Morphological and economic impacts of rising sea levels on cliff-backed platform beaches in Southern Portugal

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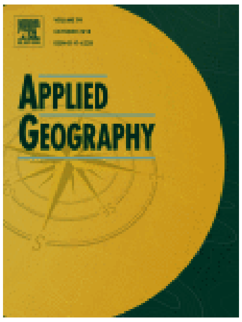

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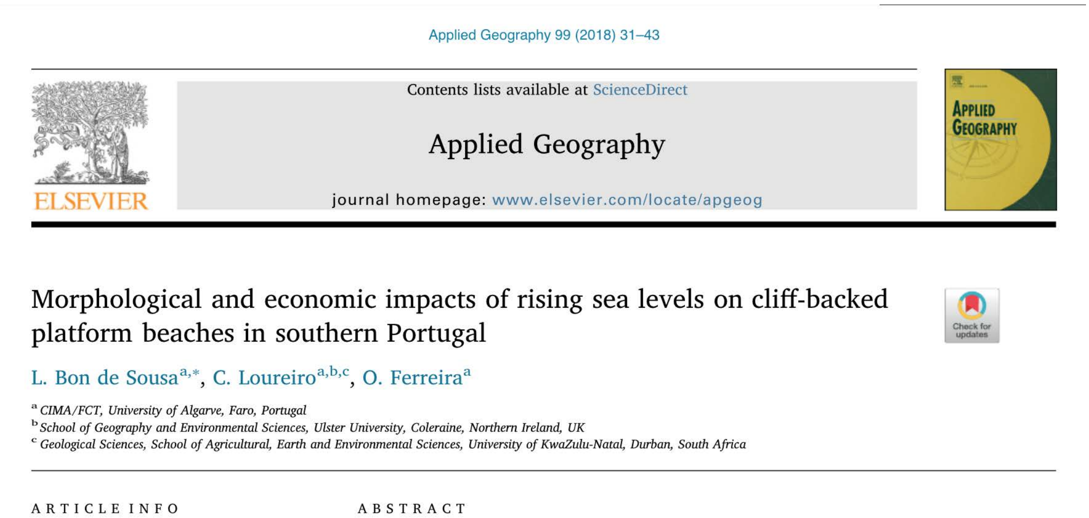

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ARTICLE INFO

ABSTRACT

Highlights

- New model to explore the morphological response of platform beaches to SLR
- A SLR of 0.5 to 1 m leads to considerably shorter and steeper beaches
- SLR will reduce beach area and beach carrying capacity in the south of Portugal
- Negative impacts to local and regional economy based on beach and sun tourism
- Beach nourishment is a cost-effective option for beaches in southern Portugal

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Abstract

Projections from the Intergovernmental Panel on Climate Changes (IPCC) point to a global mean sea level rise (SLR) of close to 1 m by 2100 for a worst-case scenario. This will have a significant impact on coastal areas worldwide, primarily by modifying the shoreline position and coastal morphology, but also by influencing the coastal economy and livelihoods. Generally, it is assumed that sandy barriers will adapt to SLR through shoreline retreat and barrier inland migration. However, for embayed beaches backed by cliffs and/or underlined by shore platforms, constraints to inland migration will compromise such morphological response, with SLR-induced shoreline retreat leading to reductions in beach width and area. This will have impacts on beach use and carrying capacity.

Aiming to analyse the morphological changes induced by SLR at cliff-backed platform beaches, this study explores simple mathematical models to quantify beach morphological change. 2D cross-shore profiles, representing the morphology of the beach and the underlying shore platform, were analysed using two geometric models of beach profile response. The model of Taborda and Ribeiro (2015) was applied for profiles with berm, while a new model is proposed for profiles without berm. The models assume that for profiles with berm there is both retreat and rise of the berm, while for profiles without berm the beach face becomes steeper and the sub-aerial beach narrower in response to SLR.

Using a high-resolution topo-bathymetric LiDAR dataset, 94 cross-shore profiles from 32 beaches in southern Portugal were analysed. Their evolution was modelled considering the IPCC RCP8.5 scenario, which projects a SLR between 0.5 m and 1 m by 2100. From the 48 profiles with berm, 15 will experience complete berm erosion by 2100 for a 1 m SLR worst case scenario. The modelled average berm/beach width reduction is 7.9/5.8 m and 9.5/9.6 m for a SLR of 0.5 m and 1 m, respectively. A total of 26 beaches will become steeper and may be submerged if a threshold equilibrium beach slope is exceeded.

Changes to the beach carrying capacity due to reduction in beach area will impact the local and regional economy, since the southern coast of Portugal is strongly influenced by beach tourism. The modelled changes to beach area result in a maximum potential economic loss ranging between EUR 215,000 and EUR 561,000 per day during peak summer months if no mitigation measures are considered. Beach nourishment was found to be a cost-effective measure to prevent the modelled reduction in beach area and mitigate the associated economic impacts.

Keywords: beach profile; embayed beaches; morphological evolution; sea level rise; beach carrying capacity; beach nourishment.

1. Introduction

Global mean sea level has been rising over the past century, with the main contributors to sea level rise (SLR) being ocean thermal expansion, glacier and polar ice sheet melting (e.g. Gornitz and Lebedeff, 1987; Solomon *et al.*, 2007; FitzGerald *et al.*, 2008; Cazenave and Llovel, 2010; Church *et al.*, 2013; Williams, 2013). The latest review by the Intergovernmental Panel for Climate Changes (IPCC) presents different scenarios to project SLR according to various levels of greenhouse gas emission and associated global warming (Church *et al.*, 2013). According to the RCP8.5 scenario sea level will rise between 0.52 and 0.98 m until 2100, when compared to the 1986-2005 reference level. The RCP8.5 is considered as the worst-case scenario, as it considers the influence of ice melting and thermal expansion to be higher than in others scenarios (Church *et al.*, 2013), while disregarding the impact of mitigation measures on the increase of CO_2 emissions (Horton *et al.*, 2014).

