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REDUCING SEA CLIFFS HAZARDS IN POCKET BEACHES THROUGH BEACH NOURISHMENT ON THE BARLAVENTO COAST (ALGARVE, PORTUGAL)

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ABSTRACT: Tourism based on "sun and beach" is the main economic activity in the Algarve region. A considerable part of the beaches of the Barlavento coast corresponds to embedded sand accumulated along the irregular lacework-like coastline of rocky cliffs cut into Miocene calcarenites. The pattern of touristic occupation in the Algarve and the geodynamics of the rocky sea cliffs, characterized by discontinuous and intermittent occurrence of slope mass movements, result in a high level of risk to beach users along pocket beaches. In order to mitigate the risk associated with the cliff geodynamics, artificial beach nourishment was performed in Castelo and Coelha pocket beaches on the Barlavento Coast, in 2014, increasing the beach area by 3.5 times. The effects of the beach nourishment on the occupation patterns of those beaches along the 2006-2016 decade, before and after the beach nourishment, are herein presented and discussed. Occupancy data were obtained covering different seasons along the year, by counting the number of beach users, regardless of age, using periodic and systematic photographs taken at strategic points that provide full coverage of the beach areas. Before the beach nourishments the area of dry sand outside high and moderate hazard zones, measured at half-tide under average summer wave conditions was 500 m^2 at Coelha beach and 800 m^2 at Castelo beach. After beach nourishment the same area increased to 6700 m^2 at Coelha beach and 7100 m^2 at Castelo beach. Results show that, following the beach fill, beach occupation by recreational users naturally shifted seaward, moving out from the cliff hazard areas. After the intervention, the occupation of high and moderate hazard areas reduced significantly, from 37 % to 11 % in Castelo beach and from 59 % to 27 % in Coelha beach.

Keywords: beach nourishment; hazard; rocky cliffs; Algarve; Portugal.

RESUMO: *O turismo de "sol e praia" constitui a principal actividade económica da região do Algarve. Parte considerável das praias da costa do Barlavento corresponde a praias encaixadas acumuladas no traçado irregular da costa do Algarve, cortado em arribas de calcarenitos do Miocénico. O padrão da ocupação turística e a geodinâmica das arribas, caracterizada pela ocorrência intermitente e descontínua de movimentos de massa, resulta num elevado nível de risco para os utentes daquelas praias. Com o intuito de mitigar o risco associado à geodinâmica das arribas foi realizada alimentação artificial nas praias encaixadas do Castelo e da Coelha no Barlavento em 2014, aumentando o areal 3.5 vezes. Neste artigo são apresentados e discutidos os efeitos da operação de alimentação artificial na década de 2006-2016, antes e após o alargamento das praias. Os dados da ocupação das praias foram recolhidos ao longo do ano, com contagens de utilizadores, independentemente da idade, utilizando fotografias tiradas em pontos estratégicos, cobrindo a totalidade dos areais das praias. Antes da alimentação artificial, a área de areia seca fora das zonas de risco elevado e moderado, medida a meia-maré e perante condições de agitação marítima de verão, era de 500 m^2 na praia da Coelha e 800 m^2 na praia do Castelo. Depois da alimentação artificial a mesma área aumentou para 6700 m^2 na praia da Coelha e para 7100 m^2 na praia do Castelo. Os resultados mostram que, após a alimentação artificial, a ocupação do areal pelos utentes foi naturalmente transferida para próximo da água, afastando-se das faixas de risco das arribas. Após a intervenção, a ocupação das faixas de risco elevado e moderado reduziu significativamente, de 37 % para 11 % na praia do Castelo e de 59 % para 27 % na praia da Coelha.*

Palavras-chave: *alimentação artificial de praia, perigo, arribas rochosas, Algarve, Portugal.*

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1. INTRODUCTION

Tourism based on "sun and beach" is the main economic activity in the Algarve region. With a wide geomorphological diversity of beaches, the original success of Algarve Beach Tourism is associated with the natural beauty of the small pocket beaches, that occur along the recesses of the irregular yellow cliffs. A considerable part of the beaches of the Barlavento coast corresponds to embedded sand accumulated in the irregular lacework-like coastline of rocky cliffs cut into Miocene calcarenites. The pattern of touristic occupation in the Algarve and the geodynamics of the rocky sea cliffs, characterized by discontinuous and intermittent occurrence of slope mass movements, result in a high level of risk to beach users. On the 21st of August, 2009 an instantaneous topple on a sea stack killed five Portuguese tourists and injured two more, that were resting at the base of the cliff on the Maria Luísa beach, near Olhos de Água (Figure 1). Since this accident, the coastal management entity (currently the Portuguese Environment Agency) has been reinforcing the hazard warning and information signs, aiming to increase awareness and alert beach users of the dangers arising from the geodynamics of the cliffs. A network of warning signs, implanted in all the accesses to the beaches supported by rocky cliffs was subsequently developed. The signs are intended to inform users about hazard zones, which could be affected by debris from mass movements and are therefore potentially liable to cause serious damage to users who remain in those areas (Teixeira, 2014).

