of the river delta mouth, which can be used to predict future coastal changes to be expected in the following decades. In this sense, by analysing changes in the surface by means of the geomorphological maps together with a shoreline analysis, a differential behavior has been described at both sides of the river mouth: the left side, El Garxal wetland, shows an accretionary trend with rates reaching +40 m/year, while the right side, San Antonio Island, shows erosive trends of more than -20 m/year. This last side also presents a surface reduction of more than 50 ha in the last 60 years. These results suggest that, approximately by the year 2050, the emerged San Antonio Island may disappear if shoreline retreat trends are maintained, making El Garxal exposed to easterly storms, the main erosive dynamic processes in this zone and, therefore changing the entire configuration of the Ebro River delta mouth in the upcoming years. Despite possible solutions have been described in recent works, they may not contribute to a total recovery of the most natural part of the Ebro Delta. Urgent management plans are required to attempting to slow or reverse these trends, otherwise one of the most valuable ecosystems of the delta could disappear.

Cambios morfológicos históricos (1956-2017) y tendencias de futuro en la desembocadura del delta del río Ebro (NE de España)

RESUMEN. El presente trabajo analiza los cambios morfológicos registrados recientemente en el delta del río Ebro, utilizando fotografías aéreas de las últimas seis décadas y examinando los cambios principales a través de mapas geomorfológicos. Se presentan mapas geomorfológicos de los años 1956 y 2017. Los resultados obtenidos dan pistas muy valiosas sobre las tendencias recientes de la desembocadura del río, que pueden utilizarse para predecir los futuros cambios costeros que se esperan en las próximas décadas. En este sentido, mediante el análisis de los cambios en los mapas geomorfológicos junto con un análisis de la línea de costa, se ha descrito un comportamiento diferencial a ambos lados de la desembocadura: el lado izquierdo, el humedal de El Garxal, muestra una tendencia a la acreción con tasas que alcanzan +40 m/año, mientras que el lado derecho, Isla San Antonio, muestra tendencias erosivas de más de -20 m/año. Este último sector también presenta una reducción de superficie de más de 50 ha en los últimos 60 años. Estos resultados sugieren que, aproximadamente para el año 2050, la isla San Antonio actualmente emergida podría desaparecer si se mantienen las tendencias de retroceso de la línea de costa, dejando a El Garxal expuesto a las tormentas del este, los principales procesos dinámicos erosivos en esta zona. Se cambiaría, de esta forma, toda la configuración de la desembocadura del delta del río Ebro en los próximos años. A pesar de que se han descrito posibles soluciones en trabajos recientes, es posible que no contribuyan a una recuperación total de la parte más natural del Delta del Ebro. Se requieren planes de manejo urgentes para intentar frenar o revertir estas tendencias, de lo contrario uno de los ecosistemas más valiosos del delta podría desaparecer.

Key words: Ebro River delta, Coastal retreat, Cartography, Geomorphology, Coastal management.

Palabras clave: Delta del río Ebro, Retroceso de costa, Cartografía, Geomorfología, Gestión de costas.

Received: 26 October 2021

Accepted: 13 February 2022

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1. Introduction

Present trends and rates of shoreline change are commonly associated to a combination of geological factors, variations in sediment supply and fluctuating climate (Hapke *et al.,* 2013). Sea level trends also play a determinant role in shoreline evolution, especially on low, sedimentary coasts (Dyer *et al.,* 2021). In this sense, it is broadly accepted that a medium to long-term sea-level rise will increase long-term erosion rates (Zhang *et al.,* 2004). Most of the European sandy shores are presently affected by erosion. Although coastal erosion is a natural process, very often it is triggered or intensified by human practices (Pranzini and Williams, 2013). A very common cause of beach erosion is the disruption of sediment fluxes from rivers to the sea (Abeyta *et al.,* 2017), due to sediment retention in reservoirs, land reclamation, agricultural practices, coastal urbanization and coastal engineering works (Sherman *et al.,* 2002).

In the case of Spain, 35% of the Mediterranean coast of the Iberian Peninsula is protected and adapted to climate change (European Commission, 2009). However, a number of places along this coast are very vulnerable to sea level rise and sediment retention in the fluvial catchments, which historically has produced shoreline erosion (Semeoshenkova and Newton, 2015). This problem is particularly remarkable the case of deltas, which very often are densely populated and highly vulnerable areas (Wolters and Kuenzer, 2015).

The Mediterranean deltas constitute a particular case, where historical human practices have transformed estuaries into deltas over the past 2000 years and have conditioned their morphological evolution from initial progradation to later erosion along this period (Cooper and Alonso, 2006). This trend has been recorded by deltas like the Po and Nile cases, where human perturbation of catchments during Roman times triggered erosion. After a short progradation period during the Little Ice Age, the last two centuries have been characterized by sediment flux reduction due to catchment reforestation, sediment retention in reservoirs, fluvial regulation and dredging. This situation of progressive delta degradation will be exacerbated by sea level rise, which can lead to delta destruction (Anthony *et al.,* 2014).

Different previous approaches have been made on the recent Ebro Delta morphological evolution (Jiménez and Sánchez-Arcilla, 1993; Ibáñez *et al.,* 1997; Rodríguez-Santalla *et al.,* 2011b; Somoza and Rodríguez-Santalla, 2014; Ramírez-Cuesta *et al.,* 2016). However, most of them do not present any consistent proposal of present trends of morphological change and modifications expected to occur in the near future. Only a very recent study ordered by the Spanish Government analyses such a problem with certain detail (CEDEX, 2021), although without considering any possible sediment by-pass processes within the deltaic system, despite the fact that this process had been already evidenced by Ramírez-Cuesta *et al.* (2016). Obviously, the possible trends will also be conditioned by the climatic and sea level behavior, an aspect already considered by Romagosa and Pons (2017).