Dubois (2002) reported that understanding and quantifying the response of beach profiles to SLR was one of the most important questions for investigation in coastal geomorphology, a statement that is still valid nowadays (e.g. Le Cozannet *et al.*, 2014, 2016). To investigate the impacts of SLR on sandy beaches, several authors have applied the Bruun rule (Bruun, 1962) or modification to this rule, which predicts shoreline retreat as a simple function of the change in sea level, with material eroded from the beach being deposited on the shore face (e.g. Hands, 1983; Leatherman, 1991; El-Raey *et al.*, 1999;

Davidson-Arnott, 2005; Ferreira *et al.*, 2006). The Bruun rule has been widely criticised within the scientific community (c.f. Cooper and Pilkey, 2004; Pilkey and Cooper, 2004), with many studies indicating that it can be applied only to a very limited range of conditions. Recently, Le Cozannet *et al.* (2016) concluded that the application of the Brunn rule may be restricted to storm-sheltered and low-energy gently sloping sandy beaches without geological control, which are under sedimentary budget equilibrium and with small gradients in longshore drift. Therefore, the Bruun rule cannot be applied to embayed or pocket beaches with lateral and vertical geological control, reduced sand availability and where shoreline retreat is limited by the presence of a cliff. Trenhaile (2004) and Brunel and Sabatier (2007) developed morphologic models distinct from the Bruun rule to simulate shoreline retreat for beaches overlaying a shore platforms. The morphologic model developed by Trenhaile (2004) considers that SLR and limited accommodation space contribute to sediment losses on platform beaches, given that not all sediment will be displaced to build a higher berm due to rising sea levels. Alternatively, the principle of dynamic submersion employed by Brunel and Sabatier (2007) proposes the progressive flooding of the beach, with horizontal migration but without changes to the beach profile configuration. Taborda and Ribeiro (2015) developed a simple morphological model to estimate the evolution of platform beaches due to SLR, based on changes to the height and width of the berm. This model assumes an invariant profile slope, which is in equilibrium with the mean sea level and wave conditions. The model considers that the berm will rise by the same amount as sea level, with the sediment volume being maintained by increasing the height of the berm while reducing its width. This reflects the constraint in horizontal accommodation space in cliff-backed beaches and the assumption of sediment volume conservation (Taborda and Ribeiro, 2015). Sharing some of the assumptions of Taborda and Ribeiro (2015) model and expanding the model presented in Trenhaile (2004), Trenhaile (2018) presents a new modelling study to investigate the factors that determine, under stable sea level conditions, whether different types of beach sediment can accumulate on rigid foundations under variable wave conditions.

A common limitation to some models described above is that they only consider morphological changes in beaches with well-developed berms, wide enough to accommodate morphologic changes imposed by SLR scenarios. However, embayed and platform beaches backed by cliffs often lack a berm and the beach profile can be schematized exclusively as a linear beach face, extending from the beach toe to the cliff base. For such situations, the models described above assume that the beach face will be progressively flooded until submergence occurs, without readjusting to the SLR. However, as Aagaard and Hughes (2017) indicate, a berm-less profile will necessarily respond differently to SLR when compared to a berm profile, requiring a different modelling approach.

Since embayed platform beaches are present throughout the world's coastlines, an approach that combines the three occurring profiles types (berm, berm-less and changing type) has a large potential for investigating the morphological response of such beaches to SLR. Moreover, despite a recognised need for in depth analysis of SLR impacts in pocket or embayed beaches, an overall determination of SLR-induced morphological changes in a large number of pocket beaches within a regional framework is still uncommon.

The main objective of this study is to present a comprehensive approach to determine the morphological evolution of platform beaches under SLR considering the IPCC RCP8.5 scenario for the 21st century. This investigation is based on the model of Taborda and Ribeiro (2015) for beaches with berm and on a new model for berm-less beaches, both of which are applied to the southern Portuguese coast as a case study. For the coast of Portugal, Ferreira *et al.* (2008), Taborda *et al.* (2010) and Ferreira and Matias (2013) had previously stated that for coastal areas where inland migration is not possible, SLR would lead to a reduction in beach width. These authors, however, did not quantified such impacts and only Taborda and Ribeiro (2015) provided berm retreat estimates, although for a limited number of beaches (two beaches nearby Cascais, Lisbon). Our work builds on the previous studies and demonstrates the possibility of applying simple, exploratory models (c.f. Murray, 2003) to determine SLR impacts at embayed beaches for large areas (~100 Km) and for tens of beaches. The study is complemented by a cost-effectiveness analysis of beach nourishment as a coastal management option to overcome the projected reduction in carrying capacity of bathing beaches, considered here as the area required by each individual bather, for a highly touristic region based on the potential economic losses.

2. Response of platform beaches to SLR

Platform beaches are depositional landforms that develop in rocky, predominantly erosional coastlines, where sediment accumulates over an underlying rocky platform (Kennedy and Milkins, 2015). Platform beaches, also known as perched beach (e.g. Gallop *et al.* 2012), are generally limited landward by a cliff (Taborda and Ribeiro, 2015) and laterally by rocky headlands (Loureiro *et al.*, 2012). The profile of platform beaches can be simplified to two main morphological types, depending on the foreshore/backshore morphology: i) profiles with berm; ii) profiles without a distinguishable berm (berm-less), characterized by a dominant linear to sub-linear beach face (Figure 1).