Artificial beach nourishment, involving building up a beach with sand dredged from another location, is a worldwide current practice in coastal engineering, used for several purposes: increase of recreational area for bathing (Vera Cruz, 1972; Benavente *et al*., 2006); reducing coastal erosion, either on dunes (Pinto *et al*., 2015, Pit *et al*., 2020) or cliffs (Teixeira, 2019, Bitan and Zviely, 2020); as a subproduct of port dredging (Hanson *et al*., 2002, Gallien *et al*., 2015); as a measure of sediment budget management (bypassing), especially in areas with coastline changes associated with the construction of jetties to access port structures (Marcomini, 2006); as a coastal defence (Castelle *et al*., 2009, Psuty *et al*., 2009); as a measure for improvement of the comfort of the users by altering the sand grain size (Anthony *et al*., 2011). In Portugal beach nourishment has increased significantly in the last decades and has evolved to be the major contributor to a regional and national-scale coastal protection strategy focused on coastal sediment management (Pinto *et al*., 2020). In the present case, beach nourishment has been used in the Barlavento Coast of Algarve with the objective of mitigating the risk associated with the dynamics of rocky cliffs (Teixeira, 2016). This intervention intended to reduce the risk to beach users, by both minimizing the frequency of the incidence of waves at the cliff base (geodynamic component) and by promoting the use of the beach in a zone farthest from the toe of the cliffs (anthropic component), and thus reducing the exposure of users to danger.

In line with the regional objective of risk mitigation for beach users associated with the natural geodynamics of the cliffs, beach nourishment was carried out between August and October 2014 on six pocket beaches of the Barlavento Coast: Carvoeiro, Benagil, Nova, Cova Redonda, Castelo and Coelha (Figure 1), resulting in the widening of the beaches between 30 m and 50 m. These interventions, promoted by the Portuguese Environment Agency, had a total investment of 2M €. A total of 338000 m^3 of coarse sand was dredged from an offshore site (Figure 1) and subsequently deposited along the six beaches. This paper describes the results of the 2014 nourishments and evaluates to what extent the risk prevention objectives associated with the natural geodynamics of the cliffs on the beaches of Castelo and Coelha were met.

2. STUDY AREA

2.1 Climate and oceanographic regime

The Algarve region is located in the extreme southwest region of Europe, with a typical Mediterranean climate, with dry summers and mild rainy winters (Figure 2). Annual precipitation reaches 500-600 mm, 80 % of which is concentrated in the wet season (October-March). The average annual number of rainy days does not exceed 75 days and in the dry season (April to September), there are no more than 18 rainy days on average (fig. 2). Between May 15th and October 15th the average temperature exceeds 20° C, reaching 25° C in the months of July and August (Figure 3). Wave regime is moderate, with a mean annual significant wave height of 1 m (Costa *et al*., 2001). Sea storms ($Hs \geq 2.5$ m) occur almost exclusively during the autumn and winter months.

The wave regime on the south coast of Algarve is markedly bimodal, with wave prevalence from W (52.3 %) and SW (18.3 %). The E and SE waves represent about a quarter of the occurrences (Costa *et al*., 2001) and are associated with the eastern wind generated in the Strait of Gibraltar (Pires, 1989). This dissymmetry of the wave direction produces a potential net longshore drift, from W to E. The tidal regime is

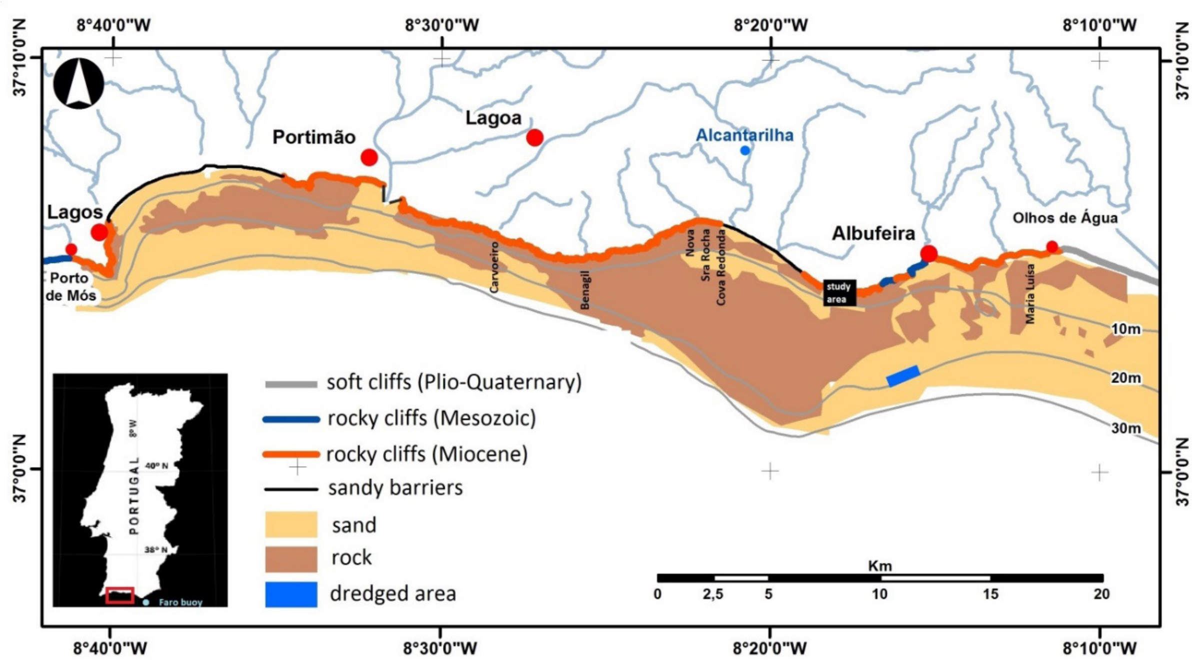

Figure 1. Geographical location of the study area. a) Geomorphology of the coastal area of Barlavento Coast. Main cities (red circles); Alcantarilha meteorological station (blue circle); Area of dredging site used for beach nourishment (blue).

semi-diurnal with a mean tidal amplitude of 2 m, reaching 3 m in spring tides and a maximum of 3.5 m in equinoctial tides. According to data recorded in the Faro oceanographic buoy (Figure 1), since 2001, by the Hydrographic Institute (available at http://www.hidrografico.pt/boias-ondografo.php), during the summer season the sea water temperature remains above 18º C, reaching values up to 24º C in August and September.