The present work focuses on the recent morphological changes recorded by the Ebro River delta, by using aerial photographs taken in the last six decades. The geomorphological maps obtained after them give very valuable clues about the recent shoreline trends of the delta, which can be used to predict future coastal changes to be expected in the following decades. The results are fundamental for facing any kind of recuperation plan and/or management program along the river delta coast.

2. Study zone

2.1. Geographical background

The Ebro River delta mouth (Fig. 1) is located on the Mediterranean coast of the Iberian Peninsula and is one of the most important deltas in the western Mediterranean (Ibáñez *et al.,* 1997). It is also one of the six greatest rivers of the Iberian Peninsula and the only one of them draining to the Mediterranean Sea. The extension of the emerged area is 325 km^2, which represents only a 15% of the total area of the delta (Rodríguez-Santalla and Somoza, 2019). The elevations do not exceed 5-6 m and approx. 50% of the total surface lies below 0.5 m above Mean Sea Level (MSL; Genua-Olmedo, 2017). The current shape of the Ebro Delta can be described as two hemideltas separated by the main river channel (Fig. 1). In the left side of the main channel, the development of the beach and dune ridges led to the formation of a submerged meadow (Garxal), sheltered by the sandy barrier.

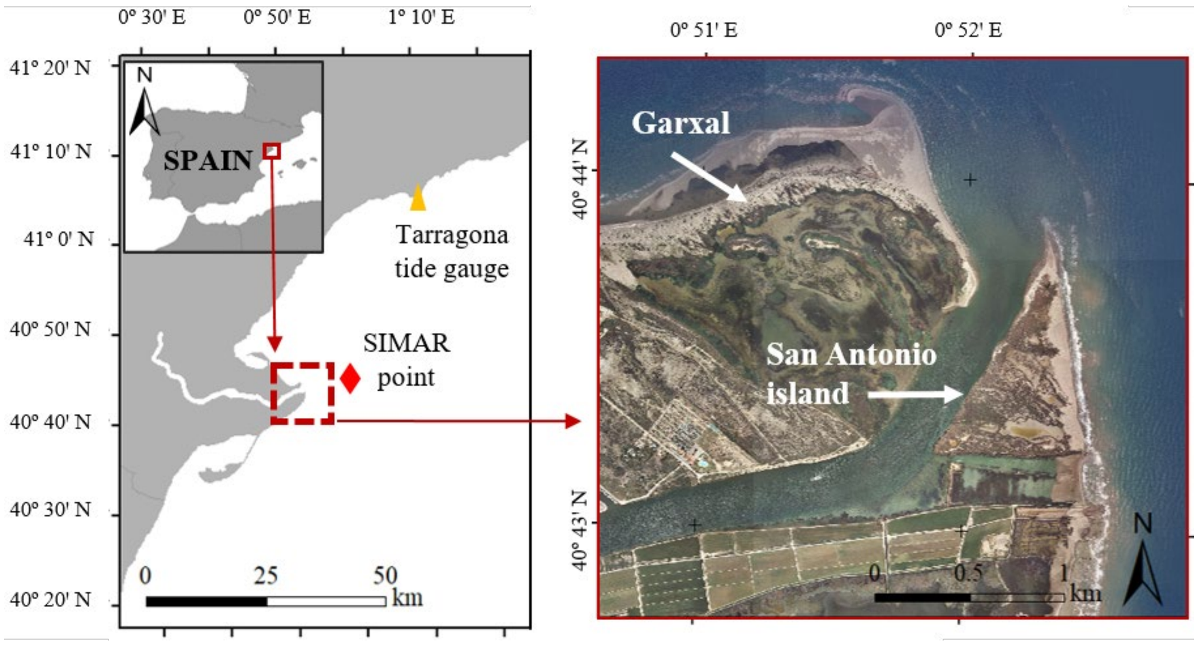


Figure 1. Location of the study area. The SIMAR point and the tide gauge's positions from which the hydrodynamic data have been extracted are indicated.

Additionally, the average subsidence of the delta was estimated in 1 to 3.2 mm/year in recent decades (Ibáñez *et al.,* 1997). The medium-long term effects of this subsidence together with the relative sea level rise (RSLR) estimated for this area (1-2 mm/y), result in an effective RSLR between 3 and 6 mm/y in the areas close to the mouth (Barnolas, 1995; Day *et al.,* 1995; Ibáñez *et al.,* 1995; Verdaguer, 1983). Ibáñez *et al.* (2010) described that floods and river overflowing enhance vertical accretion, minimizing the effects of the RSLR in the mouth complex. However, recent strong storm episodes, like Gloria Storm in January 2020, produced severe damage and intense erosion. The increasing frequency of such energetic events could accelerate the rate of shoreline retreat (Vousdoukas *et al.,* 2016), which could lead to a severe delta modification (Fig. 2).

Apart from this, the ecological values of the habitat diversity on the Ebro River estuary (beaches, dunes, wetlands, coastal lagoons, etc.) coexist with an intensive economic activity mainly focused on rice crops. The singularity and relevance of the Ebro delta led to the declaration as Natural Park in 1983. Besides, some zones are protected as Biosphere Reserve, Site of Community Interest and Special Protection Areas for Birds zones due to the great biodiversity of species and ecosystems, as well as Natura 2000 Network area. All these ecological aspects significantly increase the vulnerability and interest in studying the recent evolution and possible future trends of the delta shores.