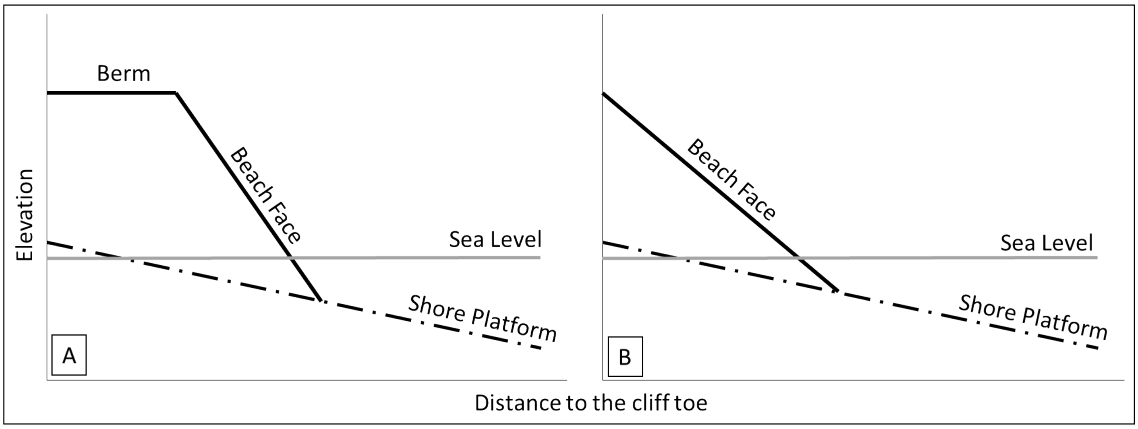

Figure 1 Schematization of the different profile types. A – profile with a berm; B – profile without a berm (berm-less profile). The profiles are backed by a rocky-cliff.

2.1. Morphological parameters

Different morphological parameters can be identified for each beach profile, including the shore platform slope ($tan\alpha$), the berm elevation (hB) and width (xB), the beach face elevation (hF) and slope ($tan\beta$) and the beach width (xF) (see Figure 2 for representation). The shore platform is defined as the rough and irregular section in the lower intertidal to subtidal part of the profile, for which the average slope ($tan\alpha$) can be obtained by linear fitting all data points along this section (Figure 2). It was considered as cliff base or cliff toe the contact between the beach and the cliff itself, and the extraction of all profiles started at that contact point (Figure 2). The berm, when present, corresponds to the horizontal or sub-horizontal section extending seawards from the cliff base (Figure 2A), with the berm elevation (hB) taken as the mean elevation relative to MSL of this flatter section while the berm width (xB) represents the horizontal difference between the initial and end point of this section. The beach face is considered as a linear adjustment for that section of the profile, even though for some profiles a concave shape can be observed (Figure 2B). The beach face elevation (hF) is determined for profiles without a distinguishable berm and corresponds to the elevation of the beach at the cliff base (also relative to MSL). The beach width (xF) is given by the horizontal distance from the cliff base to the interception between the beach face and the shore platform (Figure 2). Representation of the berm and beach face as linear features required some level of simplification of the real beach profile. Such simplification was performed by creating a schematic profile configuration that reproduces as close as possible the real profile, while aiming to maintain the volume of the real profile. For some cases this implies that the limits of each section are not necessarily coincident with the solpe breaks of the real profiles (see Figure 2A for an example).

Furthermore, the height of the sedimentary wedge (zB) is given by the vertical difference between the berm/beach face elevation and the elevation of the projected shore platform at the cliff intersection (determined by extending the shore platform inland according to its' average slope).