2.2 Geomorphological framework

The geomorphology of the Barlavento Coast is dominated by yellow rocky cliffs, with heights varying between 6 m and 40 m, cut in miocene calcarenites, intensely fractured and karsified. Atop the Miocene calcarenites deposits there is a plio-pleistocene layer of red clayey sands. The contrast in resistance of the materials constituting the cliffs and the spatial diversity of the karst cavities lead to a very irregular pattern of coastline evolution. The resulting lacework-like pattern, profuse in stacks, arches, caves and sinkholes, is in fact the brand image of the Algarve coastline.

The irregular shape of the coastline facilitates the accumulation of pocket beaches, with variable dimensions. The study area corresponds to a small stretch of the Barlavento Coast, with an extension of about 1 km that includes the beaches of Castelo and Coelha (Figure 1). These beaches, individualized by natural rocky headlands contain a thin sand cover accumulated over intertidal cut shore platforms. Under storm conditions coincident with spring tides, the swash sweeps the entire beach, reaching the toe of the cliffs (Figure 3).

Castelo beach is a small pocket beach (Figure 3) with a sea front of 150 m, and an average width of 20-25 m. Subvertical sea cliffs that limit the beach rise 12-15 m above the sand. Beach sediments are coarse sand D50 = 0.65 phi (0.73 mm), with carbonate content of 30-50% (Teixeira, 2009). Coelha beach is a small pocket beach (200 m long) that accumulated in a recess of a hanging valley. The beach is supported by cliffs with heights of about 18 m. The Coelha beach sand texture is identical to the sand texture of the Castelo beach.

3. HAZARDS ASSOCIATED WITH ROCKY CLIFFS DYNAMICS

The cliffs of the Barlavento, cut in the Miocene calcarenites, evolve through a discontinuous and intermittent sequence of slope mass movements. Movements occur in multiple forms, from the big movements associated with the collapse of karstic cavities (that can displace tens of thousands of cubic meters) to the simple detachment of small decimetric blocks. On average,

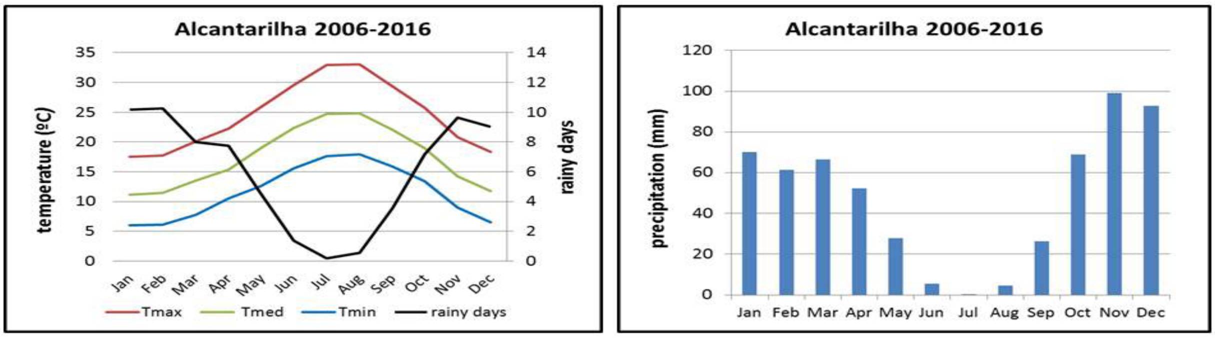

Figure 2. Annual distribution of precipitation and temperature in the 2006-2016 decade. Data from the Alcantarilha station (location on fig.1), available from http://www.drapalg.min-agricultura.pt.

