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The effects of the anthropic actions on the sandy beaches of Guardamar del Segura, Spain

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ABSTRACT

There are many activities and uses in the coastal environment, which has historically attracted the humans. This attraction has led to many anthropic actions that have generated imbalances, more important as the human pressure increases. This research focuses on the effects of these pressures along of 11 km of the coastline of Guardamar del Segura, a high-value environmental area where is the Segura River mouth and one of the last dune systems of the southeast of Spain. The historic evolution of the shoreline position has been analysed using 60 years of aerial images from 1950s to 2014, the seabed depth changes, the maritime climate, the distribution of the sediment grain size and the anthropic actions such as urban development or the channelling of the river. All data were integrated and processed using a Geographic Information System (GIS). The results show that the lack of sediment supply by Segura River and the cut-off in the longshore transport due to the breakwaters and others anthropic actions has led into an increase in the beaches erosion rates, with a loss of more than 3.2 million m^3 of sand in the last 58 years (≈ 55200 m^3/year). The conclusions of this research could be useful to the coastal managers at the moment of making the decisions of action and/or conservation on a coastal system to achieve positive results in the medium and long term.

Keywords: *beach erosion; GIS; sand; anthropic; shoreline evolution*

1 INTRODUCTION

Coastal tourism is one of the most important, and its rapid growth in the last 60 years has resulted in great urban development in coastal areas (Scott *et al.*, 2012). This development has led to many anthropic actions that have generated imbalances in the area (Martín-Antón *et al.*, 2016), for example, the change in the type of land cover (Xian *et al.*, 2007), the construction of harbours (Jiang *et al.*, 2017; Naik and Kunte, 2016), urbanizations, channellings or breakwaters on the coast (Burak *et al.*, 2004; Newton *et al.*, 2012; Pagán *et al.*, 2016), producing remarkable changes in the bathymetry and the texture of sediments deposited in depths where the hydrodynamics of the waves does not affect (Aragonés *et al.*, 2016a; Zhu *et al.*, 2016). All these actions are usually associated with large imbalances of the coastal system, which is usually translated into a retreat from the coastline causing a vulnerability of any settlement located around it (Newton *et al.*, 2014).

One of the elements most related to the change in the evolution of the coastline are the sediments, due to the relation that exists between its size, specific weight and the energy of the waves (Salazar *et al.*, 2004). Therefore, it is necessary to know both transport, sedimentation and spatial and temporal sediment distribution. Within the cross-shore transport to the coast it has shown a tendency to classify them seawards due mainly to the change in the energy of the waves as they reach the coast and currents in the process of sediment transport (Guillén and Hoekstra, 1996; Narra *et al.*, 2015; Niedoroda *et al.*, 1985).

All of the above should be added the threat of climate change that predicts an increase in the intensity and frequency of extreme events, and an increase in sea levels (Arnell and Lloyd-

Hughes, 2014; Jiménez *et al.*, 2017; Oldfield and Steffen, 2014) and the insufficient contribution of the rivers (Aragonés *et al.*, 2016a; Chaplot and Poesen, 2012; Newton *et al.*, 2012). Therefore, it is necessary to know/understand the physical environment, the relationship between the agents and processes of each of the involved fields (marine, coastal and terrestrial), to make decisions aimed at preserving or regenerating the affected areas. With respect to the insufficient material contributed by the rivers to the beaches, there are several studies in which the basins and flows of different rivers are analysed, concluding that there is an increase in the runoff due to the enthronization of the soil (Xian *et al.*, 2007), which has caused a lower load of suspended sediments in the river currents (Liu *et al.*, 2007; Mutema *et al.*, 2016; Syvitski *et al.*, 2005). For example, according to Syvitski *et al.* (2005) less than the 50% of the soil eroded by the rivers reach the world's coast.

Due to the complex relationships between continental shelf and the agents involved in sediment transport (waves, tides, currents, sources, benthos, etc.), three-dimensional study is necessary to understand these relationships and get the ecosystems balance. Nowadays, three-dimensional studies is possible thanks to the geographic information systems (GIS), which has been widely used to study coastal risks (Brown, 2006; Budetta *et al.*, 2008), the evolution of the cliffs topography and seabed (Castedo *et al.*, 2015; Dawson and Smithers, 2010; Mills *et al.*, 2005), or the evolutions of the coastline from aerial images creating applications such as the Digital Shoreline Mapping System, DSAS (Thieler and William, 1994). This kind of tools allow the user to represent and analyse complex environmental systems using spatial and statistical analysis, and thus improve understanding of the behaviour of coastal systems (Robin and Gourmelon, 2005).

Therefore, the objective of this study is to explore the processes undergone by the study area (channellings, construction on dune systems, etc.), which have caused the serious problems presented by this complex biophysical system between land, sea and air. For this purpose, the evolution of the coastline, the seabed and the maritime climate, and the distribution of sediment on the seabed will be analysed as a means of predicting future behaviour in the study area, as well as the consequences that must be taken into account before taking anthropic actions in any area of the world.

2 STUDY AREA

The area under study corresponds to the beaches both north to south of the Segura river, (Guardamar del Segura, Alicante, southeast of Spain), with length of 11 km (Figure 1). The surroundings of these beaches are configured by various ecosystems that results to a unique landscape. A dune cordon covers the entire littoral of Guardamar del Segura, from north to south. A series of human actions have been carried out within the study area, which have gradually changed its coastal morphology. The beaches studied and their main characteristics are listed in Table 1.

Table 1. Beach characteristics.

Beach	Length	Coast	Promenade
Los Tusales	1.7 km	Dunes	No
Los Viveros	1.4 km	Dunes	No

Babilonia	1.0 km	Urban	Yes
Centro	1.6 km	Urban	Yes
La Roqueta	1.0 km	Urban	No
El Moncayo	2.0 km	Dunes	No
El Campo	1.2 km	Dunes	No
Les Ortigues	1.0 km	Dunes	No

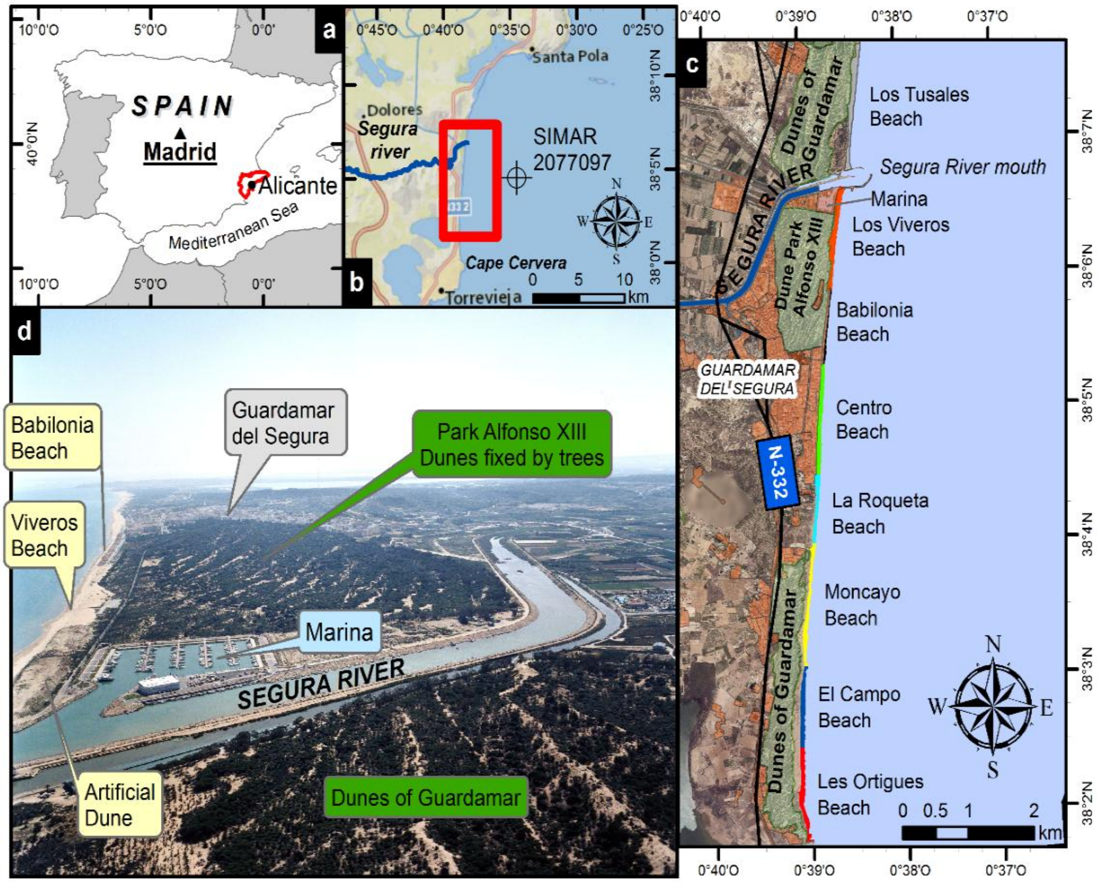


Figure 1. a) Study area located in Alicante, SE of Spain. **b)** Detail of the studied area, with the location of the SIMAR node used for wave data. **c)** Location of beaches and significant elements on the coast of Guardamar del Segura. **d)** Aerial image of Segura river mouth (MAPAMA, 2017).

