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**Storm Impacts on a Coupled Human-Natural Coastal System: Resilience of
Developed Coasts.**

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Abstract

Human occupation of and alteration of the world's coast has transformed large stretches of it into Coupled Human-Natural Systems (CHANS) in which humans both influence and are influenced by coastal evolution. In such systems, human activity is as critical on natural resilience as processes and sediment supply derived from the natural setting. Pre- and post-storm observations of these interactions on the intensively developed Atlantic coast of the Gulf of Cádiz, (Spain and Portugal) are examined to determine natural and engineering resilience. Three case studies are used in three CHANS, showing that human interventions interact in complex ways with the natural system influencing post-storm recovery. In natural coasts, storm impact is assessed in terms of geomorphological response; on developed coasts, it is quantified as damage to infrastructure or loss of amenity. Preparedness, availability of resources, choice of response and the speed at which human agencies respond affect resilience for post-storm beach behaviour. Results show in some sites natural resilience adjusting by post-storm sediment transfers and an equilibrium morphology that may differ from pre-storm morphology; engineering resilience ensured that CHANS regained their pre-storm human infrastructure and amenity. Their management requires a fundamentally different approach to that of natural coastlines. The current immature stage of understanding of CHANS (especially the human preparedness and response components) is illustrated by the case studies presented where short-term political decisions and reactions to storms play a strong role in post-storm response. The nature and extent of many developed coasts as CHANS is slowly becoming more widely acknowledged, but to increase natural resilience and decrease vulnerability in CHANS better planning is required so that future storms are anticipated and when they happen, pre-planned human response actions are activated. Storms are an integral and inevitable element in the behaviour of coastal CHANS, not a disaster or emergency.

Key Words

CHANS; Gulf of Cadiz; Storm impact; Natural Resilience; Engineering Resilience;

Graphical Abstract

1 Introduction

Connections between human and natural systems are often implicit in discussions of coastal environmental management (e.g. Nordstrom, 2004; McNamara et al., 2011). Indeed, many beaches and coasts have been transformed by humans to the extent that, in many locations, human activity equals or exceeds natural processes in importance as a driver of coastal change, especially at annual to decadal timescales. Such beaches can be viewed as coupled human-natural systems (CHANS) (Polhill and Gotts, 2009; Quinn and Wood, 2017) whose functioning differs markedly from their original natural behaviour (Lazarus et al., 2016). This coupling affects not only the coastal strip itself but the terrestrial hinterland and nearshore environments that control sediment budgets of beaches (Cooper and Jackson, 2019). How these coastal CHANS operate and how their resilience can be assessed has not been sufficiently studied (Lazarus, 2017). Yet, with the increased human population at the coast (Navas et al., 2012; Neuman et al., 2015) and the intensification of activity there that involves built infrastructure and often associated sea defences (whether hard or soft), understanding the response of such systems to slow onset impacts such as sea-level rise, and episodic and immediate impacts such as storms, has become an important societal need. Detailed studies are needed of such systems if they are to be properly understood at societally relevant time and space scales.

Much of the Atlantic and Mediterranean coast of Europe has been intensively modified by human activity during the past half century (Malvarez, 2012). This has often been to facilitate economic activity associated with tourism in its many current formats (Navas, 1996; Malvarez & Navas, 2015). It has long been recognized that such infrastructure and activities are at risk from (and pose a risk to) coastal morphological change (Cooper & McKenna, 2008; Navas et al., 2017) and consequently, a range of management activities have been implemented to maintain the shoreline's position and tourism-related facilities (including the beach area itself). While these activities are traditionally viewed as human interventions in a natural system, they have evolved

93 to such an extent that some (Lazarus, 2017) maintain that they now form an integral part of a
94 coupled human-natural coastal system that is characteristic of (and a response to) conditions
95 prevailing in the Anthropocene. In natural beaches, changes in morphology are driven by
96 dynamic forces (waves, currents), operating on a particular volume of sediment, within the
97 confines of the surrounding geological framework and position of sea level (e.g. Orford et al.,
98 1999; Cooper et al., 2004; Pilkey & Cooper, 2004). Changes in morphology thus reflect a natural
99 trend toward equilibrium via entropy. Although these processes and forces remain also drivers
100 and responses in developed beach systems, morphological change is assessed from the degree
101 to which it impacts human activities. Human responses to change thus become an integral
102 component of the beach and nearshore system (Cooper & Navas, 2004). The nature and
103 efficiency of beach management arrangements, thus, is coupled with natural processes as a vital
104 component of coastal resilience. However, as natural systems are so immensely distorted by
105 human action natural and built environments co-exist in a blurred and complicated definition of
106 resilience (Masselink and Lazarus, 2019). High wave energy events (storms and tsunami) on the
107 open coast can cause immediate and significant coastal morphological change. The typical
108 response to storms on natural coasts involves sediment redistribution either longshore, offshore
109 via rip currents and/or storm return surge (Loureiro et al., 2012), or onshore via overwash (Matias
110 et al., 2010). In post-storm conditions, beach gradients and volumes generally increase as
111 sediment is returned from offshore and the beach is restored under fairweather conditions
112 (Maspataud et al., 2009). The shoreline may stabilize in a more landward position if there has
113 been net sediment loss, especially in cases of overwash losses, which cannot easily return to the
114 foreshore (Armaroli et al., 2012). If the coastal system has been intensively modified by human

activity the baseline to which (or from which) the morphosedimentary system needs to be adjusted requires human intervention, thus defining a CHANS.

Inherent in the functioning of the complex interactions of coastal environments is its “ecological resilience”. The concept infers that the resilience of a given natural (eco)system can be regarded as the ability of a system to persist in a particular stable domain by maintaining the key structures and processes that characterise that stable domain (Francis, 2013). This implies an adaptive capacity of the system to re-organise in face of disturbance while maintaining key structures and processes. In a coastal setting, this stable domain can shift in position (e.g. by roll-over, retreat/advance) and retain all the key structures and functioning. This contrasts with the definition of “engineering resilience” (sometimes also called recovery) where the stable domain (and functions) need to be restored in the same position (Adger et al., 2005; Francis, 2013; Flood & Schechtman, 2014). Both types are key concepts in the discussion of the findings of this article, given that the combined measure of ecological and engineering resilience ties well with determining the potential performance of the CHANS and its durability. However, to adapt the concept to the purely geomorphological study of the coastal system, in this paper the term used is natural resilience since no biological components are included.

In this paper, the response of three coastal CHANS of the Atlantic coast of the Iberian Peninsula to an extreme storm (Storm Emma of 2018) is documented. The impacts of the storm and the subsequent recovery (especially emphasizing the human intervention) together provide an insight into the behavior of developed coastal systems worldwide that can be contrasted with the better-known wholly natural systems. The efficiency of governance and administrative arrangements that facilitate coastal management are potentially critical components of developed coastal systems. Their operation before, during and after extreme events tests them and provides insights

138 into their role in coastal resilience. Consequently, these arrangements are scrutinized in the study
139 sites in order to derive generic insights.