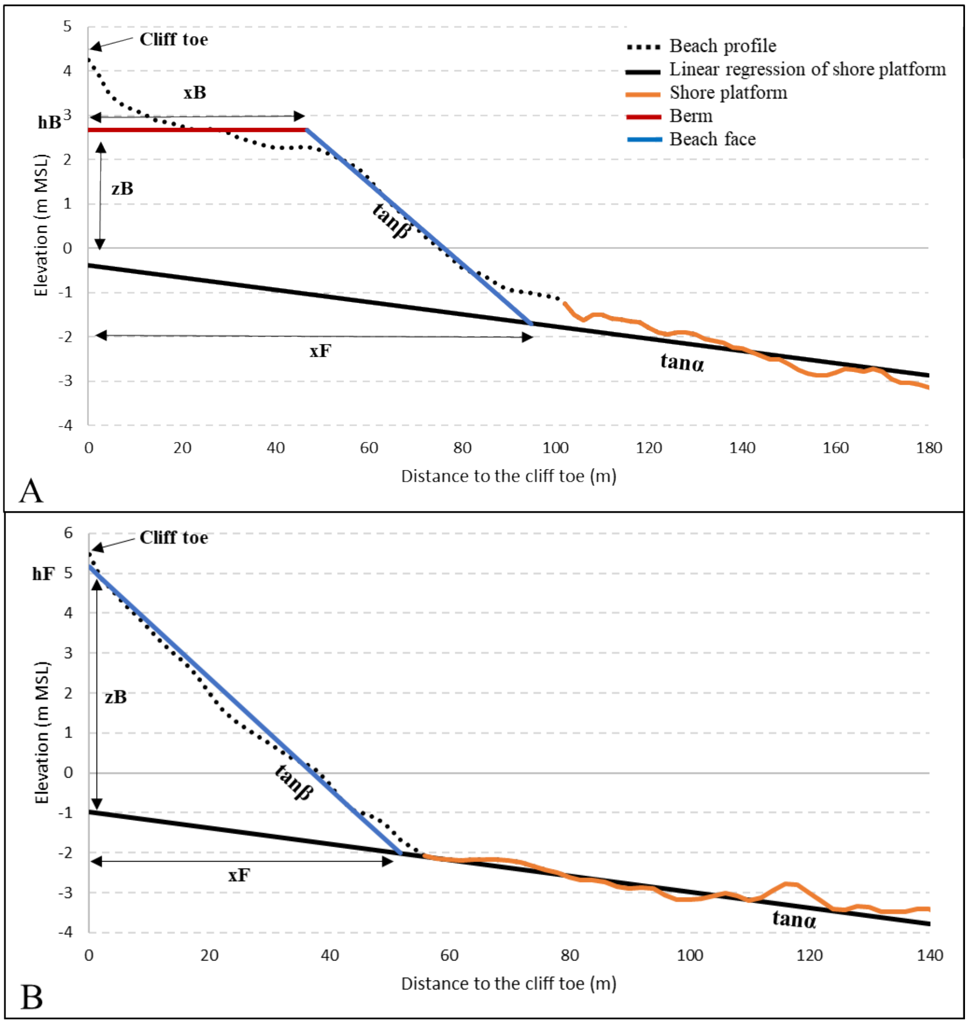

Figure 2 Representation of the morphological parameters for profiles with berm (A) and for profiles without berm (B). hB – berm elevation; hF – beach face elevation; zB – height of the sedimentary wedge; xB – berm width; xF – beach width; tanα – shore platform slope; tanβ – beach face slope.

2.2. Models of beach profile response

Two models of platform beach profile response were applied according to the morphological types of the profiles. For profiles with berm for which the total erosion of the berm after SLR does not occur, the model developed by Taborda and Ribeiro (2015) was used to determine the berm evolution and associated morphological changes. The model considers that the berm will adapt to SLR through an increase in height by the exact same value as SLR, as well as by a reduction in width in order to conserve the profile volume (Figure 3A). Thus, it considers embayed or pocket platform beaches as closed systems, without significant changes in terms of sedimentary volume through time.

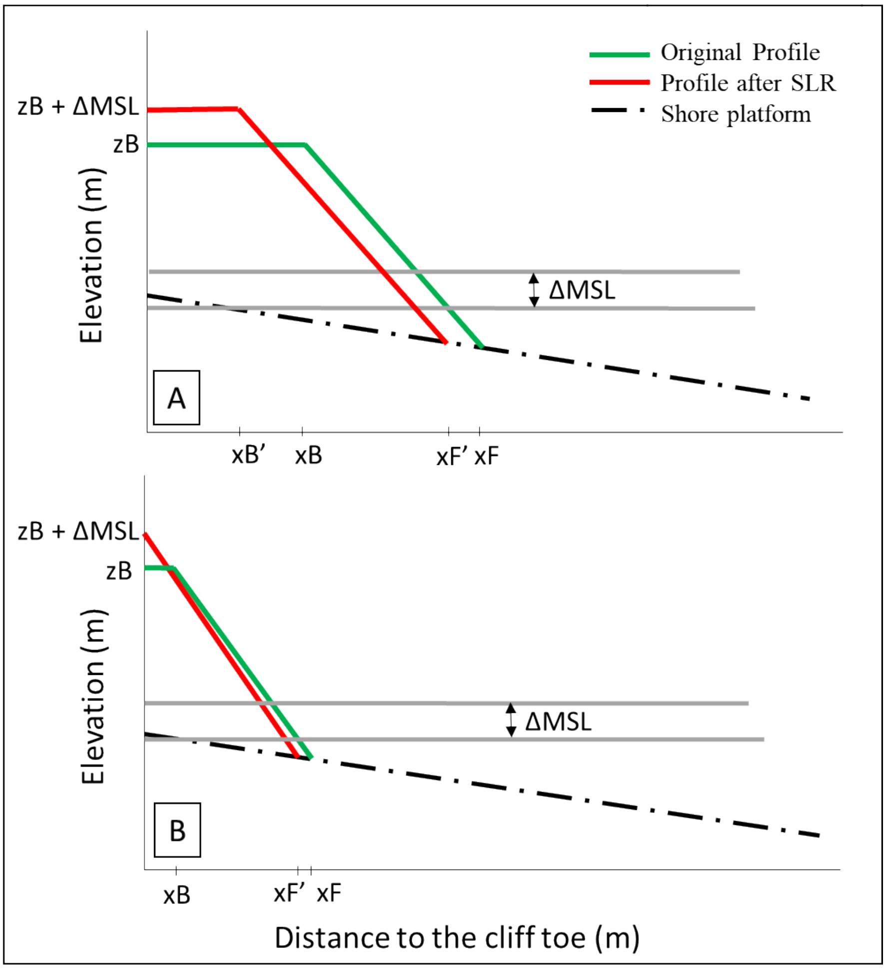

Figure 3 Conceptual models of SLR-induced beach evolution for a beach with parcial berm erosion (A) (adapted from Taborda and Ribeiro (2015)) and with complete berm erosion (B). zB – height of the sedimentary wedge; ΔMSL – variation of mean sea level, equal to SLR; xB – initial berm width; xB' – berm width after ΔMSL; xF – initial beach width; xF' – beach width after ΔMSL

According to Taborda and Ribeiro (2015) the total sedimentary volume (V) of platform beaches with a berm can be computed by:

$$V\,(xB,zB,\alpha,\beta) = zB \times xB + \frac{xB^2 tan\alpha}{2} + \frac{(zB + xB\,tan\alpha)^2}{2\,(tan\beta - tan\alpha)} \tag{1}$$