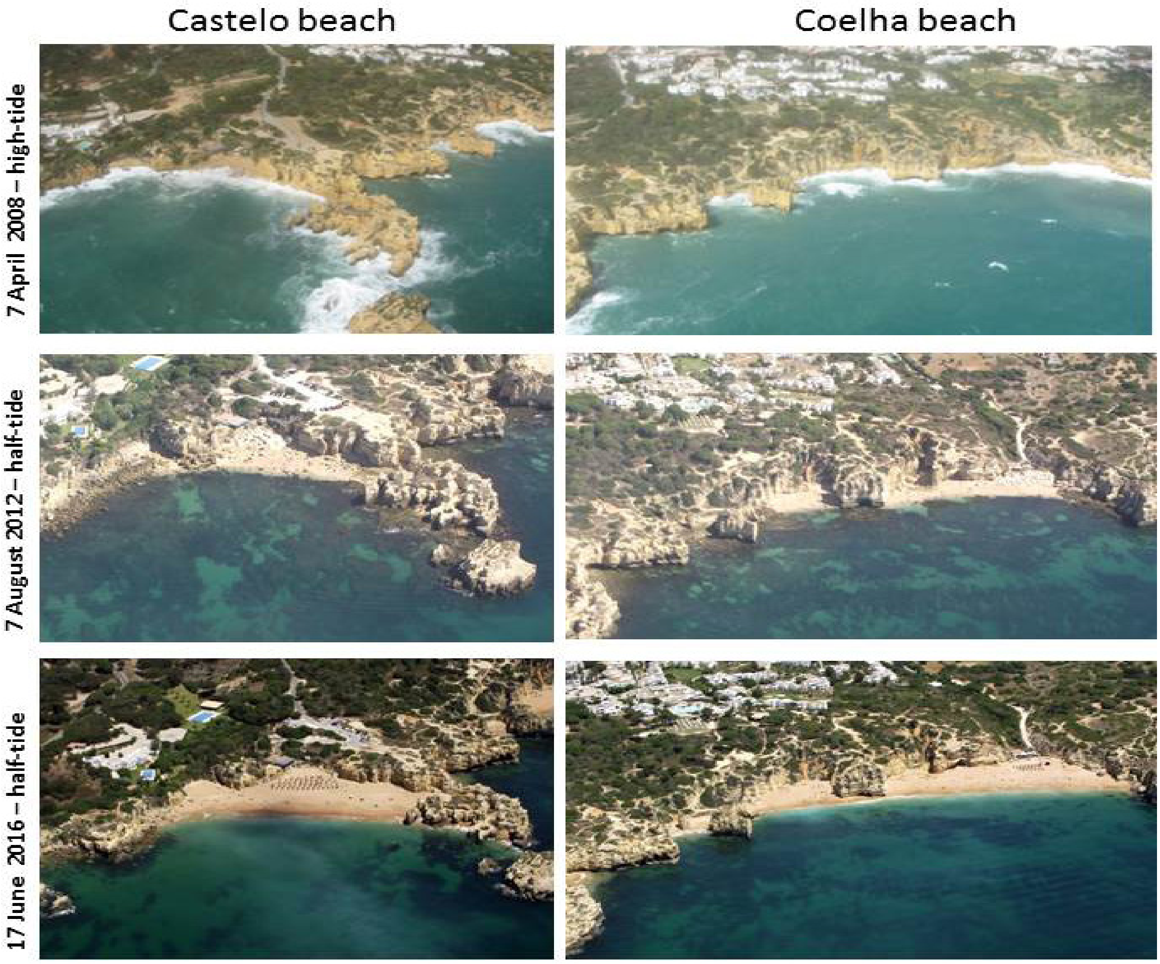

Figure 3. Castelo and Coelha beaches under storm conditions at high spring tide (7 Apr 2008, upper panel), under average summer wave conditions at half-tide before beach nourishment (7 Aug 2012, central panel) and under average summer wave conditions at half-tide before beach nourishment (7 Aug 2012, central panel) and under average summer wave conditions at half-tide after beach nourishment (17 Jun 2016, lower panel). Photos by the author.

0.2 % of the 46 km of coastal front of Miocene cliffs is affected annually by mass movements (Marques, 1994, 1997; Teixeira, 2003, 2006, 2014). In the last two decades, in the study area, 13 mass movements with a width greater than 1 m were recorded (Figure 4A), displacing a volume of about 24000 m^3 and altering the sea front along an extension of 165 m. The largest movement occurred on March 22nd, 1998, East of Coelha beach, which resulted in the death of a fisherman. This mass movement involved a maximum instantaneous retreat of the cliff of 24 m, with the mobilization of 20000 m^3 (Figure 3A). Maximum slope mass movement on a beach, occurred on Coelha beach on February 1998, with the mobilization of 1200 m^3 (fig. 4B).

The natural geodynamics of the cliffs and the model of tourist occupation of the Barlavento Coast determine the existence of danger for beach users. The study area is under the regulations of coastal management plans that include a hazard area on beaches backed by sea-cliff extending seaward from the cliff toe. These hazard areas are defined by a width 1.5 times the cliff height and correspond to the maximum expected extent of cliff failures debris. Based on the analysis of more than a hundred mass movements recorded between 1995 and 2014, Teixeira (2014) established a hazard table – the probability of occurrence as a function of the distance from the cliff toe. The results obtained from that analysis show that, in the event of a mass movement, a beach user resting on the sand at a distance greater than 0.86 times the cliff height reduces by 50 % the probability of being hit by the debris generated by the cliff failure. This probability rises up to 95 % if the distance from the cliff base reaches 1.5 times the cliff height. Based on these results, the Portuguese Environment Agency has developed hazard cartography for all beaches supported by rocky cliffs in the Algarve, and the information is provided on panels placed along all beaches access points (available on http://www.apambiente.pt).

Figure 5 reproduces the cartography resulting from this information on Castelo and Coelha beaches. Two hazard bands are identified: the red band (high hazard) corresponds to the area where, in the event of collapse, the probability of being hit by the rock debris is greater than 50 %. The yellow band (moderate hazard) covers the area where the probability of being struck by the debris is less than 50 %. In the remaining area of the beach not covered by the two ranges the probability of being hit by debris of any mass movement is less than 5 % (low hazard).