140 **2 Study Sites**

141 The Gulf of Cádiz, in the Southwest of the Iberian Peninsula includes the South of the Algarve
142 and the Atlantic Andalusian coast to Cabo Trafalgar in Spain, close to the Strait of Gibraltar. With
143 a general exposure Southeast - South – Southwest, it represents a large coastal cell where
144 sediment transport is generally homogeneous in the direction of the dominant wave and wind
145 direction from Southwest sectors providing a West to East trend along the 150 kilometres from
146 Faro, in Portugal to Cádiz, in Spain (Anfuso et al., 2015). Three sites located in the west (Faro),
147 central (La Antilla) and eastern (Camposoto) sectors of the cell were selected to characterise both
148 the natural and anthropogenic response of beaches to a high energy event that affected
149 infrastructure and property and stimulated human intervention (Figure 1).

Figure 1: Location of the study sites in SW Atlantic Europe.

150

151 The study sites have several aspects in common: a high level of urbanisation, the presence of
 152 sea defences and a very long history of direct occupation by humans. The beach
 153 geomorphological response and the human element are interlinked in various ways. The direct
 154 action of humans may not be easily identified on the coastline but from a broader influence of that
 155 has reshaped various key components of the coastal system. Such is the sediment supply and
 156 direct interruption of littoral drift. Sediment supply into the coastal cells in these latitudes is often
 157 almost entirely dependent on fluvial sources. The catchments feeding the system in natural
 158 conditions, with an approximate area of the combined river basins of some 134460 km² have
 159 been severely distorted by human action. Along with the many minor impoundments impeding
 160 the natural flow of water and sediments, in the Spanish side of the watershed alone there are 57
 161 major dams managed directly by National and/or Regional authorities; but the largest of all is the
 162 Alqueva Dam. The recent strong river flow regulation has limited the maximum river discharges

163 to 2,500 m³/s. Such vanishing of unusually high discharge events has affected both the short-
164 term and long-term morphodynamics of the Guadiana ebb-tidal delta (Dias et al, 2004). Likewise,
165 the longshore sediment transport is significantly interrupted by 5 major jetties along the coastal

cell (Vilamoura, Guadiana, Piedras, Huelva and Mazagon) with an average length of 2 kilometers each.

Thus, all three sites are located in a landscape that has long been modified by human input. La Antilla and Camposoto beaches have been nourished directly and Faro has been the subject of updrift preventive nourishment. Figure 2 illustrates the landscapes of the three sites.

Figure 2: Landscapes of the three sites. A: Faro, B: La Antilla and C: Camposoto. Lines with measurements across beachface indicate a graphical scale. Images from Google Earth.

2.1. Ria Formosa, Faro.

The Ria Formosa barrier island system is roughly triangular in shape, with a shoreline length of about 55 km. It comprises five islands and two peninsulas, separated by six tidal inlets. The barrier system is extremely dynamic as a result of tidal inlet evolution, shoreline evolution, longshore drift, overwash processes, dune formation, backbarrier processes and artificial

nourishment actions (Ferreira et al., 2016a). Tides in the area are semi-diurnal, with average ranges of 2.8 m and 1.3 m for spring and neap tides, respectively. Maximum ranges of 3.5 m can be reached during spring tides. Wave energy is moderate with an average annual offshore significant wave height of 1.0 m and an average peak period of 8.2 s. Dominant incident waves are from the W–SW (Costa et al., 2001). Storms (events with significant wave heights greater than 3 m) from SW are on average more energetic and frequent than SE storms (Costa et al., 2001; Almeida et al., 2011). Net littoral drift and longshore currents are typically from West to East, and their magnitudes vary according to authors (Vila-Concejo et al., 2006), ranging from $6 \times 10^3 \text{ m}^3/\text{yr}$ (Andrade, 1990) up to $3 \times 10^5 \text{ m}^3/\text{yr}$ (Bettencourt, 1994). Faro Beach is located at Ancão Peninsula, the westernmost barrier of the system. It is exposed to the W–SW dominant waves and is relatively protected from E–SE conditions. The central part of Faro Beach is characterized by a steep beach-face with an average slope of around 0.1, varying from 0.06 to 0.15 (Vousdoukas et al., 2011), that can be classified as ‘reflective’. However, during energetic winter events the beachface tends to be more intermediate (Vousdoukas et al., 2012). Sediments are medium to very coarse sand with a mean grain size of about 0.6 mm (Achab et al., 2014). The western part of Ancão Peninsula is characterised by high foredunes (up to 9 m above Mean Sea Level -MSL-) with blowouts and dune bluffs; the eastern part is more dynamic with lower (less than 6.5 m above MSL) and wider foredunes. The oceanic beach is generally narrow and the peninsula width ranges from 65 m to 280 m. A beach berm (sometimes two) is usually present, except after energetic storms, having variable width (from less than 15 m to more than 40 m).

The dunes within the central part of Faro Beach were replaced by human occupation such as infrastructure (parking lots and roads) and houses. Hence, this part of the oceanfront is often overwashed during spring tides and storms with long period swell waves (Almeida et al., 2012). Aeolian transport regularly causes the burial of roads and house yards, whereas overwash has caused property damage and barrier breaching. Likewise, foredune erosion leads to damage and

destruction of houses and roads located on the shorefront. Faro Beach is the most urbanised and exposed area of the barrier island system with a large number of houses and infrastructure (Ferreira et al., 2016b).

In terms of management, the urban development at Faro Beach occupies the Portuguese maritime public domain from 1956 and is thus under the direct jurisdiction of the Faro Council. Thus, at Faro Beach all houses, roads, concessions and infrastructures, as well as any coastal management interventions, are the responsibility of the municipality. However, the remaining surrounding extensive areas (up and downdrift) are managed by the Ria Formosa Natural Park and the National Portuguese Environment Agency. Therefore, for the rest of the Ancão Peninsula the managers are Regional and National authorities working on the principles of natural conservation rather than the management of a developed coastal system (as carried out when urban planning is in place). A riprap seawall was placed to protect houses and infrastructure after major storms in early 1990's and afterwards. The most relevant recent human interventions have been updrift and include a succession of beach nourishment schemes performed between 1998 and 2010, with the placement of more than $2.2 \times 10^6 \text{ m}^3$ of sand (Ferreira & Matias, 2013; Pinto et al., 2018). To the East (downdrift) the coastal management action has mostly involved the relocation of the Ancão Inlet by dredging (Vila-Concejo et al., 2004; Popesso et al., 2016). The municipality has a detailed plan for Faro Beach that includes house demolition at the front dune, dune rebuilding, beach nourishment and restriction of vehicles and traffic. That plan has not yet been implemented and alternative plans may rise up in the future.