Sand dune fixation

The anthropic pressure on this area began early XX century. In 1900, a large reforestation work was carried out with the aim of fixing the dunes, whose movements threatened the town of Guardamar. This environment, formerly mobile and threatening by the action of the wind, results in the current coastal forest. The main species that can be found in the area are: *P. Pinea, P. halapensis, Eucalyptus rostrata, occidentalis, robustia, globulus and colossea, and Phoenix dactylifera* (García-Esteban, 2002).

Babilonia houses

Another anthropic pressure that this area suffers is related with the urban development. In Babilonia beach a series of terraced houses were built in the beachfront as part of the reforestation project of Ingeniero Mira. Currently, almost 80 houses still occupying the beachfront. The administrative concessions date from the decade of 1940, when they were allowed to occupy the maritime-terrestrial public domain (MTPD) as a way to protect the dune system.

Protection Plan against Flood in Segura River Basin

One of the areas that has undergone the greatest change due to the action of man has been the mouth of the Segura River. During the 1980s, the low course of the river suffered some heavy rains episodes that led to the river overflow and the flooding of much of this area, causing great human and material loses (Aragonés *et al.*, 2016a). To avoid this hazard, the Confederación Hidrográfica del Segura improved the drainage capacity of the river mouth. In 1986, a first 300 m long breakwater was built in the north side of the mouth. In 1992, a new channel and a 400 m long breakwater were executed in the south side of the river mouth, which increased its width from 100 m to 350 m. All this works are described in detail in the document "Plan de defensa contra avenidas" (Confederación Hidrográfica del Segura, 2007).

Marina and artificial dune

In 1998, a new marina was built in inland lands near the river mouth. Based on the conviction that the dredged materials were of a similar nature to those formed by the nearby dunes, basically composed of sands and silts, the sludge from the dredging of the dock was poured in the beachfront. A new artificial dune was created, with a length of 500 m and variable height, which oscillates between the 10 meters of the sector closest to the fluvial channel, to the scarce two meters of the southern part (Matarredona Coll *et al.*, 2006). The construction of this marina as well as the artificial dune with the excavated material created a strong controversy, as it was not been considered suitable for this environment.

Beach nourishments

Given the evident state of erosion of the Centro beach, in 1988 and 1990 about 150000 m^3 and 250000 m^3 of sand were dumped from municipal lots (Aldeguer Sánchez, 2008).

3 METHODS

In order to study this complex area, the procedure is as follows: i) historical evolution analysis of the shoreline, coastal environment and maritime climate, ii) cross-shore sediment position analysis and iii) study of the flood level.

3.1 Historical evolution of the shoreline

The study of the shoreline evolution was carried out by the vectorization of the shoreline from aerial images since 1956. The available dates of the images and their formats are shown in Table 2. The first step was the photogrammetric restitution of those images without spatial reference (191 scanned photograms), applying the methodology described by Pagán *et al.* (2016).

Table 2. Summary of the dates, source and format of the aerial images available.

Date	Source	Image	Format	Spatial reference
1956	American Fly	Orthophoto	WMS	UTM ETRS89

				H30N
1969	GEOFASA	Orthophoto	WMS	UTM ETRS89 H30N
1981, 1986, 1990, 1992, 1994, 1996, 1998	DGC – SPC Alicante	Aerial Color (1:10000 – 1:5000)	ECW	None
2002, 2005, 2007, 2009, 2012, 2014	PNOA	Orthophoto	ECW	UTM ETRS89 H30N

The georeferencing process (the assignment of coordinates to the photograms raster datasets) was carried out using ArcGIS 10.1. The target image was the most recent referenced orthophoto, from 2014. Each photogram was georeferenced identifying a series of ground control points (GCP) that link locations on the raster dataset with locations in the spatially referenced data (target data). For each raster between 40 and 60 GCP spread for the entire image were used. Once the GCP were placed, the transformation of the raster was carried out using the adjust transformation. This transformation optimizes for both global and local accuracy. It is built on an algorithm that combines a third order polynomial transformation and triangulated irregular network (TIN) interpolation techniques. The total error is computed by taking the root mean square (RMS) sum of all the residuals to compute the RMS error. In this research, the acceptable RMS was settled in 0.25 m. It should be noted the difficulty of this work, not only by the high amount of control points used in total (10279), but also because as a coastal area most of the rasters have half of its area covered by the sea – impossible to use for ground reference. However, because the frames presented a high degree of overlap (20%-40%) to each other, it was possible to create a mosaic with the central areas of the photograms, less deformed than the edges, improving the results of the process of georeferencing (Table 3).

Table 3. Georeferencing results.

Date	1981	1986	1990	1992	1996	1996	1998	TOTAL
Cell size	0.5	0.5	0.5	0.5	0.5	0.5	0.5	**0.5**
RMS	0.106	0.115	0.114	0.145	0.171	0.169	0.187	**0.144**
Nº Rasters	28	31	13	31	23	31	34	**191**
Nº GCP	2034	2774	950	1371	1090	1042	1018	**10279**

Once loaded in the GIS environment the mosaics with the orthohotos of each year, the next step was the vectorization of the shoreline. The methodology followed was the same as the applied by Pagán *et al.* (2016) in their study of the Marineta Cassiana beach (Denia, Spain). It consists in the visual identification of the higher high water height on the beach, marking this line as the shoreline. All the aerial images were collected in summer and the state of the sea was calm, so the shorelines obtained are suitable for its comparative study. The 11 km of coastline were vectorised for each of the 15 years available (Table 2).

For the study of the evolution of the shoreline, the fundamentals of the DSAS program for ArcGIS (Thieler *et al.*, 2009) were used, increasing its capacities calculating the erosion-accretion surfaces. A series of perpendicular transects to the shoreline were created, spatially separated 100 m. The origin of these transects is located in the baseline, drawn following the base of the dunes or the promenade. From its intersection with the previously vectorised shoreline it can be obtained the beach width in each transect for each studied period, and thus its evolution in time. For the analysis and interpretation of the results, the study was divided into time intervals related to the main anthropic actions: 1956-1986 (from the first data to the date when the north breakwater was built); 1986-1992 (channelling of the Segura River); 1992-1998 (construction of the marina and artificial dune); 1998-2007 (sediment samples collection); 2007-2014 (last orthophotos available).

3.2 Sedimentological and seabed depth change study

161 sediment samples were available from the Ecolevante (2006) survey, ranging from backshore to 40 m depth. Using GIS interpolation techniques, described in Aragonés *et al.* (2016a); Pagán *et al.* (2016), the distribution of the sediment grain size along the coast was obtained. This has allowed to use continuous surface mapping of the sediments, making possible to obtain cross-shore transects and the analysis of the position of the sediment by depth.

To evaluate the depth change of the seabed, the digital elevation models (DEM) of the years 1989 and 2006 are available, and together with the procedures described in Aragonés *et al.* (2016a) a map of the nearshore depth change is obtained. However, as the DEM from 1989 only reaches the bathymetric -8 m, the beach profile had to be rebuilt from the equilibrium beach profile (EBP) using the methods described by Aragonés *et al.* (2016b).

Finally, the volume of the material lost until the depth of closure (DoC) during the whole period of study (1956-2014) is calculated. The DoC is obtained using the formulation proposed by Birkemeier (1985), and the volume of the material using CUR (1987).

3.1 Maritime climate

As for the marine dynamics of the area of study, this, like the rest of the Mediterranean, hardly experiences tidal intensity, where the oscillations due to the atmospheric pressure are even more influential than the tide itself. In this sense, the importance of the astronomical tides is very little significant, with values that oscillate around 0.3 m, while the meteorological tides can reach values of up to 0.45 m (http://www.puertos.es, and Ecolevante (2006)).

The waves in the area are conditioned by the Santa Pola Cape to the north and by Cervera Cape to the South (Figure 1b); so the range of incidental waves is between N69°E and N180°E. Wave data (significant wave height, period and direction) were provided by Puertos del Estado, based on the SIMAR series. Wave data were collected over 56 years, during the period 1958-2014, making it the most complete database for the Mediterranean Sea (Infantes *et al.*, 2009).