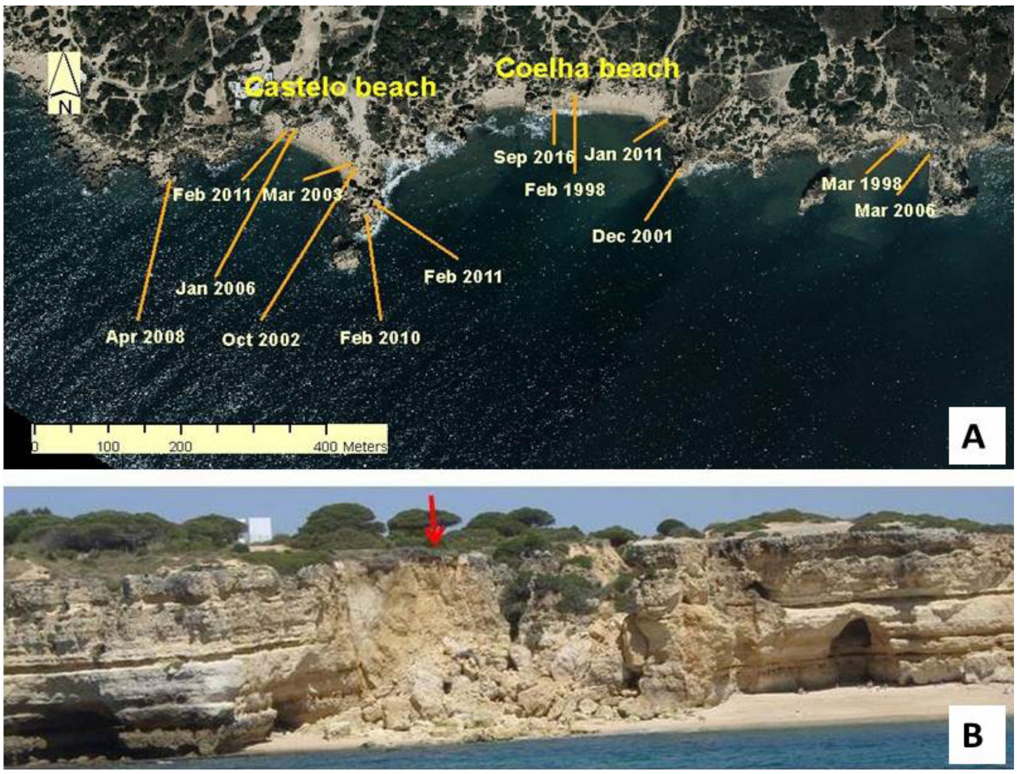

Figure 4. A: Recorded mass movements of the study area over 20 years (1996-2016), ortophoto 2008 (Direção Geral do Território); B - Mass movement occurred on Coelha beach in February 1998 that displaced a rock volume of 1200 m^3 (photo by the author).

Figure 5. Sea cliff hazard signs of Castelo and Coelha beaches. Available at http://www.apambiente.pt/index.php?ref=16&subref=7&sub2ref=10&sub3ref=923.

4. BEACH NOURISHMENT

Beach nourishment of Castelo and Coelha beaches took place in September 2014 through the deposition of 120000 m^3 of sand, spread between Castelo (45000 m^3) and Coelha (75000 m^3) beaches, corresponding to a density of fill of 300 m^3/m of linear length of the beach. The borrow area for the beach nourishment was an offshore deposit located at 20-25 m water depth (fig.1). The offshore sediments corresponded to coarse sand (D_{50} = 0.0 phi; 1 mm), with a mean carbonate content of 25 %, coarser than the native sands of the nourished beaches.

Beach nourishment consisted on the deposition of sand directly on the subaerial zone, because it allowed for the use of the beach immediately after the intervention. This project option inevitably entails losses resulting from the subsequent adjustment of the beach profile (Van de Graaff *et al*., 1991). The experience obtained from previous beach nourishments of the subaerial zone in the Algarve shows that in the first winter after the deposition, the beach profile loses on average 25 % of the initial width after completion of the work (Teixeira, 2011, 2016). Therefore projects usually consider overfeeding in the subaerial zone of the beach.

5. METHODS

5.1 Occupation of beaches

The assessment of the occupation of the two studied beaches was made through systematic counts of the number of users present in the beach, regardless of the age group. For this purpose, large series of photographs taken with a digital camera, were obtained from locations that allow for the full coverage of the beach and with sufficient definition to allow for the counting of all the people present in the beach sand or associated water plan, including bathers. In addition to the photographs taken at strategic points on land, the photographs obtained from coastal monitoring surveys were also used, both the oblique aerial photos obtained on board aircraft and the photos obtained on board of a vessel.

The photographic record spans over a decade, between 2006 and 2016, and distributed throughout the year, covering the time interval between 8:00 AM and 8:00 PM. The two studied beaches have a longitudinal orientation, being limited by rocky headlands and with a direction close to W-E, a framework that implies the existence of shade in the sand in the early hours of the day and in the late afternoon. These circumstances, combined with the usual pattern of bathing hours by beach users, causes beach use to be mainly concentrated between 10:30 AM and 6:30 PM in the semester between May and October. Thus, in order to standardize the information for both periods, before and after the beach nourishment, the photographs obtained on weekdays between 10:30 AM and 6:30 PM between May and October were used, and in the remaining months, photographs were obtained in the interval between two hours after sunrise and two hours before sunset. This set of information totalized 421 observations (Table I).

To assess the number of persons within the hazard areas, the official hazard bands were overlayed on the photographs. The top of the cliffs have an almost linear planimetric contour and show small change in relief, therefore the hazard zones correspond to bands approximately parallel to the toe of the cliffs. The delineation of the hazard bands on the photographs was made assuming this linear pattern, taking as auxiliary references specific points to delimit the boundaries of the

Table 1. Beach occupation data (p – persons).

		Castelo beach	Coelha beach
2006-2014 Before beach nourishment	Nº observations	100	79
	Average annual occupation	24 p	28 p
	Maximum observed occupancy	116 p (2 August 2006; 15h00m)	131 p (3 Aug 2011; 12h00m)
2014-2016 After beach nourishment	Nº observations	118	114
	Average annual occupation	40 p	48 p
	Maximum observed occupancy	252 p (18 August 2015; 11h45m)	295 p (28 Aug 2015; 17h00m)

bands, used systematically in all the observations. In each photograph analyzed, the total number of users, divided into three groups according to their location in relation to the hazard bands of the cliffs was counted: the group that occupies the maximum hazard band (red hazard area), the group that occupies the moderate hazard band (yellow hazard area) and the group occupying the area outside the previous bands (blue hazard area). The number of persons counted includes all age groups, including children.