2.2. La Antilla

The La Antilla beach is a 5 km-long stretch of south-facing coastline in the province of Huelva, Spain (Figure 1 and 2). It is a dynamic coastal system, with significant changes in morphology to the barrier islands and spit system that forms part of a large-scale cell between the Guadiana and

226 Tinto-Odiél river mouths. The barriers and spits are composed of medium-fine sand and enclose
227 large lagoons and marshes between the mainland cliffs and the sandy shoreline.

228 The dominant wind and wave direction are from SW. Although the wave energy regime is low
229 (75% of H_s is smaller than 0.5 m) during Atlantic storm wave height exceeds 1.5 m. Mean tidal
230 range is 2.10 m, varying between 0.70 m at smallest Neap tide and 3.85 m during largest Spring
231 tides (Morales et al, 2006). Given the influence of SW wind and wave approach and the south
232 exposure, littoral drift is intense and mostly unidirectional to the East at La Antilla. Estimates range
233 from $1.8 \times 10^5 \text{ m}^3/\text{yr}$ (Cuenca, 1991) to $3 \times 10^5 \text{ m}^3/\text{yr}$ (CEEPYC, 1990). However, wave refraction
234 produces a longshore drift reversal on the eastern side of the mouths of the main rivers (Morales
235 et al., 2004).

236 In terms of morphodynamic states, La Antilla beach tends towards dissipative but their exposure
237 to the south (i.e. at a 45-degree angle to prevailing wave/wind direction) influences changes
238 towards intermediate states when waves are not dominated by swell types. Undeveloped sections
239 of the beach are flanked by dunes. These dunes are 500 meters wide on average and illustrate
240 the abundance of sediment supply that once fed the littoral system. To the east, dunes give way
241 to a prominent drift aligned feature of El Rompido, a 12 kilometer spit whose growth rate of 30-60
242 m/yr from 1940s to 1980s has now reduced to 8 m/yr through sediment starvation (Ojeda &
243 Vallejo, 1995).

244 La Antilla, as a settlement and recreational summer enclave, originates from small scale fishing
245 around the 13th century and because of its “remote” location in relation to the main activity centres
246 in Seville, remained undeveloped in terms of human activities other than large public forestry
247 activities (Jurado Almonte, 1992). Only during the second half of the 20th century did urbanization
248 occur in La Antilla. The area was not favoured during the first wave of Government-backed tourism
249 development of the 1960 (Ley 197/1963, Zonas y Centros de Interés Turístico Nacional) by which

4 activity centres had been targeted in along the coast of Huelva. Thus, infrastructure and attention from officials was never established. This gave rise to *ad hoc* and somewhat spontaneous development during various phases. The settlement developed greatly during the 1980s as a consequence of improved road access from Seville. It is now a second home coastal town with heavily seasonal occupation.

In terms of management structure, the coastal strip delineated beyond private property is legally defined as the public domain throughout Spain through the Shores Act (MAAMA, 2013), in which there can be no private ownership, and where ownership and management rests with the National Government. The public zone is regulated at province level by “Demarcación de Costas”, Provincial offices whose authority derives from the National Ministry for the Environment (currently known as Ministry for Ecological Transition -MET-). Business concessions, however, for example to restaurants, are directly managed by the Municipal government (the Municipality). Then, depending on planning zone status (i.e. urban, development or non-development land) a buffer of the municipal land plan up to 500 meters exists in which there are several areas and various restrictions to private ownership. Although restrictions are very rigorous nearer the public zone these get more moderate away from the sea. However, there are many instances of unplanned and thus unlicensed constructions. This is the case in a section of La Antilla, where an entire row of houses that were built within the public land are in the process of being ‘normalized’ (brought into the legal framework) by *ad hoc* planning instruments. The aim is to guarantee the protection of the public land as to ensure the right of the citizens to the integrity and access to the sea and shores. Therefore, storm damage to the beach may affect the National Government interests and the private concessions given by the municipality to business established on public land. If damage extends beyond the actual beach and affects infrastructure, then the Regional and

Municipal Government may also be involved (as sewerage, storm drains and roads are managed at municipal and/or Regional levels).

A recurrent erosion problem at La Antilla threatens infrastructure and nourishment or other management actions have been proposed (MTE, 2018). An attempt to replenish the length of the urbanized beach was dropped in 2016 because the results of the beach material analyses carried out in the possible offshore extraction areas showed that the material exceeded national limits for Mercury and organic matter (MTE, 2018).

2.3. Camposoto

Camposoto is located in the southern sector of the Bay of Cádiz, in the municipality of San Fernando (Figure 1 and 2). It forms the northern sector of a NNW-SSE oriented spit that extends over 5 km and is composed of quartz-rich sandy beaches, dunes, and saltmarshes of high ecological value. Up to 1980s the area was used as a military firing range. However, military operations ceased during that decade and, because of its natural state and limited degree of development, it was included in the Bay of Cádiz Natural Park, created in 1989. Under this designation, natural as well as cultural elements have been preserved (such as the long-established salt pan structures that date back to Roman times and which have now been restored). It is an important recreational beach on which recreational facilities are provided. It has been awarded blue flag status since 2000. The area also presents economic and touristic interest and hence some zones, like the Northern sector of the spit, are partially anthropic. In this regard, the dune ridge is backed by an artificial channel that supplies water to several fish farms located inland. In addition, the area includes a road located 150 m landward of the high water mark and behind a mobile and partly vegetated dune system. There is also a parking lot, and several

wooden paths that give access to the beach. Other facilities are installed and removed seasonally (e.g. bars, showers, etc.), according to the demands of tourism and recreation.

The partly vegetated dunes form a foredune ridge with some small intradune wet depressions. In general, the dunes are lower and narrower in the Northern sector than in the South (5 and 7 m, respectively). The foredune is interrupted by several washover fans, which increase in number and decrease in size to the South.

Since waves rarely exceed 1 m height, this stretch of coast is classified as a low-energy area (Benavente et al., 2013). The most energetic storms typically approach from the W and SW during the winter, associated with Atlantic low-pressure systems that can increase wave heights up to 4 m (Del Río et al., 2013). Tides are semidiurnal and mesotidal, with a Mean Tidal Range (MTR) of 2.18 m (Benavente et al., 2000). The dominant beach state is intermediate-dissipative with seasonal oscillations. Distance from the nearest fluvial sediment supply and the impacts of human occupation have caused a chronic sediment deficit and significant vulnerability to storm waves, which produce severe erosion every year (Benavente et al., 2002). Also, little longshore drift comes from the north as it is interrupted by a rocky outcrop. As a consequence, to protect the road and provide recreational beach space, Camposoto beach has been repeatedly nourished (as in 1998, 2010, and 2015). Despite such interventions, even after the second nourishment the spit was retreating at an average rate of 1 m/year.