For this work, the database of the SIMAR Node 2077097 (0.58°W, 38.08°N), located about 5 km east of the study area (Figure 1b), was used. The data of this point were treated by the software AMEVA v1.4.3 (IHCantabria, 2013), obtaining for each of the study periods the significant wave height, the wave height $H_{s,12}$ (exceeded twelve hours a year), and their corresponding periods, directions and probabilities of occurrence. In addition, the curve for

Gumbel maxima was obtained, from which the wave height and the period for a return period of 5 years were calculated.

3.2 Flood level

This section determines the flood level as the maximum level of the sea on the beach profile under the action of a storm with a return period of 5 years. The estimation of the flood level was made as the sum of the Meteorological Tide (MT), the Astronomical Tide (AT), the consideration of the effects of climate change (CC), set-up (η) and run-up ($R_{u2\%}$). Thus, the MT, the AT and the CC were obtained through the web viewer C3E that is part of the project "*Cambio Climático en la Costa de España*" (Available: http://www.c3e.ihcantabria.com/), promoted by the Ministerio de ciencia e Innovación and carried out by the University of Cantabria. The set-up and run-up due to the great variety of formulations proposed for its calculation and the wide range of results of the same, seven of the formulations that can be found in the literature were used (Douglass, 1992; GIOC, 2001; Guza and Thornton, 1982; Guza and Thornton, 1981; Holman and Sallenger, 1985; Nielsen and Hanslow, 1991; Resio, 1987; Stockdon *et al.*, 2006). Table 4 shows a summary of the equations used, which are described in Supplementary data 1.

Table 4. Summary of the formulas used for the analysis of set-up and run-up.

Set-up	Run-up
Guza and Thornton (1981)	Guza and Thornton (1982)
Holman and Sallenger (1985)	Holman and Sallenger (1985)
If tan β<0.1 Guza and Thornton (1981) If tan β>0.1 Holman and Sallenger (1985)	Resio (1987)
If tan β<0.1 Guza and Thornton (1981) If tan β>0.1 Holman and Sallenger (1985)	Nielsen and Hanslow (1991)
	Douglass (1992)
	GIOC (2001)
	Stockdon (2006)

4 RESULTS

4.1 Shoreline evolution

The historic shoreline evolution in the area of study (Figure 2 and Supplementary data 2) shows that the beaches closest to the Segura river mouth are the ones that have suffered major changes. For example, in the transect T16, during the period 1956-1969, almost 47 m of beach width were lost, while during the same time interval but in a southern area (T80-T96) the beach remains stable or even an accretion of 9 m is detected (Figure 2h). Another significant change is observed in the transect T20, where after a period of relative stability (1956-1986), in 1990 the shoreline erodes about 20 m, recovering in the next period (1990-1992) 50 m due to the fill of sand from the dredging of the marina channel (Aldeguer Sánchez, 2008). The sand poured at this point was dredging material (silty/clayey sand; Figure 4 and Supplementary data 3) so it was quickly displaced by the waves, losing 30 m of beach width in the next period, 1992-1994.

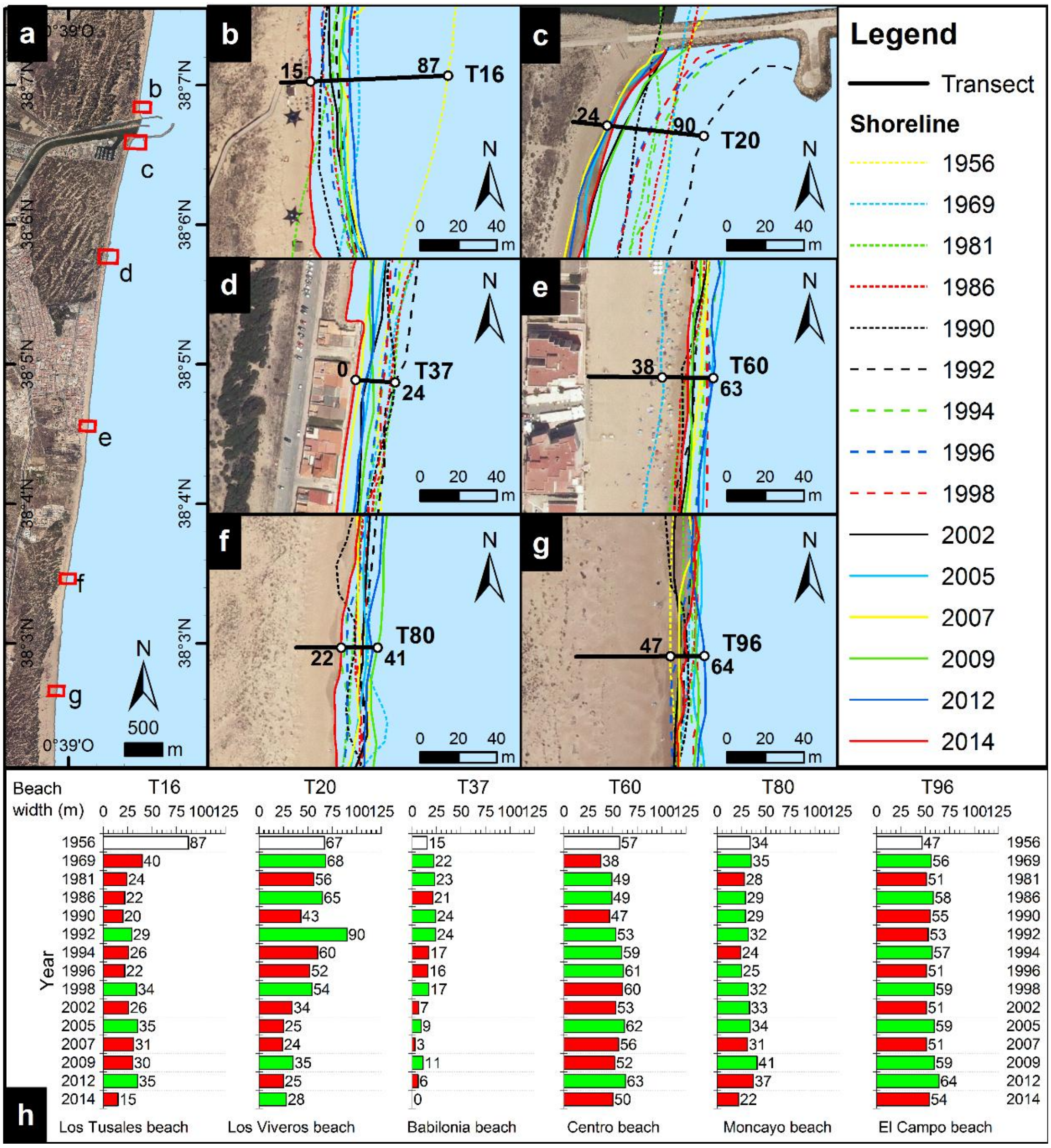


Figure 2. Shoreline evolution, the shoreline change envelope is marked in meters. **a)** Location of the beaches. **b)** Los Tusales beach. **c)** Viveros beach. **d)** Babilonia beach. **e)** Centro beach. **f)** Moncayo beach. **g)** El Campo beach. **h)** Beach width for each period, red for erosion and green for accretion regarding to the previous period.

Figure 3a shows the net shoreline movement between 1956 and 2014 for each transect. It is easy to appreciate the great regression that have suffered the beaches of Los Tusales, Viveros and Babilonia, being in this last the beach width null today. These changes show a strong relationship with the different human actions carried out in this area. Thus, the analysis of the linear regression rate-of-change (LRR) for the first time interval (1956-1986, prior to the first main anthropic action) (Figure 3b) shows that to the south of the river mouth the annual rates-of-change were almost null, whilst the north beach of Los Tusales suffered an erosion rate of 2.5 m/yr. However, before to the river mouth works (1986-1992) and the marina construction (1998) it can be observed that Los Viveros and Babilonia beaches began to increase its erosion rates, passing from a beach width of 90 m and 24 m to 54 m and 17 respectively. From the construction of the marina and the artificial dune in Los Viveros beach (1998-2007), erosion rates increases up to 3.5 m/yr, affecting also the Babilonia beach (rates of 1.5 m/yr) causing that the waves reach the houses of the beachfront. Instead, further to the south the shoreline change rates remain stable. Finally, it is in the 2007-2014 period when it is observed a general erosion, with rates that reach the 4 m/yr to the north of the mouth and exceed the 2 m/yr in practically all the beaches to the south of the Segura River. This has caused the sea to reach the ridge of dunes during the storms and cause damage to the houses of Babilonia beach (Figure 4f)