5.2 Topographic surveys

The systematic photographic records were complemented by topographic surveys carried out with GNSS equipment at the scale of 1: 2000, before (July 2014), immediately after (September 2014) and one year after the beach nourishment (July 2015) on both beaches. Based on the topographic surveys the beach area was calculated and the space available for the users (dry sand) was evaluated, under average summer wave conditions (Hs = 0.5 m), and in average low tide, average half-tide and average high tide situations. Using the equations developed by Teixeira (2009) for wave run-up on beaches of the south coast of the Algarve, it is verified that in both beaches, that have very similar slopes, wave run-up reaches approximately 1 m above the water plane under summer wave conditions. Based on these results, the seaward limit of the dry sand area was set at: 0 m (MSL-Mean Sea Level) contour for the mean low tide situation, +1 m (MSL) for the mid-tide situation, and 2 m (MSL) for the average high tide situation. Beach areas were calculated between the contours of 1, 2 and 3 m (MSL) and the cliff toe. This information was then compared with the cartography of the hazard bands, considering, in addition to the high hazard band (red) and moderate hazard (yellow), a third hazard band (blue) containing the remaining beach area outside the first two hazard zones. This third hazard zone (low - blue) is the area of the beach where, in the event of mass movement of the cliffs, the probability of being reached by the debris is less than 5 % (Teixeira, 2014).

6. RESULTS AND DISCUSSION

6.1 Beach nourishment

Beach nourishment of the Castelo and Coelha beaches provided a very significant increase in the dry beach area available for beach users (fig.6). The beach area above the MSL increased about 3.5 times on both beaches. One year after nourishment, Castelo beach lost 15 % and Coelha beach lost 22% of the sand initially deposited. These values are in agreement with records and reports from other artificial nourishments in the subaerial zone in the Algarve region and that reach up to 25 % initial losses (Teixeira, 2011, 2016).

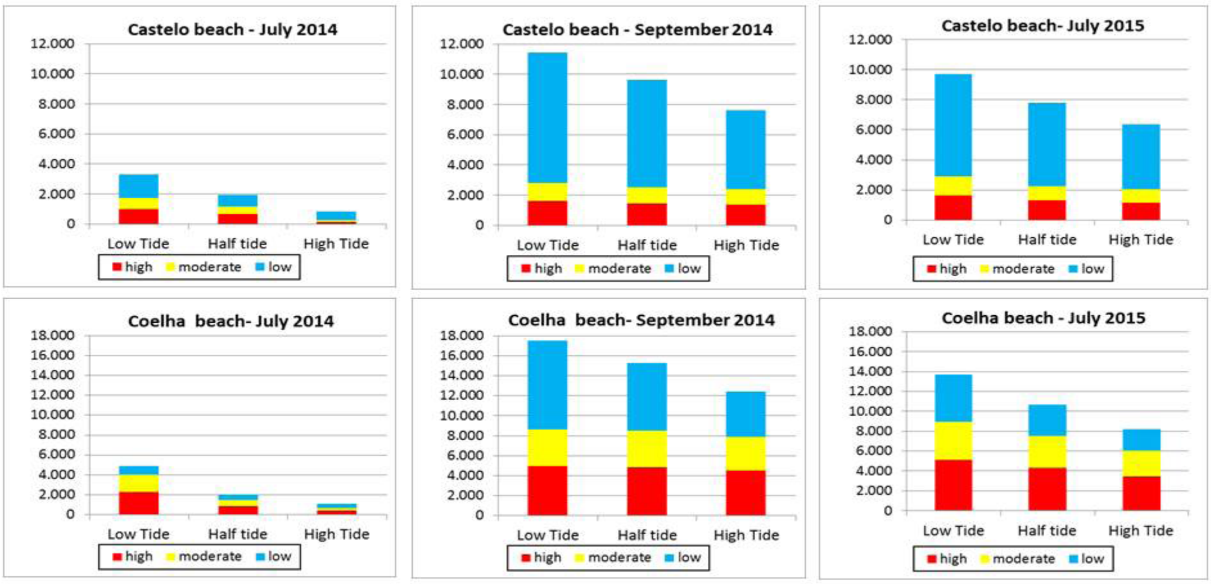

Figure 6. Dry beach area (m^2), before beach nourishment (left panel), after beach nourishment (central panel) and one year after beach nourishment (right panel), depending on the state of the tide, under average summer wave conditions: average low tide, half- tide and average high tide. Dry beach areas (m^2) on the high hazard zone (red), moderate hazard zone (yellow) and low hazard zone (blue).

The results show that most of the dry beach was included in the maximum and moderate hazard areas before beach nourishment, due to the small width of the original beaches (Fig. 6), indicating that their users were only safeguarded from this danger when bathing. In Coelha beach the area available to users in the low hazard area was always very small, not exceeding 830 m^2 during low tide. After beach nourishment, the dry beach area in the low hazard area was 8900 m^2, decreasing to 4800 m^2 one year after the works. At Castelo beach the low hazard area was 1600 m^2 before the beach nourishment, increased to 8600 m^2 after the intervention and remained at 6800 m^2 one year later. Results are more expressive in average high tide conditions. In Coelha beach the area available in the low hazard area was 430 m^2, increased to 4500 m^2 after the intervention and remained at 2150 m^2 one year after the intervention. In Castelo beach, these values were, respectively 580 m^2, 5200 m^2 and 4300 m^2. These figures show that the beach area outside the high and moderate hazard areas increased very significantly on both beaches.