In a broad sense, management of Camposoto beach follows the same structure as in La Antilla, as defined in the Spanish Shores Act (MAAMA, 2013). However, as a substantial difference with respect to La Antilla beach, Camposoto beach is included within a designated Natural Protected Area, the Bay of Cádiz Natural Park, which is managed by the regional network of Andalusian Natural Parks (RENPA -Red de Espacios Naturales Protegidos de Andalucía-). Management practices in the beach and dunes of the area are in this case agreed between the National and

the RENPA Regional institutions. Specific interventions for maintaining beach sediment volume and elementary dune reconstruction are typical tasks of the Demarcación de Costas via specific agreements that deal with restoration or maintenance of the dune system (Sanjaume & Gracia, 2011). The Regional Government (RENPA) focuses its attention on the vegetation and fauna, maintenance of wooden access paths to prevent trampling of dune plants, installation of a peripheral fence when needed, etc. After Emma both institutions rapidly agreed to establish an Inter-Agency board for management of the emergency in order to distribute their roles and minimize the damage as soon as possible (Diario Información, 2019).

3 Materials and Methods

The goal in this paper is to integrate a detailed geomorphological examination of the signature of an extreme energy event (very low depression and associated extreme weather during storm Emma), the reaction from management as part of the recovery process in combination with natural beach resources in what is demonstrably a CHANS. Therefore, this methodology section illustrates (2.1) how authors have studied the driving forces of the meteorological event, (2.2) how they have measured the geomorphological reaction of the beach and dune systems and (2.3) how the concept of resilience is tackled to help understanding the findings in the light of a conceptual model that illustrate through system's resilience the performance of the three sites.

3.1 Storm Emma meteorology

Emma storm (28 February to 3 March 2018) was formed SW of the Iberian Peninsula and had a direction similar to some of the most energetic and devastating historical storms in the area (i.e. the 1941 windstorm and Xynthia in 2010; see Garnier et al., 2018). Hindcast data in the study area provided by the Spanish Port Authority (Figure 3) shows that the maximum Hs during the storm was 6.9 m, with an associated peak period of 13.3 s. The wave direction during the storm varied between 210° and 240° with an average direction of 230°. The maximum Hs corresponds

to an estimated return period of about 16 years (using the values expressed at Pires, 1998 for Faro Beach). Its coincident occurrence with spring tides and the existence of a considerable storm surge (maximum values of about 0.6 m at Huelva tide gauge), contributed to a total water level of about 2.1 m above mean sea level, which corresponds to a water level return period on the order of 6–7 years, according to Carrasco et al., (2012).

Figure 3. Record of physical variables during the onset of Emma storm. Deep water wave data from SIMAR 6012036 managed by Puertos del Estado, Ministry for Development. H_0 , significant wave height in meters; Tide in meters; T_p , peak period in sec; W_{aDir} , wave approaching direction, in grades from the North; W_{iVel} , wind speed in m/sec; W_{iDir} , wind blowing direction, in degrees from North. Data is applicable to three study sites.

Due to the interdependency of storm surge and H_s in the Gulf of Cádiz (Almeida et al., 2012; Plomaritis et al., 2015), it can be assumed that the return period of the storm is mainly controlled by the wave height. However, previous research has shown that the storm impact is highly

dependent on the timing of the storm in relation to the tidal stage (Plomaritis et al., 2018) and thus the occurrence of high spring tides during the storm peak contributed to enhanced storm effects.

3.2 Geomorphological Beach surveys

At Faro Beach a short-term beach monitoring program (about 3 months) was defined after the storm alert, including a first survey just before the storm (26 Feb 2018), another at the end of the storm (02 Mar 2018) and four during the recovery period (8 Mar 2018, 6 and 20 Apr 2018, 17 May 2018). Five beach profiles, distributed along circa 2 km alongshore, were surveyed during low tide, using a Real Time Kinematic Global Navigation Satellite System, at 1 Hz. These profiles included the entire occupied area of Faro Beach. The eroded volumes (in m³/m) were computed by comparing the pre and post storm profiles and taking as lower limit 1 m MSL, since due to wave runup and tidal conditions it was not always possible to have data below this elevation. This results in a slight minimization of the total computed erosion/recovery volumes, for most profiles, although comparable since the same reference level was always used.

La Antilla beach was visited right after Emma storm and baseline volumes were established from position of shoreline in normal conditions that the beach exhibited up to the date of the storm as interpreted from interoperable orthophotographs from REDIAM (Red de Información Ambiental, Regional Ministry for the Environment of Andalusia). Oblique aerial footage from drone showed how surge affected the entire beach face as a surf zone. Subsequent post storm visits enabled volumes to be measured using a DJI Inspire 1 Remotely Piloted Aircraft (RPA) equipped with 4K ZENMUSE X3 camera for photogrammetry. Methodologies based on RPA for topographic measurements are becoming more widely used and efficient (e.g. Mancini et al, 2013; Bañón et al, 2019). In La Antilla some 185 images were combined using Pix4D to develop a Digital Elevation Model with a theoretical pixel size in the ground of around 4 cm. Overlap was established at 80-70 % front and side respectively. No Ground Control Points (GCP) were added for georeferencing

but RMS stayed relatively low ($X=2.37$ and $Y=2.73$ cms). Given that absolute coordinates were not needed and the relevant precision was necessary for local topography, elevation precision was tested at temporary benchmarks yielding an error in Z of an averaged 5 cm. Details of methodology used in La Antilla and Camposoto sites by the authors is highlighted in table 1.

The third site, Camposoto, was surveyed by means of an RPA-based monitoring program that already started in the area back in January 2017. The pre-storm Emma surveys were performed on the 14 December 2017 and 19 Jan 2018 for the Northern and Southern sectors of the beach, respectively, while the post-storm surveys were performed in both areas the 07 March 2018. The flights were planned with 85-75 % of front and side image overlap and for obtaining an image pixel size in the ground of around 2.5 cm. A 24 Mpx Sony Alpha 7 Full frame sensor RGB camera mounted on a FV-8 Atyges octocopter was used for acquiring images of the Northern sector, whilst a DJI Phantom 3 quadcopter with an integrated 12 Mpx camera was used in the Southern sector. GCP were uniformly spread and measured in the field with an RTK-DGPS in order to geoposition the images and the subsequent Digital Elevation Models (DEMs) and orthomosaics. The latter were obtained from image processing using Structure from Motion (SfM) algorithms in Pix4D software. A more detailed description of the methodology can be found in Talavera et al. (2018) and main highlights are shown in table 1. No drone-based surveys after March 2018 could be undertaken due to a complete cut-off of the road access in the area derived from an intervention that was already planned in the study site long before the storm Emma alert. Instead, several beach profiles with spacing of approximately 200 m were surveyed on 10 July 2018 using an RTK-DGPS in order to check for possible natural recovery signs. The eroded and accreted sand volumes were estimated by computing DoDs (DEMs of difference) between the pre-and post-storm surveys using Geomorphic Change Detection software (GCD) Add-in in ArcMap.

Lastly, information about the recovery of the system was analysed by comparing profiles extracted from the pre-storm DEMs with those measured in July 2018.