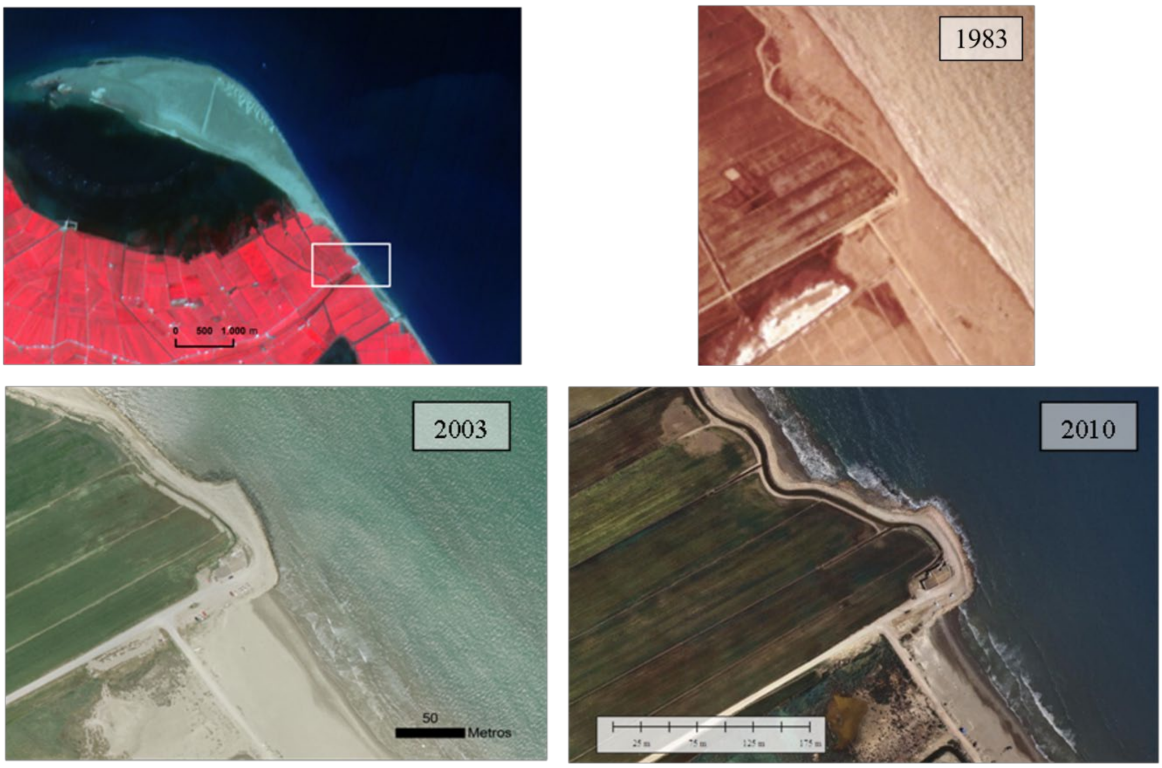


Figure 2. Examples of a strong erosion in a coastal point where a restaurant facility (Los Vascos) is located.

2.2. Historical background

The Ebro Delta began to develop at the end of the sea level post-glacial eustatic rise (Maldonado, 1986, 1977), and its shape is the results of the advance of successive deltaic lobes that have progressed radially (see Rodríguez-Santalla *et al.,* 2011a, for more information about Ebro river Delta formation). In accordance to previous conclusions achieved by Canicio and Ibañez (1999), and after applying a number of mathematic models to the morphological evolution of the delta, Nienhuis *et al.* (2017) concluded that the main recent historical progradation occurred 2100 years ago. This process was followed by river avulsions that favoured the development of the Northern (El Fangar) and Southern

(La Banya) spits between 900 and 300 years BP. The current shape of the mouth is linked to a change on the river flow in 1947 (Fig. 3). Consequently, the northern inlet or Gola Norte (Garxal) developed, which constitutes the study area of the present work. The two mouths coexisted until 1956, when the eastern mouth, named Gola Este, or Cap Tortosa, was naturally closed (Guerrero *et al.,* 2018).

The Ebro River presents the largest discharges in Spain (426 m^3/s), with a marked variability between dry and wet years (Movellán, 2004; Rodríguez-Santalla *et al.,* 2011a; Genua-Olmedo, 2017). Nevertheless, the river input of sediment has been drastically reduced by the construction of dams (e.g. Flix [1948], Mequinenza [1966] and Ribarroja [1967] dams, particularly) (Rodríguez-Santalla and Somoza, 2019). The direct effect of dam constructions in the Ebro Delta is the interruption of the sediment transport, causing morphological changes downstream, as well as modifications in the associated habitats (Guillén and Palanques, 1997; Kondolf, 1997).

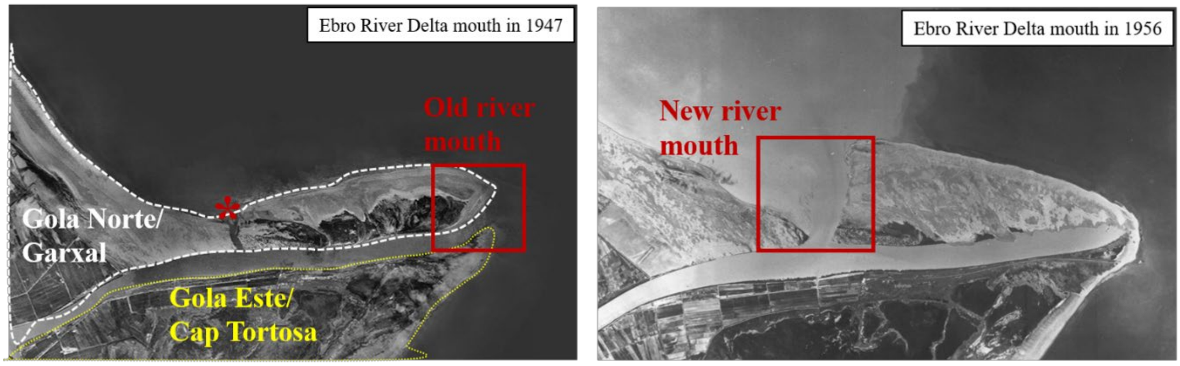


Figure 3. Aerial photographs showing the major changes recorded by the Ebro River Delta mouth between 1947 and 1956. Old and new opened river mouths are indicated (red boxes).