6.2 Beach occupation

As expected, the pattern of occupation on the two beaches presents a strong seasonal component, accompanying the annual variation of temperature and tourist activity. The peak of occupancy on both beaches is concentrated in the month of August which is the month of greatest tourist demand in the region (Figure 7).

The results of the annual distribution of occupation in the two beaches (Figure 7) show that in the period after the beach nourishment, there was a very significant increase in the demand for the beach in the period between May and October. On average, the annual increase in occupancy was 68 % in Castelo beach and 69 % in Coelha beach. These figures can only be attributed to the increase of the available beach area on both beaches.

There were no alterations made to the accesses or car parking that could have increased the demand on both beaches.

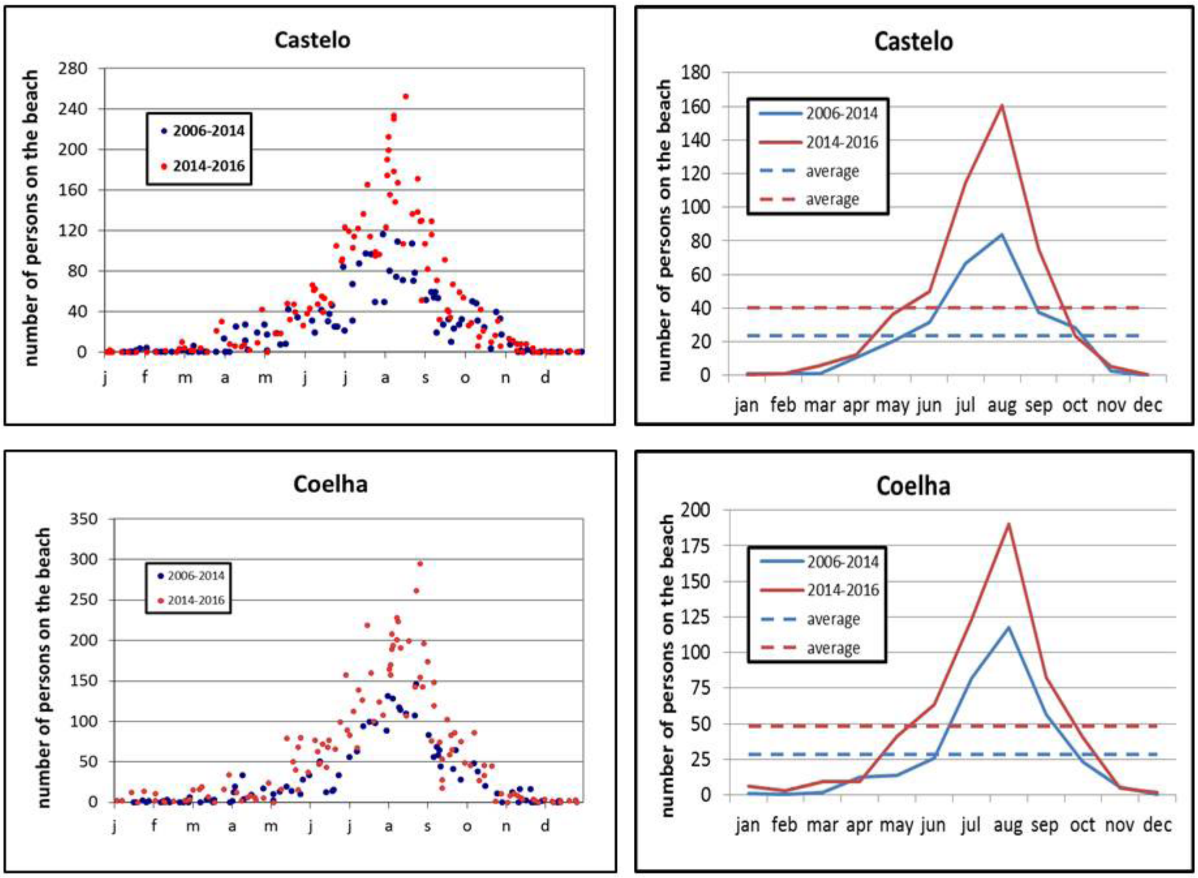

Figure 7. Annual beach occupancy data between the decade 2006 and 2016, before (2006-2014) and after (2014-2016) beach nourishment. Daily (left panel) and monthly average (right panel) beach occupation.

Therefore, the most plausible reason for the measured increase in the use of these beaches should be associated with a change in the behavior of the nearest resorts' guests, who usually did not use the beach. The enlarged beaches, located a short distance from the tourist accommodations, must have been strong enough reasons to attract these guests.

6.3 Hazard areas occupation

Figure 8 summarizes the annual distribution (with monthly average values) of the occupation of the three hazard areas (high-red, moderate-yellow and low-blue) in the periods before and after the beach nourishment on Castelo and Coelha beaches.

At Castelo beach, the change in the pattern of occupancy of the hazard areas is noticeable, with a very significant decrease in the occupation of high and moderate hazard areas (fig. 8). The annual average was 37 % of users located in those areas in the period before beach nourishment, reducing to 11 % after the nourishment project. This result should be attributed to the increase in available dry beach and consequent relocation of the users from the toe of the cliffs towards the water plan. Despite the increase in beach area, there are still users with risk behavior. On average, 5 % of users remain in the high hazard area (red band) and 6 % use the moderate hazard area (yellow band). The occupation of the high hazard area reduced to 40 % of the occupancy registered before the nourishment. Likewise, at Coelha beach there is a change in the behavior of its users, with the relocation of the occupation towards the water plan and consequent withdrawal from the toe of the cliffs. Before the intervention on this beach, 59 % of its users remained in the high and moderate hazard zones (43 % in the red area and 17 % in the yellow area). After the nourishment, this percentage reduced significantly to 27 % (14% in the red area and 13 % in the yellow area). The occupation of the high hazard area reduced to 56 % of the occupation registered before beach nourishment.