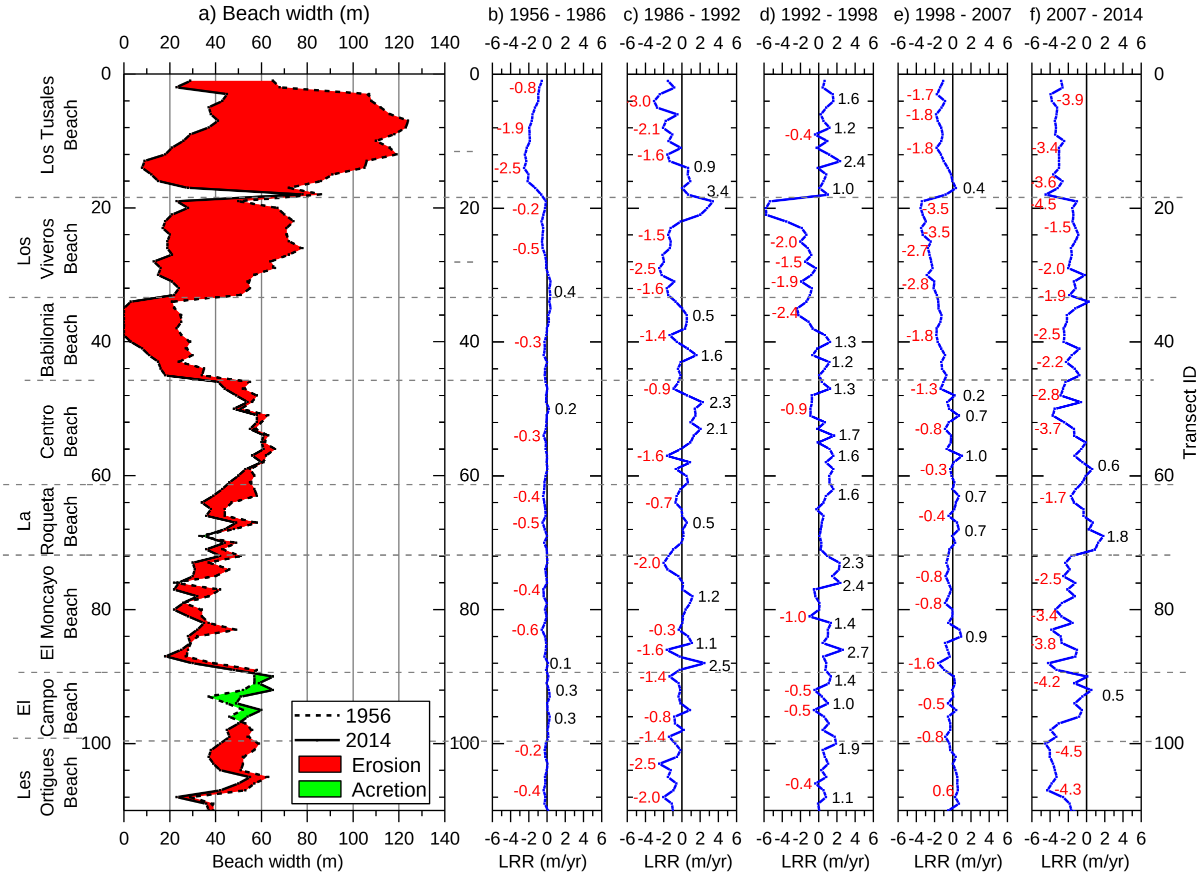


Figure 3. a) Beach width for each transect, in 1956 and 2014. **b, c, d, e y f)**, Linear regression erosion rates (LRR) for each period of study in m/yr.

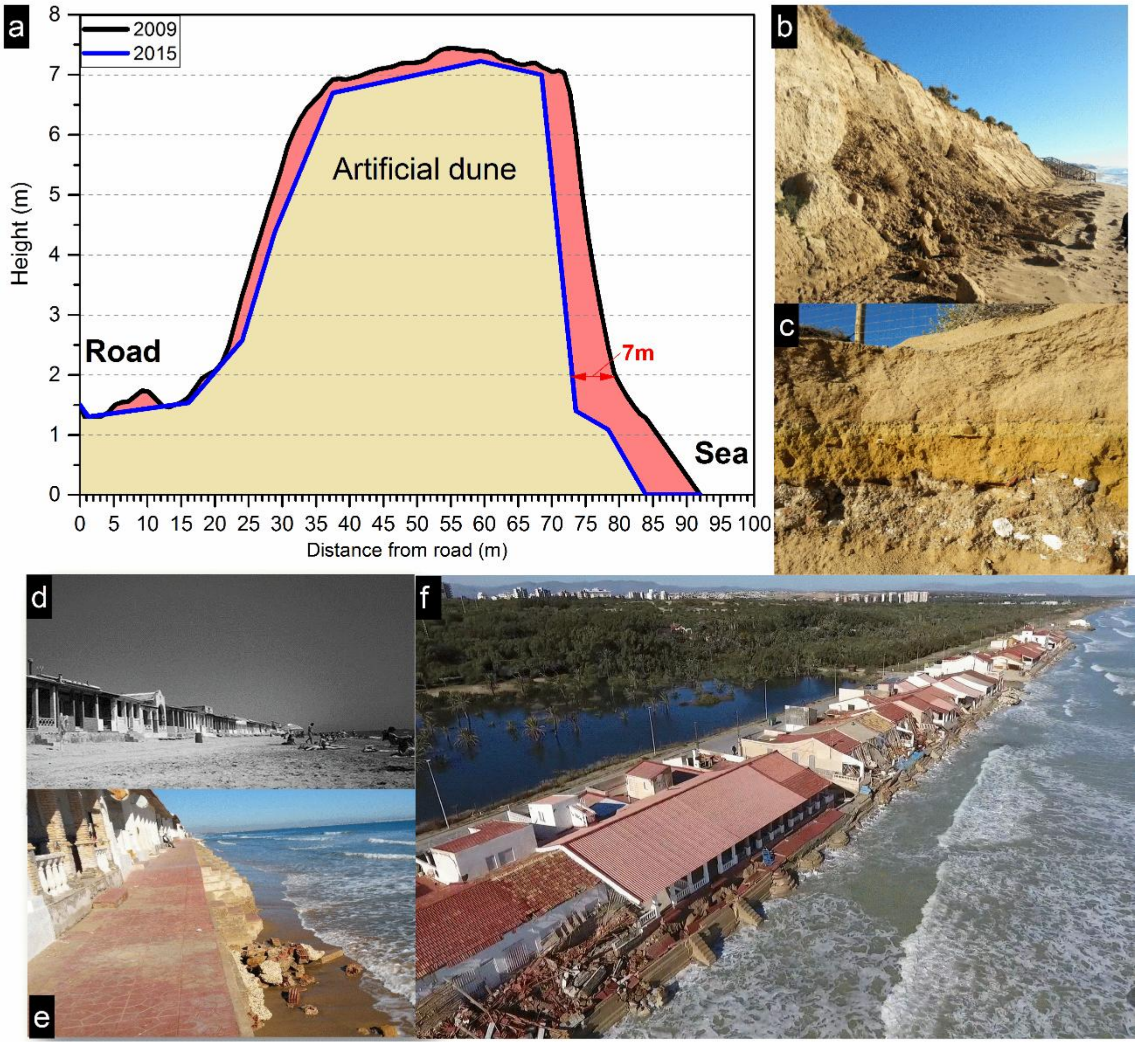


Figure 4. a) Transversal profile of the dune in front of the marina. It can be observed the seaside slope erosion of the artificial dune. **b)** Photo of this slope in Nov 2015. **c)** Detail of the material of the dune where it can be observed different layers of anthropic fillings as dredging material (silts) and construction wastes. d) Image of Babilonia beach in 1969. **e)** Same view in 2015 **f)** Aerial image of Babilonia houses affected by the storm of December 2016. It can be observed damages in the houses, the total disappearance of the beach and the reflexion of the waves.

The loss in beach width means a significant loss in beach area, of whose study it can be inferred both the longshore and cross-shore sediment transport. Thus, the results show that from 1956 to 2014 more than 250000 m^2 of coastal area have been lost due to erosion (Table 5). Analysing the data by beaches, the greatest erosion has been detected in Los Tusales beach (128000 m^2), followed by Los Viveros (64500 m^2) and Babilonia (21000 m^2). It can be also observed the 15000 m^2 of area increased due to anthropic actions in Centro beach nourishment in 1990-1992 or the 14000 m^2 of Los Viveros next to the breakwater. However, this gained area is lost totally in the following time interval, 1992-1994 (See supplementary data 4 to observe how the changes in the river mouth affected the nearby beaches). The influence of the breakwater on Los Tusales beach is evident since the sediments accumulate in that area in all the periods studied since its construction, except 1998-2002 and 2012-2014. This fact confirms that the breakwaters on the Segura river mouth has stopped the longshore transport, causing the accretion of Los Tusales beach but also an increase of the erosion on the beaches located to the south, specially Los Viveros.