2.3. Sea climate, hydrodynamics and sea level fluctuations

The Ebro Delta has a microtidal regime with a Mean Spring Tidal Range (MSTR) of about 0.20 m (Franquet Bernis *et al.,* 2017), what gives a greater importance to the meteorological tide component (surges). The combined effect of meteorological and storm surges has a strong erosive effect both on the coast and on the dune fields of this area (Sánchez, *et al.,* 2011a). Originally, the Ebro Delta was dominated by fluvial sediment deposition remodelled by waves (Sánchez-Arcilla and Jiménez, 1997). Currently, it is a wave-dominated system (Rodríguez-Santalla and Somoza, 2019) where waves come mainly from three directions: E, S and NW (Fig. 4a). The East component is the dominant direction due to its frequency and energy, and in fact it is the responsible for the main transport of sediments in the mouth of the Ebro River. Waves and currents are strongly controlled by wind dynamics in this area. The wind is an important component within this area, with strong events during spring, matching with E wave events (Fig. 4b; Cateura *et al.,* 2004). Nevertheless, the strongest winds come from NW (Mestral winds), corresponding to wave calm periods (Jiménez *et al.,* 1997). Lastly, prevailing littoral drift in the N hemidelta follows a NW direction, while in the S hemidelta it follows a N-S direction, highlighting the differential behaviour of these too close areas.

Climatically, this zone has a littoral Mediterranean climate, with moderate temperatures during winter and sub-arid weather in summer, because of high temperatures and low precipitations. The thermoregulatory effect of the sea softens the temperatures in the coastal strip throughout the year, with average values between 15.5ºC and 17ºC, and an average rainfall between 500-600 mm/year (Sánchez *et al.,* 2011a).

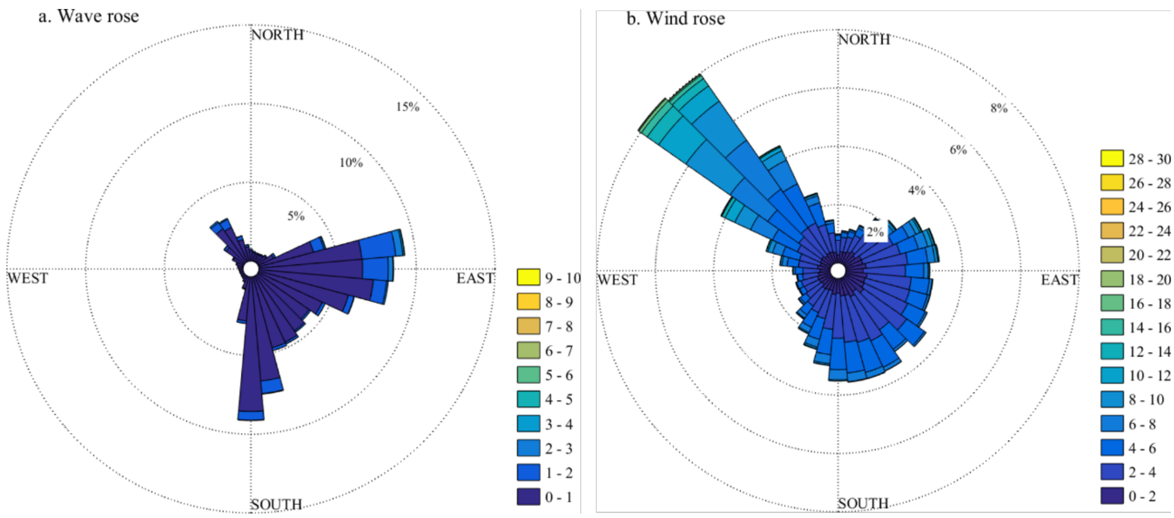


Figure 4. (a) Wave and (b) wind roses extracted from the SIMAR point (SIMAR 2095129; 0.92ºE, 40.75ºN). See Figure 1 for location of the SIMAR point. Data provided by the National Port Authority (2019).

3. Methodology

To cope with the main objective of the present work, the Ebro Delta river mouth has been mapped by means of orthophotographs of the years 1956 and 2017, obtained from the Spanish National Plan of Aerial Orthophotography (PNOA). Besides, data from a previous work (Aranda *et al.,* 2020) have been used to obtain a more extended database about the evolution of this system.

Stereoscopic photo-interpretation techniques were carried out for the 1956 images and then scanned and georeferenced in ArcGIS 10.2, through a second-order polynomial function, using at least 15 well distributed control points on every image. The accuracy of the georeference process was determined by calculating the total Root Mean Square Error (RMSE), less than 0.5 m in all cases. The 2017 cartography was developed on-screen digitization using visual image interpretation of different elements, i.e. colour, texture and plant association (Arveti *et al.,* 2016). The geodetic reference system used was the European Terrestrial Reference System 1989 (ETRS89-H30). Every feature was mapped by using the Habitat Digitizer Tool (NCCOS, 2003) extension to ArcGIS (ESRI©). Each feature was recorded with a unique ID, according to the hierarchical scheme previously mentioned. The maps were developed with a minimum scale of 1:2500, to outline small features with enough relevance to have a role in the coastal dynamics. In addition, a minimum mapping unit (MMU, Stehman and Czaplewski, 1998) was set, so areas lower than 100 m2 were not mapped. The main active processes were also mapped based on reviewed literature. Thus, the main ebb and flow directions responsible for the development of the main features were identified.

Once defined and mapped every unit together with the main hydrodynamic processes, the changes in the total surface (ha) of each year were calculated, supplementing the data with the results from the previous work abovementioned, in which the years 1984, 1994, 2003 and 2012 were also mapped, to obtain a larger temporal data series.