Considering the shore platform as horizontal (α=0) and the interception with the sea-cliff occurring at the mean sea level (MSL), the berm retreat (*R*), according to Taborda and Ribeiro (2015), can be calculated by using:

$$R = xB - \frac{xB \times zB + zB^2/2\,tan\beta - \,(zB + \Delta MSL)^2/2\,tan\beta}{zB + \Delta MSL} \tag{2}$$

As stated above, this model can only be applied to profiles with a distinguishable berm and where the berm retreat is less than the total berm width. For cases where the predicted erosion is larger than the berm width (Figure 3B), Taborda and Ribeiro (2015) model suggest a submergence of the profile. Once the berm is completely eroded the profile morphodynamics becomes dominated by beach face swash-related processes (c.f. Hughes and Turner, 1999). A higher sea level will lead to an increased mean wave height at breaking and near the cliff. In such conditions the shoreline submergence is counteracted by onshore sediment transport across the most of the shoreface and the equilibrium slope will be steeper (Aagaard and Hughes, 2017). The relatively larger impact of the waves on the seabed may cause sediment sorting on the beach, with removal of the fine sediment to deeper areas such that only the coarser sediment remains on the steeper (upper) parts of the profile (Aagaard and Hughes, 2017). This sedimentary gradation will also contribute to increase profile steepness near the cliff. A new model that considers platform beaches backed by cliffs, but where berms are inexistent and only a linear to sub-linear beach face exists is then necessary. The linear beach face is used for purposes of simplification since the developed profile may have a concave shape (as the equilibrium profiles represented by Aagaart and Hughes, 2017) and/or variable slope gradients.

Here, we describe such a model for berm-less platform beaches, maintaining the main assumptions of Taborda and Ribeiro (2015) model, including an invariant average wave climate and the conservation of the sedimentary volume. To model the morphological response of a berm-less profile to SLR the following supplementary assumptions are considered:

- The beach face elevation reflects the averaged maximum run-up to be reached for the existing wave conditions and sea level. SLR will lead to a vertical translation of the maximum run-up equal to the value of sea level change and to an equivalent increase in the beach face elevation, with a reorganization of the profile granulometry, where fin grains will be at the lower part of the profile, and the coarser at the upper part, according to Aagaard and Hughes (2017).
- The existing volume of a platform beach is maintained, thus if a vertical translation of the beach profile occurs, a change in slope, with increase in steepness, is required in order to maintain the overall sediment volume. The beach will experience a change in configuration, reflected by a

steeper and narrower profile. This modification will occur up to a given limit, which reflects a natural maximum slope that depends on grain size and incident wave characteristics, after which the beach profile is unable to adapt, and the beach starts to submerge.

Based on these assumptions, with *dF* calculated based on Eq. 3 (see Figure 4 for representation), the morphologic response of a berm-less profile to SLR is determined by the change in beach face slope (tan*k*), given by Eq. 4.

$$dF = \sqrt{zB^2 + dS^2} \tag{3}$$

$$tank = \frac{\sin i^2 \times \Delta MSL^2 - 2 \times dF \times \sin i \times \Delta MSL}{\Delta MSL^2 - dF^2} \tag{4}$$

Where *dF* is the sloping distance between the beach-cliff contact before SLR and the shoreline, given by the interception of the beach face with MSL after SLR; *dFS* is the sloping distance between the beach-cliff contact after SLR and the shoreline, given by the interception of the beach face with MSL after SLR; *i* is the angle between the cliff (vertical) and the beach face; *k* is the angle between the new and the initial beach face slopes, with *ΔMSL* being the SLR induced MSL change (Figure 4).

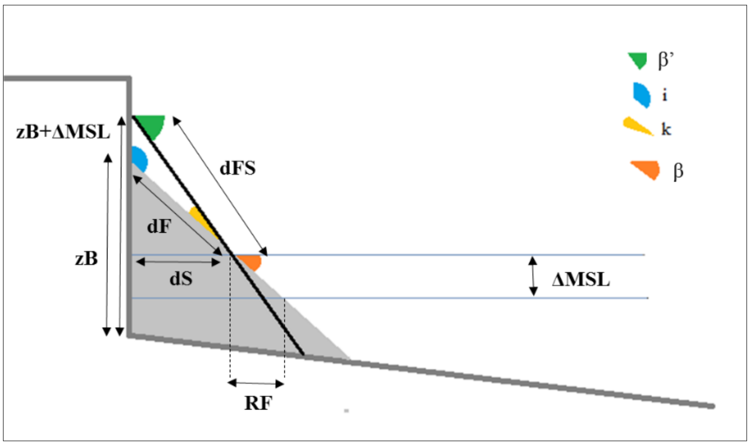

Figure 4 Model of profile response to SLR for platform beaches without berm, with indication of the beach width reduction (RF) and the slope change (k) associated to the SLR-induced morphological readjustment. The grey region represents the initial sedimentary wedge; in black the beach face after SLR; zB – height of the sedimentary wedge; i – angle between the cliff and the initial beach face; β – angle between the initial beach face and MSL after SLR; β'- angle between the beach face and the MSL after SLR; dS - the horizontal distance between the cliff and the coastline at the new shoreline position after SLR; dF - the sloping distance between the beach-cliff contact and the shoreline given by the intersection of the beach face with the MSL after SLR; dFS – the sloping distance between the cliff and the shoreline at MSL after SLR.