The study of the sediment balance (erosion/accretion) shows clearly an important imbalance. The lost areas cannot be explained just only by the longshore transport, as the eroded areas are much greater than the areas in accretion. Thus, this loss in beach surface can be only explained by the predominance of the cross-shore sediment transport instead of the longshore transport.

Table 5. Area balance in square meters for each period.

	1956-1969	1969-1981	1981-1986	1986-1990	1990-1992	1992-1994	1994-1996	1996-1998	1998-2002	2002-2005	2005-2007	2007-2009	2009-2012	2012-2014	Total
B01_ Los Tusales	**-81694**		**-973**	**-15376**	**7337**	**3019**	**-6751**	**14357**	**-23852**	**8093**	**-2956**	**2113**	**5117**	**-36518**	**-18085**
Accretion			6237	172	8479	4745	335	14425	88	8790	1431	4417	5264		137657
Erosion	-81694		-7210	-15548	-1143	-1727	-7086	-68	-23940	-697	-4387	-2304	-147	-36518	-265742
B02_ Los Viveros	**632**	**-8962**	**3075**	**-14196**	**10470**	**-12124**	**-7953**	**2713**	**-19160**	**-3870**	**-14068**	**8037**	**-3285**	**-5870**	**-64561**
Accretion	3198	1445	4276	54	13782	800	1	4520		1142	1	8758	1969	1286	41229
Erosion	-2566	-10407	-1197	-14250	-3312	-12924	-7955	-1807	-19160	-5012	-14068	-721	-5254	-7156	-105791
B03_Babilonia	**-8580**	**4015**	**1839**	**-2853**	**4493**	**-6754**	**1236**	**3455**	**-9629**	**2638**	**-7813**	**7358**	**-1006**	**-9331**	**-20931**
Accretion	1355	4214	2215	861	5585	425	1902	3685		2973		7778	1111		32104
Erosion	-9935	-198	-377	-3715	-1091	-7179	-666	-229	-9629	-335	-7813	-418	-2117	-9331	-53035
B04_Centro	**-28533**	**15783**	**8677**	**-8216**	**14585**	**1307**	**-246**	**5266**	**-8798**	**8513**	**-5316**	**2185**	**1724**	**-14137**	**-7204**
Accretion		15783	9081	745	14953	5634	2373	5897	213	9209	944	5003	5050		74885
Erosion	-28533		-404	-8961	-368	-4327	-2616	-631	-9011	-696	-6260	-2818	-3325	-14137	-82089
B05_La Roqueta	**-8860**	**481**	**-8**	**-3373**	**4375**	**2416**	**-2259**	**4844**	**-5871**	**10940**	**-8826**	**-119**	**3128**	**-5144**	**-8276**
Accretion	1258	3164	1812	246	4637	353	649	4919	37	10940	94	1382	3559	97	36147
Erosion	-10118	-2683	-1820	-3619	-262	-937	-2907	-74	-5908		-8920	-1502	-431	-5241	-44423
B06_Moncayo	**-10765**	**-750**	**3671**	**-8330**	**8712**	**-5405**	**1258**	**12995**	**-7334**	**9695**	**-12155**	**13971**	**-1393**	**-17589**	**-13419**
Accretion	1990	4815	5063	1276	10185	2182	3121	12995	1161	10428	385	14213	1731	13	69560
Erosion	-12755	-5564	-1393	-9606	-1473	-7558	-1863		-8495	-734	-12540	-242	-3124	-17603	-82979
B07_El Campo	**4032**	**-1110**	**2940**	**-7776**	**7134**	**1098**	**418**	**2587**	**-9260**	**13682**	**-11488**	**11387**	**1201**	**-12292**	**2553**
Accretion	5434	1630	3378	899	7706	3470	2474	3783	150	13696		11387	2586	62	56656
Erosion	-1401	-2740	-439	-8676	-572	-2372	-2056	-1196	-9411	-14	-11488		-1384	-12354	-54103
B08_Les Ortigues	**-9348**	**-1442**	**9113**	**-10573**	**4620**	**2675**	**-4592**	**6323**	**-2497**	**9789**	**-7361**	**13154**	**-252**	**-19765**	**-10157**
Accretion	225	2208	9198		5102	3645	731	6419	1664	9807	231	13308	1322	8	53865
Erosion	-9573	-3650	-85	-10573	-482	-970	-5324	-95	-4160	-18	-7591	-154	-1574	-199772	-64022
Total	**-102269**	**-32862**	**28333**	**-70693**	**61726**	**-13768**	**-18890**	**52542**	**-86401**	**59480**	**-69983**	**58086**	**5235**	**-120646**	**-250080**

4.2 Sediment distribution

It is already know that the cross-shore transport causes a seaward classification of the sediment grain size (Guillén and Hoekstra, 1996; Niedoroda *et al.*, 1985; Stauble and Cialone, 1997). Our results confirms this idea, since as the depth increases the mean sediment grain size decreases and the percentage of the fine fractions rises (Figure 5). Moreover, in Babilonia beach the mean size D_{50} is higher than the nearby surroundings (the results of each transect are presented in Supplementary data 5). The wave reflection due to the houses on the beachfront could explain this phenomenon, causing greater turbulence and the displacement of the fine particles seaward to deeper locations and, thus, the sediment that stills nearshore has greater sizes. In this situation, the beach profile becomes steeper, as our results shows (Figure 6).