Besides, due to the strong changes recorded in the coastal configuration during recent years and reflected in the evolutionary maps of San Antonio Island, the shoreline evolution was calculated for two different periods: long term (1983-2019; 1956 was not used as first year of the shoreline evolution study period as the shape was completely different between this year and 1983 and the calculations could not be made), and short-term (2009-2019), to quantify if the system trends accelerated in these last years. The years selected differs from the orthophotograph analysis. The shoreline evolution also included the shoreline position in 2019, as it is the last available orthophotograph. The dune foot was selected as a proxy for the identification of the shoreline. It was based on slope differences, changes in the colour of the image and the onset of vegetation colonisation in embryo dunes (Del Río, 2007; Ojeda-Zújar, 2000). Once extracted the shorelines of the different years, the quantification of change rates was performed in ArcGIS extension Digital Shoreline Analysis System (DSAS 4.3; Thieler *et al.,* 2009). The process consists on defining a baseline, as parallel as possible to the digitized coastlines and as straight as possible in order to avoid irregularities. Both the coastlines and the baseline were used as input data in the DSAS extension. Then, the statistical output was represented in transects projected perpendicular to the baseline and evenly spaced (Fig. 5). The distance between transects was set at 25 m. The evolution of the shoreline was defined using the Lineal Regression Rate (LRR; m/year). Finally, four sectors (shaded areas in Fig. 5) regularly spaced were used to quantify the shoreline evolution. Three profiles were selected before and after the central profile in order to evaluate the evolution by sectors and not at fixed points, thus being more representative of the trend of the system. In a later phase, these data were represented and projected in order to quantify, from a simple linear regression, future trends and the possible reduction, increase or disappearance of San Antonio Island.

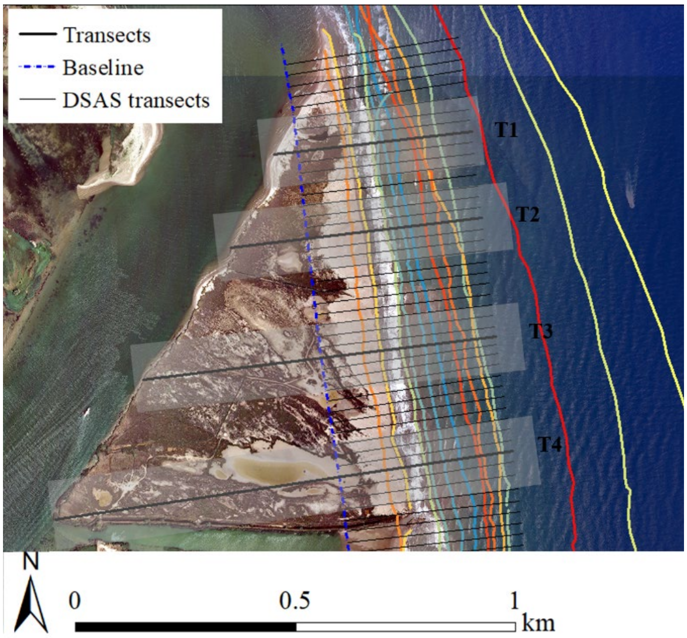


Figure 5. Example of the transects used to calculate the LRR (DSAS transects), the baseline and all the digitized shorelines for the San Antonio island changes quantification (coloured lines).

4. Results and discussion

Retrospective studies are necessary to understand processes controlling coastal systems dynamics. For that, aerial orthophotographs libraries are needed. The quality of the aerial orthophotos is an important issue as it may limit the accuracy on the identification of the features limits when mapping. The main errors come from the quality of the image and the bias of the analyst (Olofsson *et al.,* 2014). Despite that, it is not possible to make an accuracy assessment of historical orthophotographs, so that it results compulsory to accept sources of errors greater than those obtained with current methods. The data obtained from orthophotographs such as that of 1956 proportionate valuable information about the evolution of the system that, without doubt, must be taken into account when defining current and future trends, but results must be interpreted with caution.

The Ebro River Delta mouth recorded great changes between 1956 and 2017 (Fig. 6). The first available aerial photo of the zone (1947; Fig. 3) shows the old mouth of the river, presently located in the Southern part of the San Antonio Island (old channel in Fig. 6). The current active mouth derives from the breakage of the old channel on its left side, as a consequence of a river flooding episode in 1937 (Rodríguez-Santalla *et al.,* 2011b). In 1956, the original mouth was already closed and the active mouth opened very widely, initiating the shifting toward the present shape (Fig. 6). Huge sand sheets covered San Antonio Island in 1956, which could be considered as a complex sandy system with a virtual absence of muddy features, except for the proper deltaic plain. As it can be observed in the comparison between both geomorphological maps, this zone underwent important eco-geomorphological changes during the last 60 years. The most evident one is the development of beach and dune ridges forming a sandy barrier in the left part of the river mouth, and El Garxal wetland, a submerged meadow sheltered by the sandy barrier and open to the main channel (Fig. 6). During the study period, the main littoral drift transported important inputs of sediment into El Garxal wetland (main changes in the 80's according to Aranda *et al.,* 2020), enabling the formation of new recurved spits (black dotted arrows in Fig. 6). These spits have slowly connected to land with the consequent formation of a new coastal lagoon in recent years. Regarding the right side of the river mouth, i.e. the San Antonio Island, the main changes are related to a reduction in the surface of this sandy system since it has been strongly eroded in the last 60 years on its eastern side.