The variables *dF* and *dFS* in Figure 4 are assumed equal, since the difference between the two values is minimal (in the order of decimetres for the values of SLR projected for the 21st century), with insignificant deviations in the calculation of the new beach face slope (in the order of 10^{-2} to 10^{-3} of a degree).

Once the new beach face slope is determined, the beach width reduction (*RF*) is calculated according to:

$$RF = \frac{\Delta MSL}{tan\beta} \quad (5)$$

As in Taborda and Ribeiro (2015) model, we assume the conservation of the profile sedimentary volume before and after the SLR, so the volume for this type of profile (berm-less) is given by:

$$V\ (xF,zB) = \frac{xF \times zB}{2} \quad (6)$$

2.3. Carrying capacity and nourishment cost-effectiveness

Changes to beach morphology due to SLR will have relevant impacts in the beach carrying capacity, mostly by the reduction in beach width and area. In coastal regions highly dependent on beach-related tourism, this will have widespread socio-economic implications. To determine the changes to beach carrying capacity, considered here as the physical carrying capacity represented by the number of individuals a beach can physically accommodate (Pereira da Silva, 2002), it was necessary to translate the changes in beach width into changes in number of individuals. Based on the beach width reduction given by Equations 2 and 5, it is possible to estimates the changes in beach area between the cliff base and the new MSL after SLR. These can then be used to estimate the changes in the number of individuals that a beach can accommodate.

Changes to the beach carrying capacity are computed taking into consideration only the peak touristic season (July and August), when beaches are full or close to maximum carrying capacity (Teixeira, 2016). We assume that a reduction in beach carrying capacity implies the transference of beach users to other regions (or countries) if no other bathing beaches are available. The remaining months where not considered in the analysis since beaches have an occupation of less than 50% relative to the peak season (Teixeira, 2016). This implies that during all months except July and August, there is enough space to accommodate all of the tourists that use the beaches in the study area, even with a reduction in usable area due to sea level rise. Considering the above assumption, estimations of the potential monetary losses to the local economy caused by SLR-induced morphological changes in pocket platform beaches by 2100 are obtained by:

$$E_i = \frac{D \times (A_{ref} - A_{2100})}{Cc} \quad (7),$$

Where E_i is the economic loss for each beach (*i*), *D* is the average daily expenditure per beach user, A_{ref} is the beach available area in the reference year, A_{2100} is the beach available area in 2100 and *Cc* is the carrying capacity unit area, i.e. the surface area that each individual requires on a beach. The estimate of potential monetary loss (*Et*) to the local economy is given by:

$$E_t = \sum_{i=1}^{n} E_i \quad (8),$$

Where, *i* represents each beach and *n* the total number of considered beaches in the study.

In order to mitigate the impacts of SLR-induced morphological changes in pocket platform beaches, beach nourishment is here considered as the most suitable measure, as it allows to maintain or widen a beach, counteracting the effects of SLR (e.g. Leatherman, 1989). Furthermore, since these beaches are limited by salient headlands and shore platforms, it is reasonable to assume that sedimentary losses are slow and the lifetime of a beach nourishment is high. According to Loureiro *et al.* (2012), beach rotation and cross-shore sedimentary exchanges dominate at the studied beaches from the Algarve, while sediment transfer between pocket beaches is relatively reduce. However, at beaches bordered by less prominent headlands the sedimentary losses could be more significant and the lifetime of a beach nourishment smaller. It must be stressed that the current study only considers pocket beaches with prominent headlands and, therefore, with a reduced capacity of longshore sedimentary exchange.

To calculate the volume of sediment required to nourish each beach, two different approaches were used according to profile type. For beaches with berm, the model of Taborda and Ribeiro (2015) can be used to estimates the nourishment volumes per profile according to:

$$V_{nourishment} = V(xB, zB + \Delta MSL, \alpha, \beta) - V(xB, zB, \alpha, \beta) \tag{9}$$

while for beaches without berm, the nourishment volume per profile is given by:

$$V_{nourishment} = V\ (xF, zB + \Delta MSL) - V\ (xF, zB) \tag{10}$$

Since each profile (*j*) represents a given length of the beach (L_j), the total nourishment volume for each length of beach (V_p) is obtained by:

$$V_p = \sum_j^1 V_{nourishment} \times L_j \tag{11}$$

As each beach is represented by more than one profile (*i*), the final nourishment volume for all beaches (V_{tp}) is determined by:

$$V_{tp} = \sum_i^1 Vp \tag{12}$$

The estimated cost of the nourishment is then computed according to:

$$Nc = V_{tp} \times S \tag{13}$$

Where *S* refers to the cost associated to each m^3 of nourished sand.

A simple cost-effectiveness evaluation can be made with the following dimensionless index:

$$Nce = \frac{Et}{\left(\frac{Nc}{Ylt}\right)} \tag{14}$$

Where *Ylt* is the estimated lifetime of a nourishment (in years) and *Et* is obtained according to Equation 8. In the absence of indications regarding nourishment lifetime *Nce* represents the number of times that potential losses are higher than the costs of the beach nourishment. Thus, a value of Nce = 1 represents neutral cost-effectiveness, Nce < 1 represents a negative cost-effectiveness, while Nce > 1 represents positive cost-effectiveness.