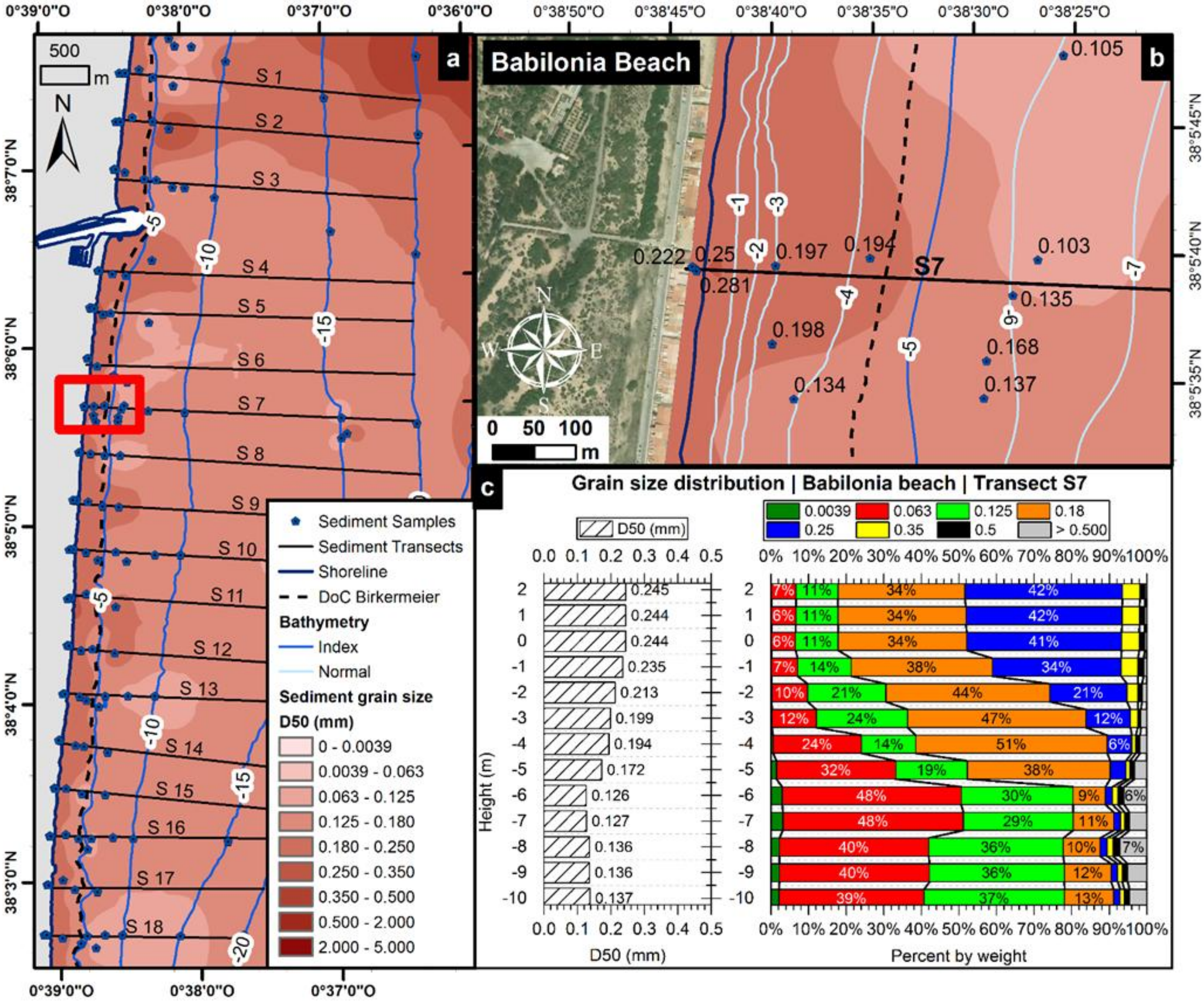
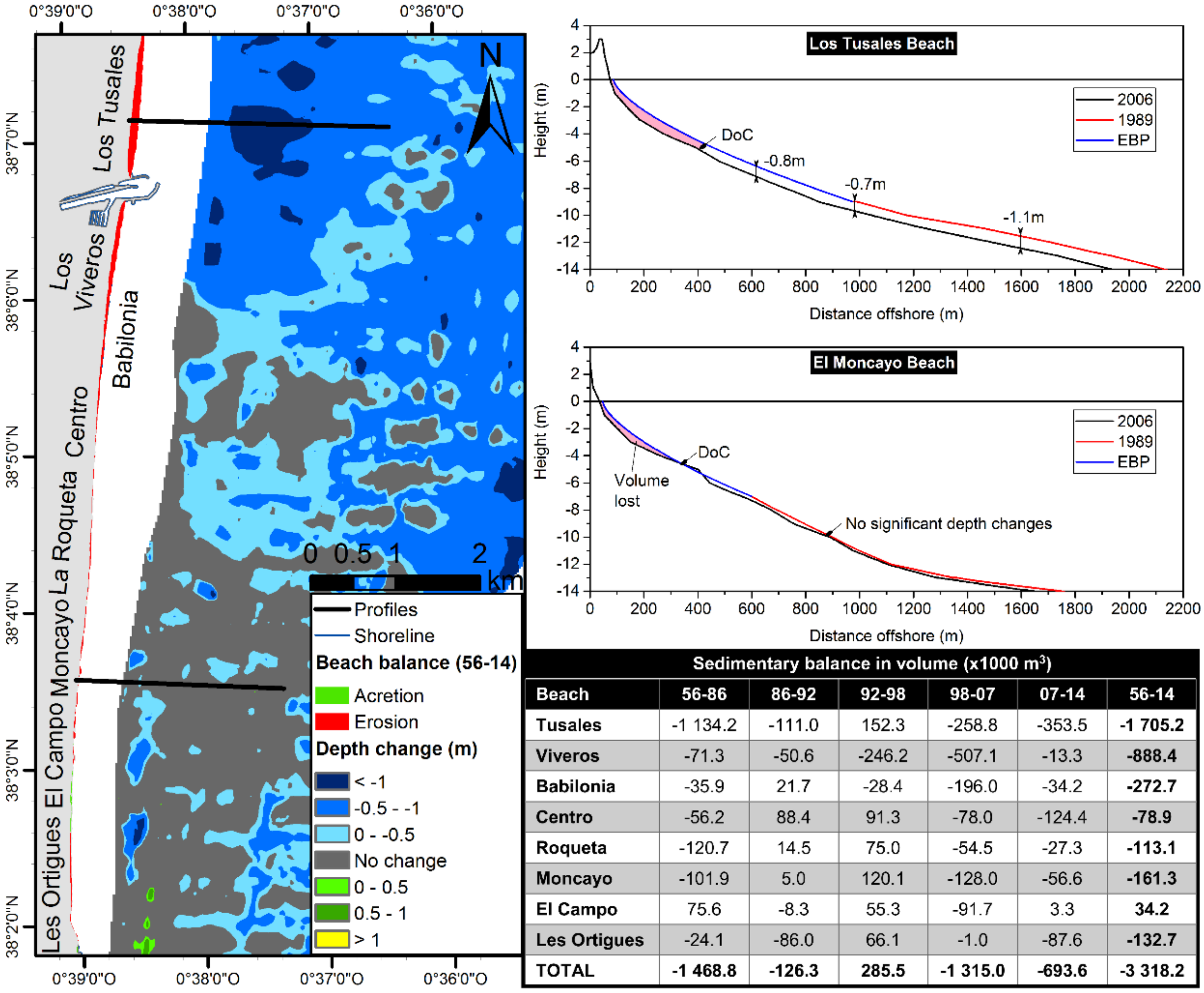


Figure 5. a) Mean sediment grain size distribution map and cross-shore transects. **b)** Detail of Babilonia beach. **c)** Example of the evolution of grain size distribution with depth.

From the study of the beach profiles and the seabed depth change, it can be noticed that in front of the Segura River mouth a significant increase in depth has occurred (Figure 6a). This increase has affected the profile morphology, becoming steeper in this area (Figure 6b and c). Comparing the profiles of the north area with the profiles of the south area, the first ones are steeper. This represents a greater volume of material lost. In the case of Los Tusales beach, for the period 1956-2014, means 1.7 million m^3 of eroded material, considering only up to the DoC. As it can be observed in its profile, a decrease of almost 1 m is detected in its extension. This has its influence on the position of the shoreline, corresponding to the area where the greater erosion has occurred. However, observing the beach profile in a stable area, such as El Moncayo beach, no significant differences in the depth seaward the DoC has been founded. The sediment transport matches the normal values of the nearshore active zone, with its erosion/accretion cycles.



Sedimentary balance in volume (x1000 m^3)						
Beach	**56-86**	**86-92**	**92-98**	**98-07**	**07-14**	**56-14**
Tusales	-1 134.2	-111.0	152.3	-258.8	-353.5	**-1 705.2**
Viveros	-71.3	-50.6	-246.2	-507.1	-13.3	**-888.4**
Babilonia	-35.9	21.7	-28.4	-196.0	-34.2	**-272.7**
Centro	-56.2	88.4	91.3	-78.0	-124.4	**-78.9**
Roqueta	-120.7	14.5	75.0	-54.5	-27.3	**-113.1**
Moncayo	-101.9	5.0	120.1	-128.0	-56.6	**-161.3**
El Campo	75.6	-8.3	55.3	-91.7	3.3	**34.2**
Les Ortigues	-24.1	-86.0	66.1	-1.0	-87.6	**-132.7**
TOTAL	**-1 468.8**	**-126.3**	**285.5**	**-1 315.0**	**-693.6**	**-3 318.2**

Figure 6. Depth change map and profile comparison. The table shows the estimated values of sediment balance for each period of study.

4.3 Influence of maritime climate on the coast

The erosion of the coast is often related to the action of the waves. In the study area, the most frequent waves come from the East with a significant wave height of 1.5 m and a probability of occurrence (frequency) of 42%. However, in the last period of time (2007-2014) there has been an increase in NE and ENE waves, with extreme events (waves exceeded twelve hours a year) that have reached 4.2 m of wave height (Figure 7c).

The direction of the average flow is N90.3°E, while the coast has an orientation of 8° with respect to North. This causes the direction of longshore sediment transport to be N-S (Figure 7a). Before 1992, the study area behaved as a unique beach 11 km long with the pivot point approximately on Centro beach. However, the construction of the new mouth of the Segura River generated a second pivot point (Figure 7b) and subsequently, after the disappearance of the beach width in Babilonia beach (2007), the houses also act as a pivot point of the shoreline. Moreover, the piers at the mouth of the Segura reach the DoC, which, together with the orientation of its mouth, causes: i) The longshore transport introduces the sediments inside the mouth, burying the entrance of the marina; and ii) The sediment is supported in the north dike, so the width of beach grows in that point, displacing the profile offshore. At present, this profile has reached its maximum support, and the new material that arrives is expelled outside the limits of the DoC, impeding its return to the coast. This interruption of longshore transport causes cross-shore transport to become more relevant. This transport is closely related to sediment size and causes the material to be ejected out of the active zone causing a further retreat in the shoreline.