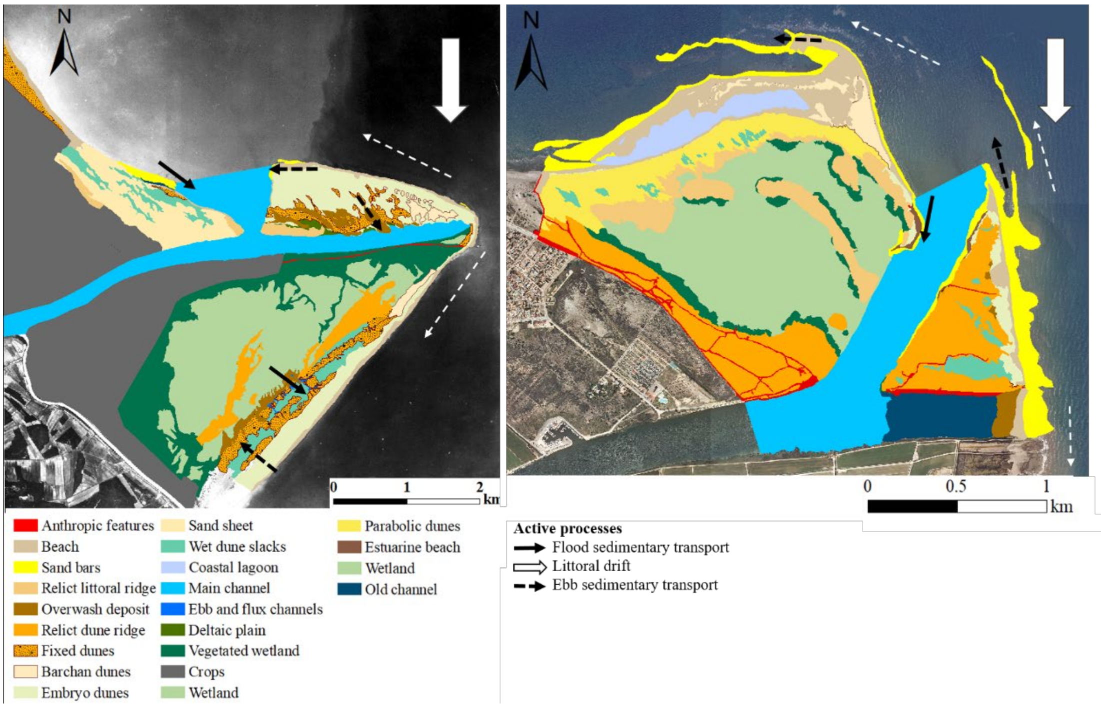


Figure 6. Geomorphological maps of the Ebro River Delta mouth in 1956 (left image) and 2017 (right image), with indication of the main prevailing processes. Dotted white arrows indicate local littoral drifts.

The total Ebro River delta mouth shows a decrease of a 10 % on its surface compared to 1984 (Aranda, 2021). This trend has been fuelled by the strong changes associated with the abovementioned erosion of San Antonio Island, which shows a decrease in the surface of more than 50 ha (Fig. 7). This process equates to erosion rates reaching almost 20 m/year (Fig. 8), which has been only partly counterbalanced by the growth of the sandy barrier on the left side of the estuary (Fig. 9). In this sense, the evolutional geomorphological maps reveal that part of the sediment forming new sandy hooks on the left side could come from the breakage of the sandy intertidal spits of the north part of San Antonio Island. This means that an active bypassing of sediment is occurring between both sides of the river mouth. In any case, other processes not included in the present work complicate the overall scheme here presented (i.e. the limitation and increasing scarcity of sediment inputs from the river, its intermittency, and the action of the NW winds, which generate currents that can redistribute part of the sediment input; Rodríguez-Santalla *et al.,* 2021). These results must be carefully interpreted, and a deeper study focusing on external factors (i.e. waves, winds, storms, river discharges…) is also needed. Furthermore, the huge erosion of this part of the river mouth is subject to temporary variations, so the trend may be accelerated or even decelerated in the future, depending on those external factors.

The erosive trend of San Antonio Island has increased in recent years, which is clearly noted in its short-term evolution (Fig. 10), with constant erosion in the northern part that becomes more differential than the long-term towards the south, where the old mouth was located. Besides, it can be noted an increasing erosional trend at the south of the former river mouth, and a decrease in the erosional behaviour in the northern part in the last 10 years. If this trend continues, approximately in 2050 the San Antonio Island could disappear (according to Fig. 7). In such a case, El Garxal wetland (left side) would be exposed to energetic wave events arriving from the East, which would most likely cause its retreat and that of the associated features. As a consequence, the current hemi-deltas of the river mouth complex would change their shape completely.

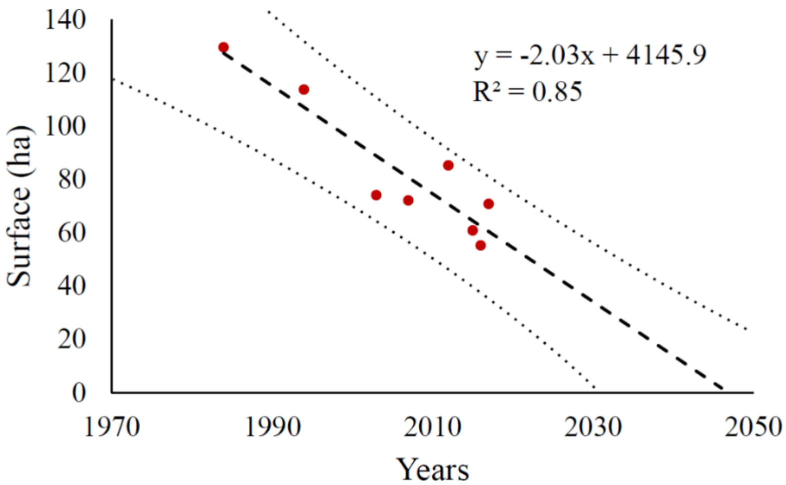
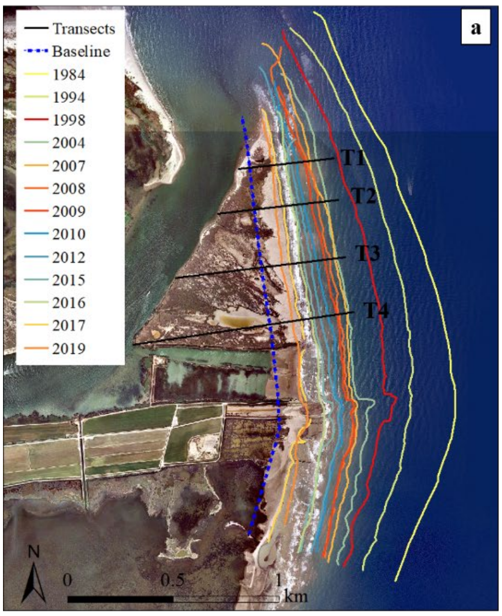
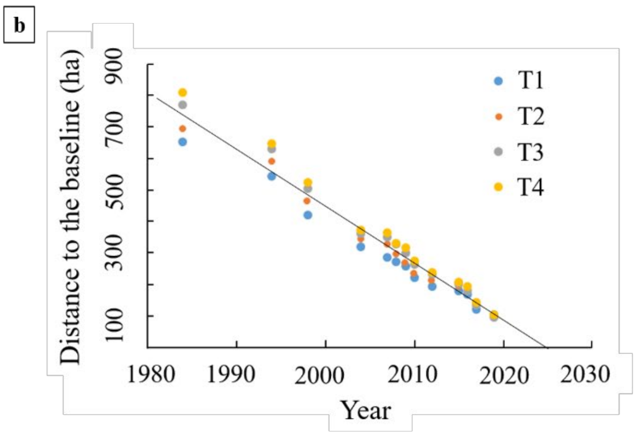