3. Application to southern Portugal

3.1. Study area

The study area, located in the south coast of Portugal, comprises approximately 100 km of rocky coastline between the Cape of S. Vicente and the Olhos de Água Beach (Figure 5). This coastal area is dominated by sea-cliffs, cut on Miocene biocalcarenites and Mesozoic marls, claystones and limestones (Manupella, 1992; Moura, *et al.*, 2006; Teixeira, 2006; Teixeira, 2014). The cliffs are interrupted by small to medium embayments where several pocket beaches have developed (Ferreira and Matias, 2013). Resting on top of shore platforms and boulder accumulations, these beaches generally have reduced sediment thickness and volume (Loureiro *et al.*, 2012). Southern Portugal is exposed to a moderately energetic wave climate, being partly protected from the North Atlantic waves, which experience significant refraction and diffraction before reaching this coast. Average annual significant wave height and peak period are about 1 m and 8.2 s, respectively, while the dominant wave direction is W-SW (71%) with E-SE condition (23%) being also relevant (Costa *et al.*, 2001). The area is mesotidal with a mean tide range of 2.2 m reaching up to 3.5 m during spring tides. Based on tide gauge data from Cascais (near Lisbon), Antunes and Taborda (2009) calculated a SLR rate of 2 mm/yr between 1920 and the beginning of the 21st century for the coast of Portugal. SLR rates computed for this tide-gauge (Antunes and Taborda, 2009) are consistent with global trends published by the IPCC.

In this study, we analysed 32 pocket or embayed beaches (Figure 5) that are confined between two headlands, backed by a sea-cliff and vertically limited by a shore platform. Only beaches that have not been impacted by coastal engineering activities, including beach nourishment prior to 2011 or construction of seawalls and groins, were included in the analysis as these can evolve naturally under SLR scenarios. The 32 beaches selected are all officially classified as bathing beaches by the regional environmental authority (APA Algarve).

Overall, the beaches along the study area can be considered as pocket or small embayed beaches (Teixeira, 1999). On average, these beaches have a length of approximately 350 m, but lengths can range from less than 100 m to over 1 km. Average beach width is 50 m, displaying also a wide variability and ranging from close to 15 m to over 150 m. The majority of beaches in the area are composed of medium to coarse sand and have a relatively steep beach face (mean *tanβ* above 0.1). Morphodynamically, the beaches along the study area can be classified as reflective or intermediate towards reflective (Loureiro *et al.*, 2013).

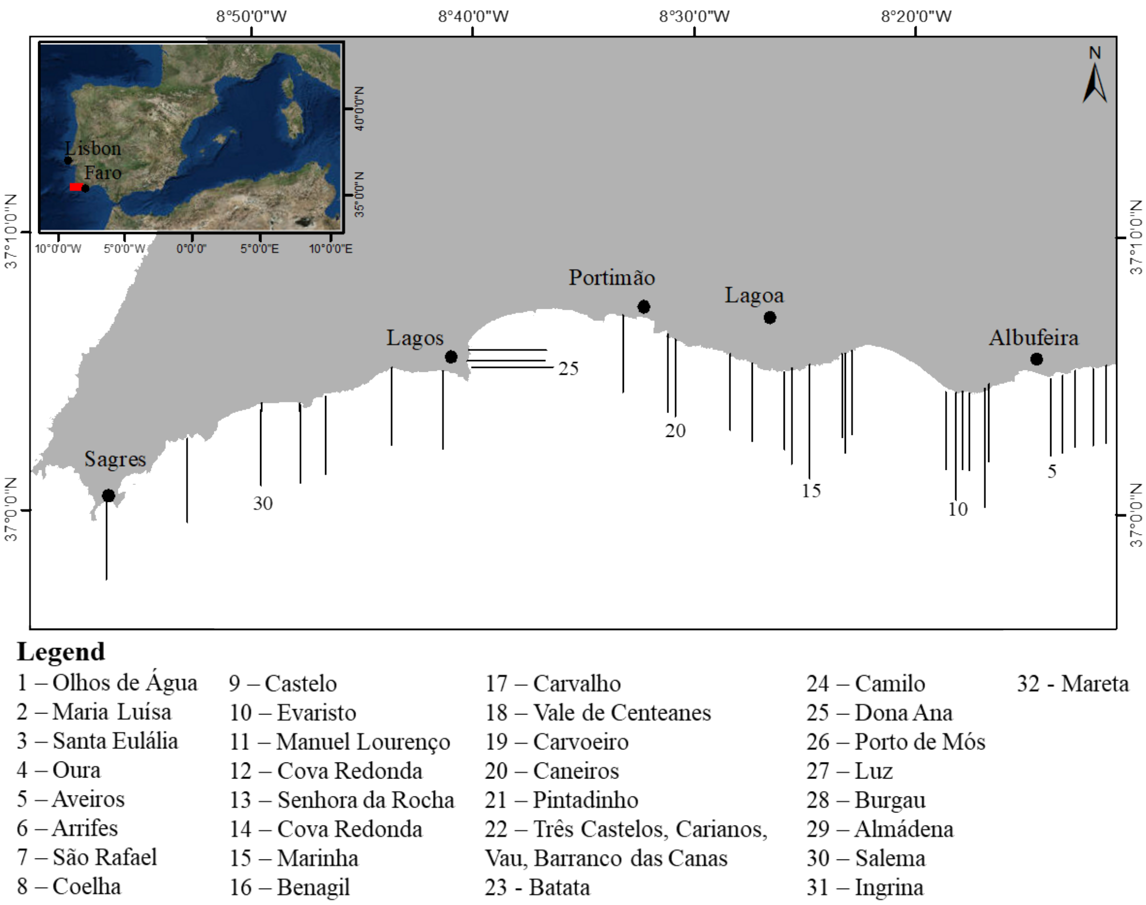

Figure 5 Distribution of the selected beaches along the southern coast of Portugal. Each beach (or group of beaches when they are interconnected) is identified by a referencing number from east (1) to west (32). Source:Esri, DigitalClobe, GeoEye, Earthstar Geographics, CNES/Airbus

3.2. SLR projections

According to the RCP8.5 scenario the IPCC estimates a SLR between 0.52 and 0.98 m for 2100 in comparison to the reference level of 1986-2005 (Church *et al.*, 2013). For this study, we considered a SLR of 0.52 m as scenario A and a SLR of 0.98 m as scenario B. Scenario B represents a worst-case scenario when compared to other IPCC scenarios and, as such, we are considering an intermediate and a potential worst-case scenario beach response. Recent estimates of SLR in Portugal suggest a rate of 3.3 mm/yr for the past decade (Antunes and Taborda, 2009). Considering this value as the SLR rate for 2005 to 2011 and assuming a linear SLR evolution, we estimated SLR rates of 5.6 and 10.8 mm/yr between 2011 and 2100 for scenarios A and B, respectively.