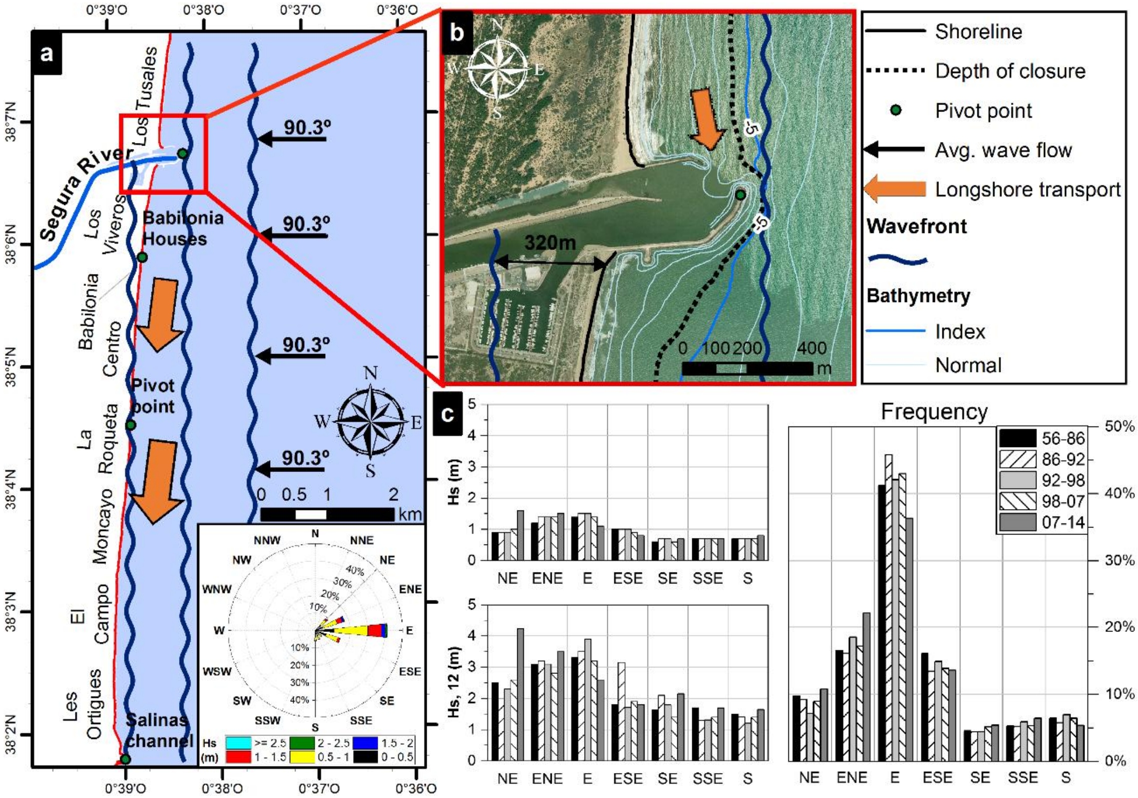
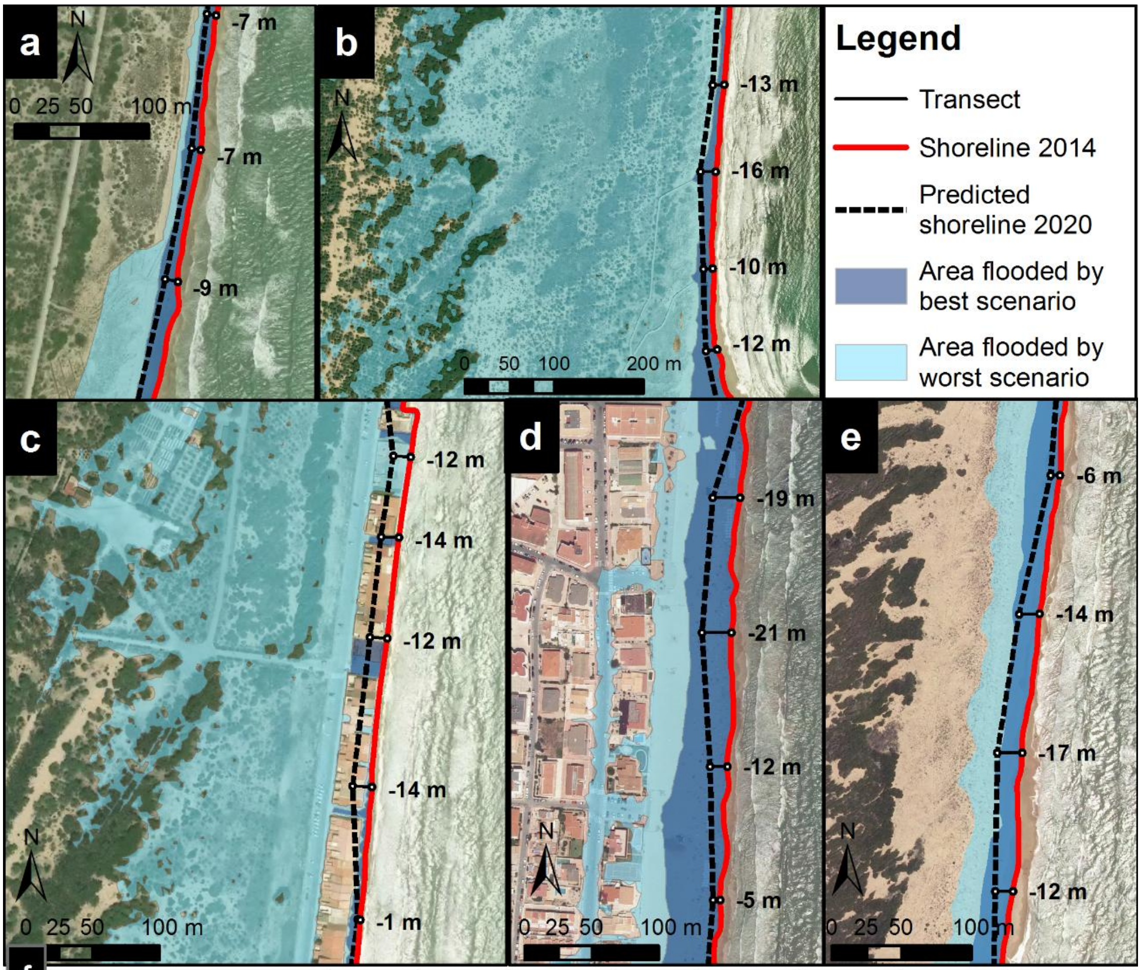


Figure 7. Wave evolution in the study area.

Finally, an estimation of the future situation (year 2020) is proposed in the study area (Figure 8), assuming: i) Demolition of the houses located on the MTPD (Babilonia beach); and ii) the same regression ratio LRR as the current one (2.5 m/yr). With these assumptions, it is observed that in the area of Tusales and Viveros the water would reach and eventually exceed the dunes, while in the area of Babilonia beach (Figure 8c) water would reach half the position currently occupied by the houses. In addition, in the current situation, there is a serious problem of flooding of the littoral zone during extreme waves. Thus, in the most unfavourable scenario (more than 5 m of flood level), the water would exceed the dunes in the area of Tusales and Viveros, penetrating much in the interior (380 m in Tusales, 60 m in Viveros, 200 m in Babilonia and 120 m in Centro). While in the most favourable case, the flood level reaches the beginning of the dune in Tusales and Viveros, and overpasses the houses and the promenade in the beaches of Babilonia and Centro.



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Method	TUSALES	VIVEROS	BABILONIA	CENTRO	ROQUETA	MONCAYO	EL CAMPO	LES ORTIGUES
Guza y Thornton (1981, 1982)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Holman y Sallenger (1985)	2.2	1.8	2.3	2.4	1.7	1.9	1.2	1.1
Resio (1987)	2.7	2.4	2.7	2.8	2.4	2.5	2.1	2.0
Nielsen y Hanslow (1991)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Douglass (1992)	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
Stockdon (2006)	2.7	2.4	2.9	2.9	2.3	2.5	1.7	1.7
GIOC (2001)	5.1	4.7	5.6	4.1	4.3	4.5	3.4	2.3

Figure 8. The red line represents the coastline in 2014, and the dashed line represents the estimated coastline in 2020. The dark blue zone shows the most favourable scenario (lower flood level), and the light blue zone is the most unfavourable scenario. **a)** Viveros beach, **b)** Tusales beach, **c)** Babilonia beach, and **d)** Centro beach.

5 DISCUSSION

Sedimentation and erosion are common problems in coastal engineering, and to understand how a beach evolves and respond to environmental changes in the study area, it is necessary to establish a historical record of the volume of material lost or gained in a relatively long period of time (Norcross *et al.*, 2002). From the analysis of the results in the study area, one of the main problems is the so-called "river-basin syndrome", which is very common all over the world (Aragonés *et al.*, 2016a; Li *et al.*, 2007; Meybeck, 2003), Which is caused by the lack of sediment supply by the Segura River as a consequence of the actions took in its channel (channelling, construction of dams, weirs, etc.). In this way, the works of the defence plan against avenues in the Segura River have caused a significant change in the dynamic behaviour of the whole coast. As can be observed (Figure 2 and Figure 3), since 1992 (last action on the riverbed), the beaches north of the mouth are much destabilized and suffer a process of permanent erosion. The area south of the mouth is characterized by a rhythmic pattern of annual alternation between erosion and accretion (Figure 2), but with a clear erosion trend except for El Campo beach (Table 5).