Figure 7. Evolution of the surface (ha) of the San Antonio Island during the period 1984-2017, showing a virtual disappearance (0 ha) around 2050 according to linear regression equation (R^2=0.84). Dotted lines show the 95% confidence intervals.





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	Distance (m)	LRR_1 (m/y)	t_1 (y)	LRR_2 (m/y)	t_2 (y)
T1	160.514	-13.4271	11.95 (2032)	-15.6785	10.23 (2031)
T2	278.2197	-15.0385	18.50 (2039)	-17.0543	16.31 (2037)
T3	504.489	-18.4914	27.28 (2048)	-18.8728	26.73 (2047)
T4	760.772	-19.4057	39.20 (2060)	-19.6171	38.78 (2059)

Figure 8. (a) Image of the 4 selected transects to evaluate the LRR and the digitized coastlines. (b) Distance from the digitized coastlines to the baseline, measured along each selected transect. y = -17.36x + 35155 (R^2= 0.98). (c) Distance of every transect (m) from the baseline to the western part of San Antonio Island; LRR_1: short-term evolution for every transect; t_1: expected time in which the width of the transect will disappear according to short-term rates (calendar years in brackets); LRR_2: long-term evolution for every transect; t_2: expected time in which the width of the transects will disappear according to long-term rates (calendar years in brackets).

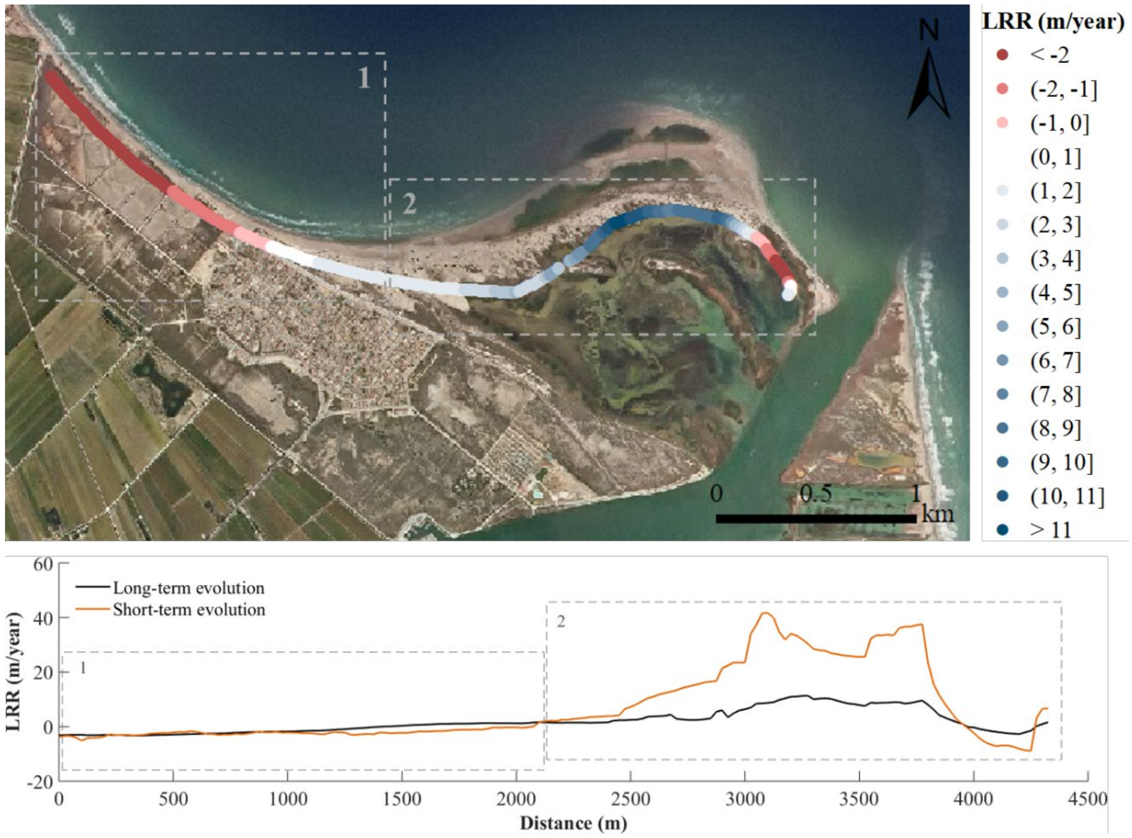

Figure 9. (a) Long term evolution (LTE) based on Linear Regression Rate (LRR) of the shoreline in Ebro River Delta mouth. Grey boxes differentiate the (1) anthropic zone from the (2) natural one. (b) Erosion rates as a function of the alongshore coordinates, being 0 the western side. Black line corresponds to long-term evolution of LRR (1983-2019) and the orange line represents short-term evolution of LRR (2009-2019).