Table 1: details of flight characteristics for RPA surveys in Antilla and Camposoto

Flight characteristics	Drone surveys in La Antilla	Drone surveys in Camposoto			
	Post-storm	Pre-storm		Post-storm	
	Combined area	Northern area	Southern area	Northern area	Southern area
Surface area surveyed (km ²)	0.210	0.2362	0.288	0.2574	0.3516
Nº GCPs used	N/A	37	30	32	34
Flying altitude (m)	90	95	60	95	60
UAS models	DJI Inspire 1 V2	Atyges FV-8	DJI Phantom 3 Pro	Atyges FV-8	DJI Phantom 3 Pro
Camera models	Zenmuse X3	Sony Alpha 7	Integrated Sony EXMOR	Sony Alpha 7	Integrated Sony EXMOR
Image resolution (Mpx)	12.4	24	12.4	24	12.4
Horizontal/vertical FOV (m)	(Diagonal) 94 deg	121/81	102/77	121/81	102/77
CMOS sensor	Yes	Yes	Yes	Yes	Yes
Nº Images	185	430	1183	531	1320
RSME in XY/Z (cm)	2.73/5	3.3/8	3.9/10	1.2/8	4.9/10
GSD (cm)	2	2	2.5	2	2.5
Image processing software	Pix4D				

3.3 Natural and Engineering Resilience

The methodology proposed to assess resilience in this paper follows the principles shared by other authors who indicate that resilience can be defined as *'the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same functions, structure, identity and feedbacks'* (Scheffer and Carpenter, 2003; Walker et al., 2004 Folke, 2006; Flood and Schechtman, 2014; Kombiadou et al, 2020).

The concept used here for assessing or measuring resilience follows Kombiadou et al, 2020. A fundamental principle is that the state of resilience can be represented in a Basin of Attraction

(BoA) model where three dimensions are used: they are related to the position of the system within the shape of the BoA (a, b and c) (Gunderson et al., 2009; Kombiadou et al., 2020). Figure 4 illustrates resilience concepts.

Figure 4: A) key concepts in the Basin of Attraction model; B Concept of Engineering resilience where the system state should not leave the predicted latitude and C) open boundary basins in the ecological (natural) resilience model. After Kombiadou, et al. "Towards assessing the resilience of complex coastal systems: examples from Ria Formosa (South Portugal)." *Journal of Coastal Research* 85 (2018): 646-650

Expressed in relation to usual description for wave geometry, (a) Latitude is the wave length of the BoA and indicates how much the system is able to change irreversibly; (b) Resistance is the wave height of BoA and depicts the amplitude of changing range prior to stepping to another "sine"; (c) Precariousness is the position of the system state in relation to a threshold, a point of no return as the system enters a new BoA. In this paper, the three dimensions of the BoA are related with the measured destabilisation of the beach morphology, which should have been in long term equilibrium state at the time of Emma hit. The measure of restoration of the system by natural or assisted "engineering" depicts its ability to recover and stay in the same state and/or position. It is understood that the natural state and position of the system prior to Emma should be the long term state and position and that any significant change in beach profile and, more

specifically, shift in position landwards of the entire system (such as those illustrated in overwash) imply natural resilience “moving” into a new BoA.

4 Results

4.1. Storm erosion and post-storm recovery

At Faro Beach, Emma storm caused the total ablation of the beach berm and cut a scarp of more than 2m-high along the entire study area (Figure 5a), exposing the existing seawall and destroying some infrastructure (e.g. seafront promenade, walls). The volume eroded above 1 m MSL ranged from 51.6 m³/m to 60.3 m³/m, with an average value of 56.3 m³/m, which for the 2 km surveyed gives more than 100,000 m³ of sand removed from the upper beach. The differences in erosion at the measured profiles are relatively small along the studied area. Most of this sediment was lost to the submerged beach (no measurements) where it formed alongshore bars. However, a smaller part was also lost inland by overwash processes, especially on the central part of Faro Beach. The higher dunes at the western and eastern limits of Faro Beach prevented damage beyond the foredunes. Overwash caused damage to a hotel, restaurants and private houses. A similar erosional trend was observed (Ferreira et al., 2019) all along the Ria Formosa barrier system (~55 km) probably corresponding to a total upper beach eroded volume at the system of

more than 3,000,000 m³ during this single storm. At some low-lying areas overwash action dominated and the sediment lost also included the sediment transported inland.

Figure 5. Vertical erosion generated on foreshore by Emma: a) Faro, b) La Antilla and c) Camposoto

At La Antilla, during Emma storm an estimated 450,000 m³ of beach material was lost along the 5 km beach. Properties adjacent to the beach were flooded. Most of the eroded sand was stored in downdrift, nearshore sand bars. Figure 5b shows the dramatic longshore sand transport inducing beach erosion and severe flooding of properties. A 2.5 m-high scarp was formed along the entire beach in front of the urbanised section (Figure 5b). It exposed the former dune deposits upon which the urban area is mostly built. Numerous elements of infrastructure were damaged including promenades, sewage pipes and water supply lines.

Vertical erosion of more than 1 m occurred on the lower and upper foreshore all along the Camposoto spit. As a consequence, an extensive area of fossil salt marsh was exposed on the beach (see central area of Figure 5c). The berm retreated and the dunes were severely damaged, although the effects varied from south to north. In the former (less anthropic), the dune ridge showed a scarp, reactivation of the existing washover fans and deposition of sediment along the

washover channels (Figure 5c). In the northern and more anthropic sector, the overwash flows inundated the back-dune area and almost caused the complete erosion of the dune ridge, which flattened considerably, although the overall barrier gained height due to washover deposition (up to 0.60 m). A significant amount of eroded sand was transported inland filling the artificial water channel and passing over the road and further inland, producing the coalescence of the old and newly formed washover fans upon the salt marshes. The eroded sediment was also transported offshore, where it probably formed intertidal shore-parallel bars in the submerged beach.

4.2. Post storm recovery: Resilience of the system.

The beach volume began to recover immediately after Emma in Faro Beach and at the first post-storm survey (6 days after the storm end) the recovery reached 10.4 m³/m, on average, which represents a recovery percentage of 18.2 % of the eroded volume (ranging between 1 % and 34 % of recovery). One month after the storm (6 April) the recovery achieved an average of 73% (ranging between 55 % and 98 %). The maximum recovered volumes were observed on 20 April, with an average of 81% (ranging between 33 % and 101 %). The higher recovered volume variability recorded at 20 April is mostly related to the presence/absence of beach cusps at surveyed profiles when compared to the previous survey. Although a significant and rapid beach recovery was observed at Faro Beach, a total amount of *circa* 20 % of the lost beach volume had not yet returned to the upper beach by the end of the surveyed period (Figure 6a). Visual observations at Faro Beach clearly identified that at least some of that material was still forming submerged longshore bars. The fast recovery is, however, also consistent with updrift re-filled sediment availability. Since 1998 three major nourishments have been performed on updrift

beaches, with a total of more than $2 \times 10^6 \text{ m}^3$ of sand being placed (Ferreira & Matias, 2013; Pinto et al., 2018) which has then been available for downdrift transport to Faro Beach.