These results are similar to those obtained by Teixeira (2016), who analyzed the effects of beach nourishment performed on two other pocket beaches, Nova and Cova Redonda (fig. 1), part of the same project. After the intervention, the occupation of high and moderate hazard areas reduced very significantly, from 92 % to 17 % in Nova beach and from 44 % to 12 % in the Cova Redonda

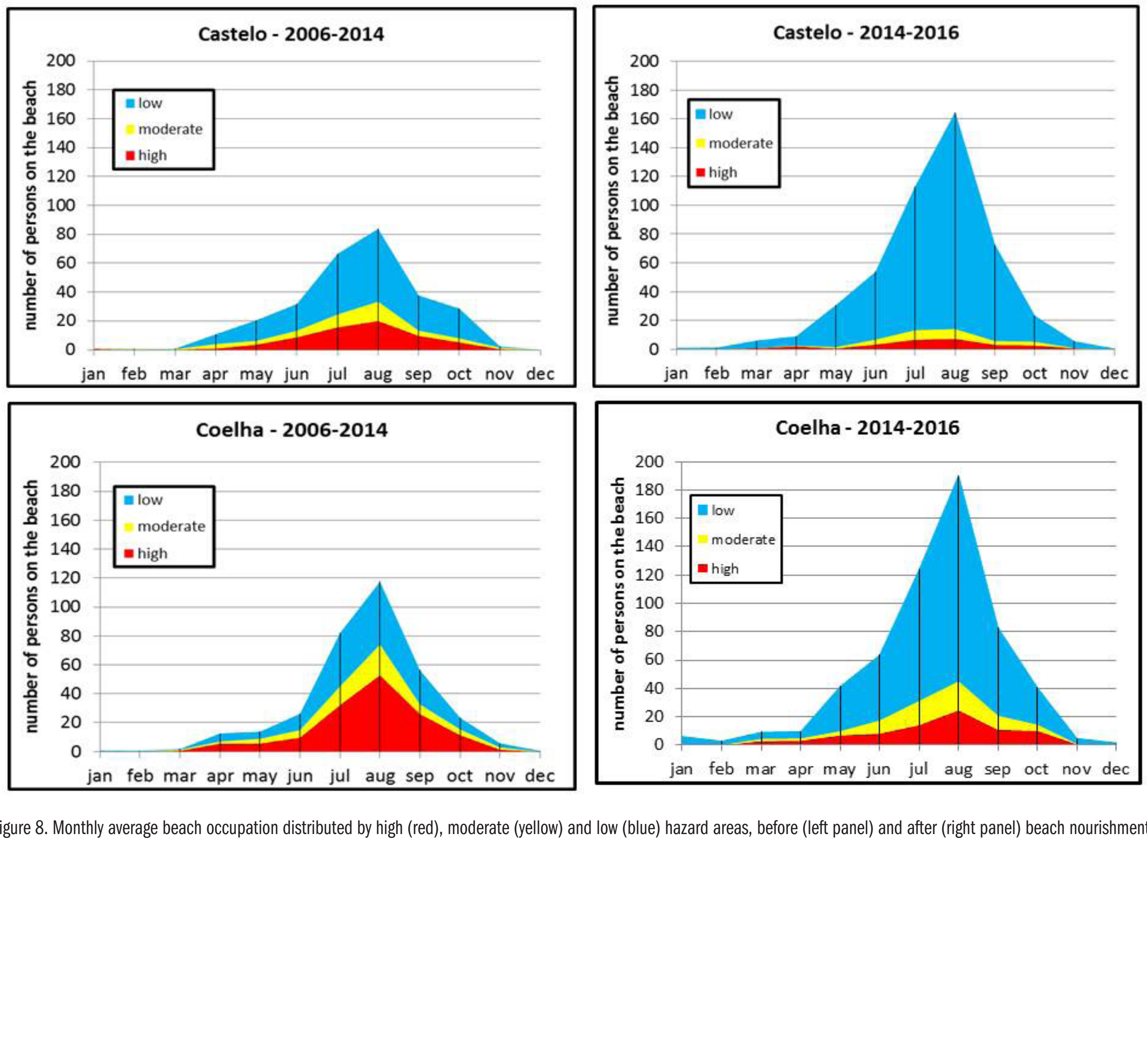

Figure 8. Monthly average beach occupation distributed by high (red), moderate (yellow) and low (blue) hazard areas, before (left panel) and after (right panel) beach nourishment.

beach. This reduction contrasts with the low 2 % reduction of the occupation of hazard areas on the pocket beach of Senhora da Rocha which was not nourished but instead was subject to an increase in hazard warning signs performed in the same year of the beach nourishment project (Teixeira, 2016).

7. CONCLUSIONS

In order to mitigate the risk associated with cliff geodynamics, artificial beach nourishment was performed in Castelo and Coelha beaches. Results show that the reaction of users to the beach nourishment and the resulting increase of the dry beach area, was their natural relocation towards the water plan, moving out from the cliff hazard areas. After the intervention, the occupation of high and moderate hazard areas reduced very significantly, from 37 % to 11 % in the Castelo beach and from 59 % to 27 % in the Coelha beach. This study shows that beach nourishment is an effective measure to reduce the risk to users of pocket beaches backed by rocky cliffs, and in the case of Algarve, is an appropriate hazard management tool.

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