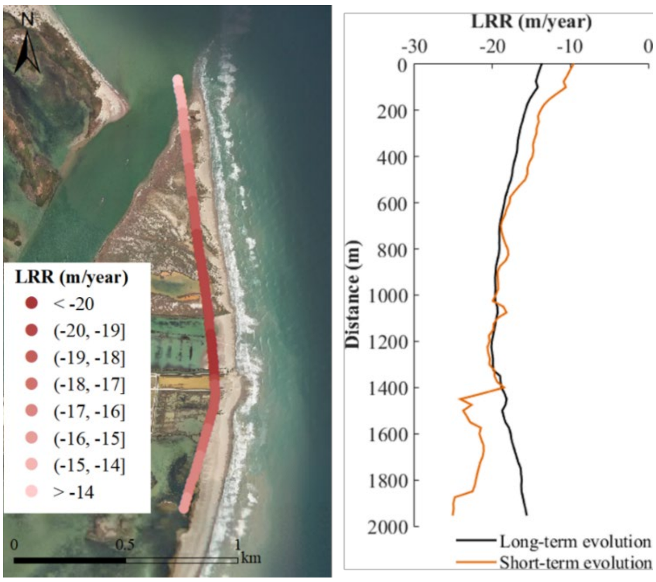

Figure 10. Left: Long term evolution based on Linear Regression Rate (LRR) of the shoreline in San Antonio Island from 1983 to 2019. Right: A comparison of the LRR as a function of the alongshore coordinates for two different time periods: black line corresponds to long-term evolution of LRR (1984-2019) and the orange line corresponds to short-term evolution of LRR (2009-2019).

The deterioration of this part of the Ebro Delta mouth, understood as coastal erosion and loss of associated habitats, could be associated with the increase in frequency and intensity of storms coming from the East (the most energetic component in this area; Cateura *et al.,* 2004), together with the effects of the SLR (which is aggravated in this zone due to subsidence; Genua-Olmedo, 2017). Nevertheless, a deep study on the functioning of river mouth marine dynamics within this system is needed. However, it is also a consequence of the lack of social and political awareness about the importance and vulnerability of coastal systems (Romagosa and Pons, 2017). An example of this vulnerability was the effects of the storm Gloria, which flooded a large part of the delta in January 2020 and washed away large coastal features. This storm was not extreme in terms of atmospheric conditions, but intense (Alonso *et al.,* 2020). Almost all the dune fields were above the sea level during the storm, especially in the left part (dune heights around 6 m at some points), proving its protective role against such erosive event. Nevertheless, to increase the reliability of the predictions additional studies combining hydrodynamic models in this zone are still needed. The process of erosion on this side is also due to the reduction of the river sediment input, as the discharges have been intensively regulated since the beginning of the 20th century (Guillén and Palanques, 1992; Rodríguez-Santalla and Somoza, 2019), causing strong negatives rates (Fig. 8).

Ibáñez *et al.* (2014) proposed three possible self-reinforcing mechanisms to cope with SLR and erosive trends in this zone: (1) increase in the frequency of delta lobe switching leading to the formation of new lobes, (2) an increase in the frequency and magnitude of flood events through natural river levees, and (3) an increase in the frequency and magnitude of overwash events, enhancing the ability of sandy beaches to adapt to sea level rise. First of all, there is not enough time to lobe switching to occur. The retreat rate of the San Antonio Island is too fast for the delta mouth to migrate and adapt. Secondly, the increase of flood events could be an option but their management through dam regulation is difficult and depends on a number of external factors (technical, hydrological, and socio-economic, among others). Additionally, the lowest reservoirs built in the Ebro river basin are too close to the delta, so there is not sufficient river catchment to produce natural flood flows that generate sediment. It is an over-regulated river, where flooding in the final parts of the river are virtually ruled out. Lastly, the overwash process is the most active one in the delta mouth, which is effectively making beaches retreat inland but, in the case of San Antonio Island, there is a physical limit, imposed by the river channel itself.

Nevertheless, most of the proposed solutions may not solve the erosion problem in San Antonio Island, so a possible solution could be to let the system act naturally and reach a new state of equilibrium, even if this entails the loss of one of the most emblematic natural parts of the Ebro River Delta. This possible evolution may consist in a westward shifting of the entire mouth complex, maintaining a certain sandy barrier in its eastern side while the Garxal wetland is being eroded. The rollover model of coastal evolution, typical of sand coasts subject to slow sea level rise trends, could be the solution to maintain the diversity of subsystems and habitats in this part of the delta. It will be necessary to assess any subtle change in the delta shoreline, especially when affected by strong easterly sea storms, that represent the main trigger of rapid coastal changes in the zone. The detailed analysis of the evolution and changes recorded by the delta during past storm episodes, together with the application of wave propagation models referred to such energetic situations could be another step that would help to predict the immediate future of this emblematic portion of the Iberian coast.

5. Conclusions

The development of sequential eco-geomorphological maps from historical images has proved to be a useful tool to assess the resilience of coastal systems under present and future pressures. In future works, the combination of aerial orthophotos, which provide the historical data for the study of landscapes, with other methods, as wave propagation models or hyperspectral or surface elevation information derived from airborne and satellite sensors, will facilitate the reconstruction and monitoring of coastal changes at landscape level, reducing time and efforts.

The Ebro River Delta mouth is exhibiting a strong positive trend on sandy features on the left side of the main river channel, but a huge negative trend on the other side. From the obtained results, it can be inferred that in between 2040 and 2050 the San Antonio Island could disappear if this trend continues. It is important to read these results with caution, since they were obtained from a simple linear regression applied to surface changes and shoreline migration. As it is eroded, other processes will occur that will either increase or decrease the dynamics of the process. That is, these results are related to the recent evolution of the system but it can change depending on external factors in the future. This assumption reinforces the need of the application of hydrodynamic and geomorphological models that could better explain future trends of this part of the Ebro Delta mouth.

Acknowledgements

This research is supported by the EMAS grant (Earth and Marine Sciences joint PhD programme between University of Cádiz and University of Ferrara) and a post-doctoral contract founded by the University of Cádiz. It is also a contribution to the RNM328 group of the Andalusian Research Plan (Junta de Andalucía).

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