Figure 6 – a) Storm induced erosion and cumulative recovery in Faro promoted by onshore transport of updrift emplacement of nourished sands prior to Emma. Lines in Black - average observed erosion; Gray - Minimum observed erosion; Dashed gray - maximum observed erosion. b) In La Antilla, severe longshore drift due to “perfect” 45 degree approach removed all available sediments downdrift and was lost for the beach system. Base image from <https://www.youtube.com/watch?v=zgd7NijPlXU> c) Onshore-offshore sediment transport dominated Camposoto during the impact of Emma. Washover fans moved the whole beach system landwards.

The natural post-storm recovery of the beach at La Antilla was fast, forming a sand bar naturally after favourable wave conditions affected the beach in the late spring promoting sediment build up on the beachface by June 2018. The first bar (immediately seaward) formed within a week after the storm. The beach began to recover without human intervention during westerly waves during May. The powerfull longshore drift during the storm (Figure 6b) provided sediment supply from updrift eroded areas and one bar attached to the beachface in 45 days, amounting to over $175,000 \text{ m}^3$ (40% of the sand volume lost during the storm). The media coverage of the storm damage was extensive and quite dramatic showing impacting images of loss of property and severe economic activities disruption, which provided the context to a visit from the Prime Minister of Spain and the President of the Regional Government of Andalusia, who visited the area on 5th

of March 2018 to assess the situation and meet with technical staff, municipal politicians and the public after which the Central Government committed to nourishing and reconstructing the beach before the forthcoming summer tourist season. This dramatic high-level intervention suggests that even though there was a plan in place, officials had to show additional concern and commit additional resources, including funds, to restoration work. On June 16th, heavy machinery and dredgers were deployed and nourishment began. Given that the natural recovery of the beach was not sufficiently fast or complete to take the shoreline and beach volume to pre-storm conditions, human intervention continued and the nourishment of 190,000 m³ of sand from the nearshore was pumped to the foreshore.

In Camposoto a restoration project (prompted by the municipality, funded by EU, approved by the National and Regional governments, and executed by a company after a public tender) was already planned in the study site prior to the storm Emma alert. The project included the construction of an elevated cyclist and pedestrian lane over the already existing artificial tidal channel for connecting different areas within the municipality of San Fernando. Among the individual activities foreseen in the project was the implementation of dune restoration measures over the most deteriorated areas of the dune ridge prior to the storm. For the construction of the cycle/walking lane, different earthmoving works were programmed using the sand already retained in the channel (transported by old overwash events -Figure 6c-): lowering of the topography along the channel, sand piling from the channel for placing the foundation piles of the lane, partial removal of the existing breakwater wall, etc. Additionally, the dune restoration measures included wire fences for controlling access, planting of *Ammophila arenaria*, and placement of several types of wooden sand traps. The start date for the project was planned for February 2018, but for different reasons it had been delayed, and it started after storm Emma made landfall in the Bay of Cádiz. No machinery and/or installations were present at that time, and no ongoing works were affected either. This project appears to have been upset by the

occurrence of Emma inasmuch as it altered the existing landscape. After Emma hit the area, there is no information about whether the sediment deposited behind the road by the overwash flows is going to be returned to the beach or not. If it remains there, it would be lost from the exchange zone of the beach-dune system. The company undertaking the project intends to bring it back to the dunes, and it will probably take part of the material used for the lane foundations as well.

Apart from the abovementioned project, artificial nourishment was also carried out at Camposoto beach in the beginning of July 2018 as a direct result of the emergency declared by the Spanish National Administration after the Emma event. A calculated 150,000 m³ of sand was placed in the northern area of the spit, whereas the southern sector remained untouched. However, the latter was able to recover naturally as observed in the topographic measurements performed on 10 July 2018 (more than 4 months after the end of the storm). The profiles showed an average recovery of 89%, which corresponds to an averaged recovered sand volume of 59 m³/m.

Table 2: Resilience (as assessed after Emma event).

Site	Latitude		Resistance		Precariousness		Threshold
	<i>Natural</i>	<i>Engineered</i>	<i>Natural</i>	<i>Engineered</i>	<i>Natural</i>	<i>Engineered</i>	
<i>Faro</i>	N/A	~100%	Reduced	50%	Reduced	No	Not exceeded
<i>La Antilla</i>	Reduced	~60%	Zero	50 %	Zero	No	Exceeded
<i>Camposoto</i>	Reduced	~60%	Medium	100%	Reduced	Yes	Exceeded

5 Discussion

All three sites, when simply measured by its ability to recover seem to be resilient, at least regarding the recovery of the apparent functions of the beach (Table 2). This resilience, in the absence of occupation, would most probably be a natural resilience, in the sense that after a given storm there would be dune erosion, overwash (eventually roll-over at some points) and the

536 subsequent recovery of the natural functions and key structures but not necessarily in the same
537 position.

538 This study reflects on the interaction between the natural behaviour of beaches in the light of their
539 changing capacity to adjust back to functioning natural systems. The three study sites provide a
540 range of insights into the behaviour of beaches in developed coasts during and after storms under
541 the influence of combined natural and human influences. However, the fact that the sites are
542 managed as artificialized environments (CHANS), provide the scenario to test to what extent
543 management becomes part of the process of recovery interfering with nature and its natural
544 resilience.

545 Faro Beach showed a cross-shore sediment exchange during and after storms that is regarded
546 as typical of open ocean exposed beaches (Scott et al., 2016; Burvingt et al., 2017; Masselink et
547 al., 2016). The storm response corresponds to that of a “fully exposed beach that experienced
548 large and alongshore uniform sediment losses”, according to the Burvingt et al., (2017)
549 classification. The recovery process was fast, with about 80 % of the lost sediment returning to
550 the upper beach in just one month. This recovery was much faster than the 50 % recovery in one
551 year reported by Scott et al., (2016) and Burvingt et al., (2017) for fully exposed
552 intermediate/dissipative beaches in the UK. This is probably related to the reflective behaviour of
553 Faro Beach and also to the fact that the formed longshore bars were at a relatively shallower
554 position, thus allowing the sediment transport and beach recovery by mid-energy wave conditions.
555 The recovery percentage is, however, relative to the erosion observed at each profile and a faster
556 recovery does not necessarily mean a more robust profile. For example, although the relative
557 recovery of profiles at the central part of Faro Beach (near the car park) was > 95% the beach
558 had a smaller pre-storm berm and smaller volume than adjacent beaches. The reason is that the
559 carpark (and nearby buildings) overlies a substantial part of the beach berm and thus a similar or
560 even a smaller recovery volume is responsible for a higher recovery percentage. This also

explains why most of the observed damage (by erosion and overwash) occurred at this central part or at other areas where occupation overlies the dune and/or the berm. Thus, without a realignment of the occupation of such areas, subsequent storms will have similar consequences and promote similar risks.