The greater erosion of northern beaches together with the analysis of surface variation and wave study shows a predominance of cross-shore *versus* longshore transport. Although there is a small longshore sediment transport to the southern beaches, looking for the balance between the coastline and the average flow (Miller and Dean, 2004), the southernmost beaches (Moncayo, El Campo and Les Ortigues) also have an erosive tendency (Table 5). The grain size is the one that promotes that the sediment moves shoreward or seaward in function of the infiltration/exfiltration respectively (for example Butt *et al.* (2001); Horn (2006); Masselink and Li (2001)). Thus, for a constant wave height, the smaller the slope of the beachface, the smaller the grain size, which indicates that the equilibrium profile is reached due to the transport of sediments seaward (Carvalho *et al.*, 2012; Reis and Gama, 2010). This fact is verified with the results obtained in this study where it is observed that the finer materials (0.125 mm and 0.063 mm) are positioned near and beyond the depth of closure (Figure 5) obtained according to Birkemeier (1985).

Moreover, urbanization on dune systems involves their complete destruction, reducing the sand reservoir of the beach (García-Mora *et al.*, 2001). In the study area, several actions were carried out in the dune system environment and ended up affecting the coastal littoral: i) The construction of physical barriers that interrupt the natural sedimentary cycle (piers at the mouth of the river), such as occurred at Cua Die Beach (Vietnam), where 30 m of beach width was lost in 5 years due to the reduction in sediment input due to the mining activities occurring in the channel (Viet *et al.*, 2015). ii) The settlement of buildings above the dunes, which agrees with that observed by Amaro *et al.* (2015) according to which the erosion rate in the study beach increased in the last period due to the high density of public constructions and infrastructures built on the dune zone. iii) The construction of the marina within the dune system. The impact of all these actions is not visible at first, but with the passage of time, the dune system loses its structure and disintegrates, as is happening in the dune system located on the Viveros beach (Figure 4). These changes have been corroborated from the cross-shore profiles obtained from the topographic and LIDAR data (Figure 4a), which show a partial disappearance of the dune front. This erosion is aggravated by the incidence of waves on the dune, partially composed of sandy loam from the dredging of the marina (Figure 4c), which implies a greater ease in cross-shore transport and no return to the coast, as is observed between the 1990-1992 and 1992-1996 periods (Figure 2).

Regarding the submerged profile of the beach, it is modified as a function of those coastal processes that occur over time, however, these changes vary around an average profile, which is remarkably constant over time (Aragonés *et al.*, 2016b; Dean, 1977). This homeostatic behaviour is characteristic of an equilibrium system; however, in the northern area of the study area (Tusales, Viveros and Babilonia) there has been an increase in the verticality of the profiles between the elevation 0 and -2 m (Figure 6). This increase in slope may be due to the reflection of the waves on the houses and the dunes, which has also caused a greater sediment cross-shore transport in that area increasing the thicker sizes compared to the rest of beaches (Figure 5). The increase in the verticality of the profile leads to a higher erosion ratio, which may also be due to a significant increase in depth of the seabed (Figure 6), which may be due to the presence of the Alicante Canyon that drags the material seawards to the bottom (Aragonés *et al.*, 2016a).

The presence of urbanizations very close to the coast is another important problem in the area of study, since the low altitude of these constructions causes that they are flooded and affected by the waves (Figure 4). This same problem has been observed in other areas of the world such as the Netherlands, Venice or New Orleans (Dawson and Smithers, 2010). Nevertheless, even being a problem, the houses along with the previously commented dune front are avoiding the flood of all the low zones behind them and the coastline recoil (Figure 8). The problem of these constructions currently located within the TMPD can be worsened by climate change. As can be seen in Figure 7, in the last decade there has been a significant increase in the energy of the incident wave passing from 2.5 m to 4 m of extreme wave height (NE direction). It has resulted in an increase in erosive process in the area of study (Figure 3), as it is known that the most extreme waves cause a greater erosion in the beach (Harray and Healy, 1978). Although it has not been possible to quantify the rise in sea level given the variability of results obtained by the scientific community (increase in the next 100 years from 3-9 mm/yr according to Crawford and Thomson (1999); 2-6 mm/yr according to Douglas *et al.* (2000); 5 mm/yr according to Vilibić *et al.* (2000)), it is clear that this will have serious consequences for low-lying coastal environments.

Often the solution chosen by the managers of the beaches consists of the contribution of material with the objective of recovering a given beach width. However, making these kinds of decisions without adequate technical background may generate a conflict of interest between immediate economic and tourist development and the environmental component of the area. This may lead to disappointments regarding the long-term benefit of a nourishment project, especially when visible sand losses in the restored area are much larger than the expected because of the lack of detailed studies required for interventions in environments as complex as the coastal. An example of this situation is found in the nourishment carried out in the 1990s at Centro Beach, which has not had the expected effect. Thus, if we perform an evaluation of the approximate net loss of sand produced in the study area, we find values around 3.2 million m^3 during the period from 1956 to 2014. In addition, the contribution of 400000 m^3 made in the nourishments of the Centro beach in 1988 (149836 m^3 and 7.2 m of beach width) and 1990 (247417 m^3 and 12 m of beach width) should be added. This sand dumping generated certain stability in the later periods (Figure 3). This result could have been avoided if the necessary studies had been carried out, since if the regeneration was analysed by the Abacus of James (1974) it is clearly observed that the granulometry of the borrowed sand (D_{50} = 0.228 mm) versus the native sand (D_{50} = 0.320 mm) was too thin and the nourishment will be unstable. This is corroborated by the results obtained in this study (Figure 2 and Figure 3), according to which the width gained by regeneration was lost in less than 10 years. Then, taking into account the volume of material lost in the period analysed, the cost of maintaining the position of the coastline on these beaches would have been approximately 35 M€ (assuming a cost of 10.8 €/m^3). If the anthropogenic changes were not carried out in the study area, this cost could have been 24.7 M€ if the erosion rate had been maintained at pre-1990 levels.

Therefore, it becomes clear that Integrated Coastal Zone Management is needed to solve coastal problems (Rodríguez *et al.*, 2009). Although there are tools and protocols for this, it is necessary to improve the communication of scientific information to decision makers and coastal managers (Murawski, 2007). On the one hand, scientists should seek dialogue with other actors and not only with their peers, disseminating the results of their research to identify the multiple stressors in the coastal system and provide useful and necessary information for society and decision makers. On the other hand, the scale and complexity of the studies to be carried out requires the commitment of the managers to provide the means to sustain the investigations in the medium and long term. In this sense, the technological tools like GIS can be of great help in the visualization, the understanding, the communication and the solution of the coastal problems.

6 CONCLUSIONS

Coastal erosion is dominated by three main factors: sediment supply, wave energy and the rise of the sea level. Thus, the classical analysis from the approaches of sediment transport and morphological changes made on a large scale, as simply integration in time and/or space from approaches made at a smaller scale is not valid. This work has taken into account all these factors and the influence of the anthropic actions in the study of the causes that have led to the evolution of the coast and in anticipation of the erosive potential of future storms, obtaining the following conclusions:

1. The main cause of the shoreline retreat is the lack of sediment supply of the Segura River, due to the channelization works against floods in the 1990s.
2. The erosion is not uniform along the 11 km of coastline, being more intense in the beaches located around the Segura river mouth, caused possibly by the increase in the offshore depth because of point 1.
3. Within the coastal system, beach-dunes, sediment flows can be extraordinarily large and fast. The annual loss rates of the studied area are about 0.8 m/yr, but erosion rates in the most affected areas are greater than 3.5 m/yr.
4. The littoral drift is clearly oriented towards the south, which makes the beaches farther away from the river mouth in this direction being the least eroded. Breakwaters built to protect the Segura river mouth stopped the longshore sediment transport that fed these beaches, increasing the erosion of the ones immediately located to the south of the mouth (Los Viveros and Babilonia).
5. There is a net loss of sediment related to the cross-shore transport. These sediments pass through the depth of closure and are lost offshore.
6. The grain size of the sediments decreases with the depth, noting that the dumping of fine material to the beach makes that it disappears in a relatively short time.
7. The houses of Babilonia beach and the dunes are acting as a dike, which has prevented the sea from flooding inland areas, so avoiding a further retreat of the shoreline.

8. Beach erosion is an expensive problem, aggravated by the continued invasion of the urbanised areas. Currently, about 80 houses are located within the maritime-terrestrial public domain, already destroyed or at high risk of being in the near future.
9. The wave height in the study area has increased in the last analysed period from 2.5 m to 4 m for NE direction. Higher waves cause more erosion on the beach.

This research reveals the complexity of the study area located in a place with a high environmental value, which has been affected by multiple pressures, both natural (waves, coastal dynamics) and human (tourism, buildings, breakwaters). Therefore, in order to make the appropriate decisions for the conservation and/or actuation within the coastal system, it is necessary a complete an historical knowledge of all those factors. This knowledge, as well as an adequate communication between the decision-makers and the coastal engineers, are key elements to achieve positive results in the medium and long term.

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