This suggests an ability to naturally adapt to climate change impacts such as expected sea level rise and increasing flood levels. However, human occupation and particularly the observed development over the dune crest and the berm do not allow this natural adaptation and reduce the possibility of natural ecological resilience (Cummings, 2011). For the last decades, including after Emma storm, the main management action has been to rebuild the occupation at the frontline, reconstructing roads, parks, bars/restaurants, etc. This can be seen as an “artificially induced engineering resilience” where the system position is preserved (Table 2). However, the protection function of the beach is not necessarily preserved and even if the percentage of recovery will remain high, the total volume in front of rigid occupied areas will be reduced and the system will be less and less effective on its inland protection, thus tending to a smaller degree of resilience with time. This management option will end-up by maintaining the position of the system but will result in resilience decrease, by higher storm impacts or even in the loss of protection functions such as total erosion of the berm and dune disappearance (Rogers et al., 2015).

At Faro and La Antilla, the location of structures on the berm and dunes influenced their exposure to storms. At Faro, the presence of updrift artificially nourished sand speeded the recovery. The ability to recover of the CHANS is here achieved because prior assistance to the natural resilience had been placed updrift and thus the system did not cross the threshold of the current BoA (Figure 7). However, at La Antilla, though natural recovery was under way within the system’s BoA, the fact that the Prime Minister of Spain and the Andalusian President visited the site before nourishment was undertaken, suggests an emergency mode was adopted to ensure full recovery and preservation of the economic assets that had been lost. Here it is presumed that the system,

despite having significant Resistance, as the threshold had passed for the human perception of the BoA immediate and significant reinforcement of the engineering resilience was put in place. The natural recovery of the beach had started after days of fair-weather conditions, but pace seemed not fast enough and the political commitment had already been made under great public opinion pressure. Emergency nourishment was undertaken. Despite existing plans from 2016, at the time Emma Storm hit the beach the system was not nourished and its engineering resilience was surpassed. The CHANS moved to a new BoA (Figure 7). Once the emergency plans were developed and put in practice, resources emerged and in October 2018 a site 2.9 km off shore eastwards from La Antilla with an area of approximately 790 Hectares was identified as suitable for extraction and nourishment granted and carried out on the beaches of La Antilla.

Figure 7: Basin of Attraction states after Emma storm at three sites.

The scheme put in place then showed a very significant reaction that satisfied public perception of managers at all levels but may have not provided any further resilience to the system. Given the urgent need for action, no study was undertaken to assess the volume of sand required, nor whether the natural recovery rates sufficed to re-establish natural resilience levels pre storm

within the same BoA. The goal of emergency reactivation of the recreational area did not take into account any of the causes but mostly the effects and nothing was done in terms of the natural resilience of the site. The Precariousness levels, given the actions taken, indicate no increase because the absence of dunes and that rebuilding of houses and business at their location which means basically that nothing was learnt (Table 2). The southern sector of Camposoto is less developed and no management activity was undertaken in response to overwash and erosion. The CHANS is generally more resilient showing a BoA that corresponds to a less Resistant state but with wider Latitude which suggests that under a wider range of energies the system may be capable of adjustment. The beach received sediment through natural drift from the west and started recovering soon after the storm without updrift nourishment from previous management measures (as did, for instance Faro). In contrast, the developed northern sector was artificially nourished almost immediately, and different dune restoration measurements are currently being performed (reconstruction of dunes, planting *Ammophila arenaria*, removal of the sediment that filled the artificial water channel, reconstruction of wooden paths, etc.) as well as new infrastructure (bike and pedestrian lanes). Because the enlarging of the dunes, at least at the proposal stage, the Precariousness parameter is increased by engineered resilience (Table 2). In this developed sector, the perception that action was needed focussed on enhancing engineering resilience and the CHANS then passed a new BoA where further engineering is predictable to maintain the shoreline position (Figure 7). The natural resilience response of erosion and relocation of the shoreline was not an option in this CHANS.

Natural systems use natural resilience to repair themselves. On developed coasts management's goal is to help ecosystems revert to natural conditions and focus is placed on the long term via the traditional structure of Plan - Programmes - Actions – Emergencies (Figure 8). The plan is the overall aim and deviations from it limited to punctual emergencies. But these are not structural or the main focus. As emergencies (brought about by human occupation and increased by Global

Change) become more frequent, plans tend to disappear and actions towards increasing engineering resilience begin to proliferate as ecological response appear to be too slow or not adapting to public demands (in time and in space).

Figure 8 Conceptual model of progressive management strategy resulting in increased engineering resilience and low ecological resilience as the emergency response is adopted more structurally.

Trying to revert to natural conditions persist as an idea but it is less and less achievable and more and more costly (see Figure 8). As this trend continues, emergencies take over and public pressure on politicians reduce long term focus (plans and programmes vanish) management is solely done by emergencies. Engineering resilience is greatly increased as documented by the different solutions shown in this study (i.e. Faro's pseudo-sand engine, La Antilla nourishment) but natural resilience has all but disappear. Trying to revert to natural conditions at this stage becomes impossible, mainly because natural conditions are long gone. The sustainability and effectiveness of this model is questionable as it becomes apparent in the three sites studied (Figure 8). Political activity like this then becomes like the storm itself - an episodic and

639 unpredictable driver of coastal change that involves rushed decisions at a scale that does not
640 take into account sufficiently the debilitated resilience levels of the natural system in the current
641 scenario of dramatic transformation to sedimentary replenishment. Knowledge of the physical
642 environment beyond repair measures is critical to achieve sustainable management of
643 human/natural systems (Navas & Malvarez, 2009).

644 The complexity lies in the need to observe natural and engineered resilience together and this
645 perhaps means that we are not dealing with totally artificialised nor natural systems. If we were,
646 then there would be a plan for how to respond if and when storms happened. Instead, it looks
647 more like unintended human interventions and spur-of-the moment human responses in an
648 essentially natural system. However, plans exist that were not yet implemented and caught
649 authorities off guard when Emma hit. La Antilla, for instance had been enforcing a plan since 2013
650 to promote “beach stability” but various administrative issues made emergency measures had to
651 be drawn up so that public opinion calmed down after Emma event.

652 The three sites studied here reacted both to natural and intervened levels differently but none of
653 them responded to a common strategy. The dimensions of the new paradigm of anthropogenic
654 beaches are twofold. The first is related to the new, distorted natural behaviours that does not
655 conform to pre-established or investigated scenarios that during the 20th century coastal
656 engineers have taken as baseline to the re-direction of “anomalous” natural functioning (e.g.
657 beach erosion). The attempt to get back to a natural condition may not make sense anymore
658 because the system whose resilience is in jeopardy now is not and will not be “natural” as
659 interpreted by baseline studies that considered a fully natural coastal behaviour. This includes, of
660 course, sediment sources and sinks that are no longer available or functioning as they were prior
661 to development at various spatial and temporal scales. Distorted river catchments, by damming
662 or many other interventions in the sediment sourcing phase is fronted by distortions at the
663 geomorphological sink phase represented by beach development, itself suffering from multiple

664 interruptions on littoral drift caused by marinas, harbours or other coastal engineering “solutions”
665 such as dykes and/or groins.

666 The second issue is that the mechanics of decision making are mutating from purely technical
667 and lacking public transparency to a politically dominated process. In the scenario of new
668 democracy fuelled by fast paced social network opinion and great influence of advisory bodies to
669 Municipal, Regional and National politicians, the process of decision making is somewhat inverted
670 and instead of technical based response (not just engineering but also at the economical appraisal
671 levels), public image of those implementing plans becomes driven by a sense of urgency leading
672 to unpredictability and potential for mistakes that can get to irreversible weakening of resilience
673 levels, excessive expenditure and general lack of coherence due to improvisation and short term
674 time and space solutions.

675 The beaches of CHANS are facing both new forcing (causes) as climate change patterns
676 generate unprecedented levels of energy and recurrence of high energy events, and responses
677 (effects) due to new fast paced governance based on immediate reaction to public opinion and
678 the provision of short term solutions. This is not a sustainable scenario for pressures faced by
679 developed coastlines.

680 **6 Conclusions**

681 On developed coasts that represent CHANS, there is a complex feedback between natural
682 processes, human infrastructure, and human response to coastal change. In cases where human
683 occupation exists to a great extension, beyond the actual coastline and into the hinterland and
684 nearshore, the system is not resilient, since the natural values are not possible to be restored by
685 themselves. There is a shift on behaviour and eventually a loss of the coastal values. These
686 values are sometimes in the form of ecosystem services as coastal protection. Those coastal
687 values can only be restored by human action again (nourishment, dune recovery, etc.) by

changing its engineered resilience to higher Resistance. In contrast in a natural system, after a storm, there would be no need for human intervention to restore the natural coastal behaviour if natural resilience is able to behave without exceeding its system's threshold. In the current accelerated climate change the degree of transformation affecting coastal system is no match by the response by human structures (management via engineered resilience) causing either unplanned reactive measures that cost vast amount of money and do not resolve the long term issues; or improvised attempts to get the natural system to its natural estate. A natural resilience which threshold may be exceeded and that not only cannot be achieved but it should not be attempted because it will induce chronic weakening of the resilience levels (both natural and engineering).

High energy events affect coasts around the world and the response of the coastal system is directly related to its resilience. This concept can be broken into engineering and natural resilience. Urgency based management solutions may partially lead to attain the engineering resilience of the systems (even if only temporarily for most cases) but they will diminish the natural ability of the systems to evolve, move and adapt their natural functioning, thus jeopardising their natural resilience.

Observations from Storm Emma on developed coasts of Spain and Portugal shows that existing coastal management is not dealing adequately to enable routine post-storm intervention and is strongly influenced by politics. Post-storm recovery on CHANS requires pre-planned systems of post-storm response for the system to be fully coupled paying attention to both their natural and engineered resilience states.

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790 [comienza-la-regeneracion-de-las-playas-con-las-dragas-a-destajo/?jwsourc=cl](https://andaluciainformacion.es/san-fernando/758746/comienza-la-regeneracion-de-las-playas-con-las-dragas-a-destajo/?jwsourc=cl))

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1 *Table 1: details of flight characteristics for RPA surveys in Antilla and Camposoto*

Flight characteristics	Drone surveys in La Antilla	Drone surveys in Camposoto			
	Post-storm	Pre-storm		Post-storm	
	Combined area	Northern area	Southern area	Northern area	Southern area
Surface area surveyed (km ²)	0.210	0.2362	0.288	0.2574	0.3516
Nº GCPs used	N/A	37	30	32	34
Flying altitude (m)	90	95	60	95	60
UAS models	DJI Inspire 1 V2	Atyges FV-8	DJI Phantom 3 Pro	Atyges FV-8	DJI Phantom 3 Pro
Camera models	Zenmuse X3	Sony Alpha 7	Integrated Sony EXMOR	Sony Alpha 7	Integrated Sony EXMOR
Image resolution (Mpx)	12.4	24	12.4	24	12.4
Horizontal/vertical FOV (m)	(Diagonal) 94 deg	121/81	102/77	121/81	102/77
CMOS sensor	Yes	Yes	Yes	Yes	Yes
Nº Images	185	430	1183	531	1320
RSME in XY/Z (cm)	2.73/5	3.3/8	3.9/10	1.2/8	4.9/10
GSD (cm)	2	2	2.5	2	2.5
Image processing software	Pix4D				

2
3 *Table 2: Resilience (as assessed after Emma event).*

	Latitude		Resistance		Precariousness		Threshold
Site	Natural	Engineered	Natural	Engineered	Natural	Engineered	
Faro	N/A	~100%	Reduced	50%	Reduced	No	Not exceeded
La Antilla	Reduced	~60%	Zero	50 %	Zero	No	Exceeded
Camposoto	Reduced	~60%	Medium	100%	Reduced	Yes	Exceeded

4
5

Figure 1: Location of the study sites in SW Atlantic Europe.

Figure 2: Landscapes of the three sites. A: Faro, B: La Antilla and C: Camposoto. Lines with measurements across beachface indicate a graphical scale. Images from Google Earth.

Figure 3. Record of physical variables during the onset of Emma storm. Deep water wave data from SIMAR 6012036 managed by Puertos del Estado, Ministry for Development. H_0 , significant wave height in meters; Tide in meters; T_p , peak period in sec; Wa_{Dir} , wave approaching direction, in grades from the North; Wi_{Vel} , wind speed in m/sec; Wi_{Dir} , wind blowing direction, in degrees from North. Data is applicable to three study sites.

Figure 4: A) key concepts in the Basin of Attraction model; B) Concept of Engineering resilience where the system state should not leave the predicted latitude and C) open boundary basins in the ecological (natural) resilience model. After Kombiadou, et al. "Towards assessing the resilience of complex coastal systems: examples from Ria Formosa (South Portugal)." *Journal of Coastal Research* 85 (2018): 646-650

Figure 5. Vertical erosion generated on foreshore by Emma: a) Faro, b) La Antilla and c) Camposoto

Figure 6 – a) Storm induced erosion and cumulative recovery in Faro promoted by onshore transport of updrift emplacement of nourished sands prior to Emma. Lines in Black - average observed erosion; Gray - Minimum observed erosion; Dashed gray - maximum observed erosion. b) In La Antilla, severe longshore drift due to “perfect” 45 degree approach removed all available sediments downdrift and was lost for the beach system. Base image from <https://www.youtube.com/watch?v=zgd7NljPIXU> c) Onshore-offshore sediment transport dominated Camposoto during the impact of Emma. Washover fans moved the whole beach system landwards.

Figure 7: Basin of Attraction states after Emma storm at three sites.

Figure 8 Conceptual model of progressive management strategy resulting in increased engineering resilience and low ecological resilience as the emergency response is adopted more structurally.

FIGURE CAPTIONS

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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