3.3. Morphological response to SLR in southern Portugal

A high-resolution topo-bathymetric LiDAR (Light Detection and Ranging) dataset from the national coastal survey performed in 2011 (Silva, *et al.*, 2012) was used to extract cross-shore profiles in each beach. The number of profiles extracted was a function of beach length: 2 profiles for beaches less than 200 m long; 3 profiles for beaches with lengths between 200 and 500 m (e.g. Figure 6); for beaches longer than 500 m, one profile was extracted at 250 m intervals. A total of 94 profiles of the nearshore and beach were obtained from the 32 beaches considered.

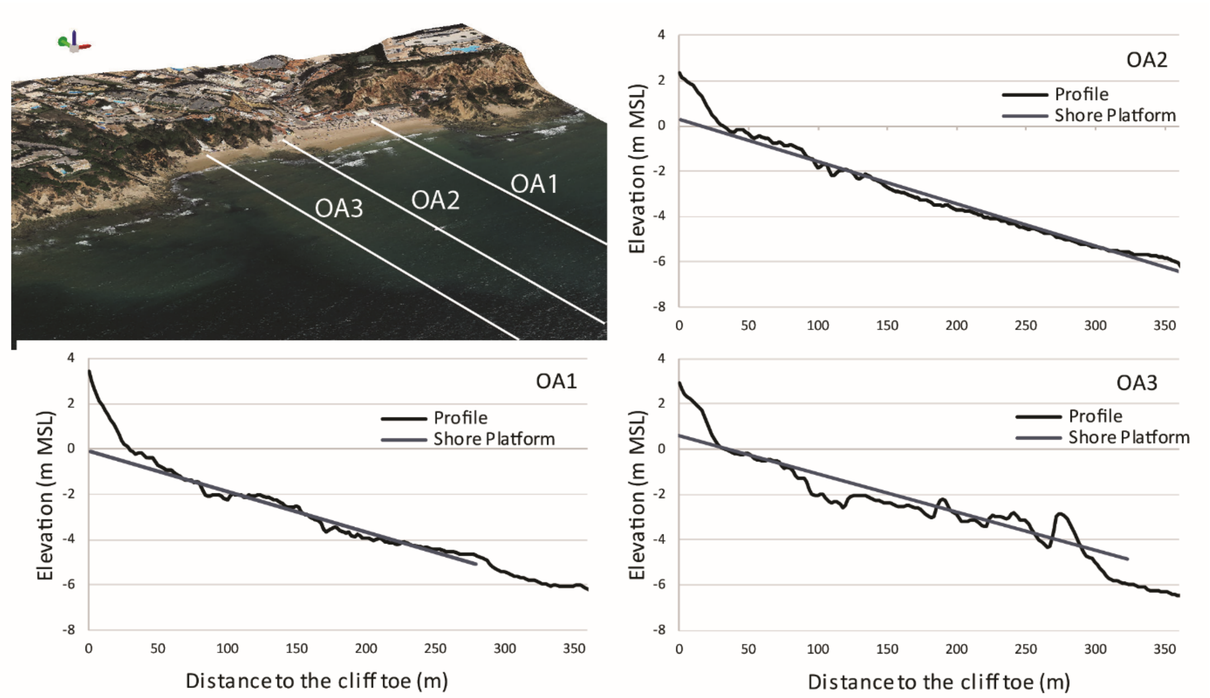

Figure 6 Cross-shore profiles extracted in Olhos de Água beach and 3D view of the beach

From the 94 profiles analysed 51% presented a clearly defined berm and 49% were characterized by a linear to sub-linear beach face, without a berm. For profiles with a berm the equations 1 and 2 were used for calculation of profile volume and berm retreat after determining the values of the parameters *xB*, *xF*, *zB*, *tanα* and *tanβ*. For berm-less profiles the equations 5 and 6 were used to calculate the new beach face slope and volume after the extraction of the parameters *k*, *zB*, *i*, *β*, *β'*, *dS* and calculation of *dF* (Eq. 3). Considering the estimated SLR rates for scenarios A and B, the year at which total berm erosion occurs (*xB* = 0) and the corresponding height of the sedimentary wedge (*zB*) were also computed for each profile that undergoes a change in profile type between 2011 and 2100.

Based on a SLR of 0.52 m, as defined for scenario A, only one profile with berm will experience complete berm erosion. For the remaining profiles, the berm will retreat on average 7.6 m (Table 1). Considering scenario B, total erosion of the berm is estimated for 15 of the 48 profiles with an initial berm. For the remaining 33 profiles an average berm retreat of 9.8 m is expected (Table 1). Results in Table 1 need to be analysed with caution, as average berm retreat values include only profiles where the berm is maintained. For example, average berm retreat in scenario A considers 47 of the 48 profiles with initial berm, while in scenario B total erosion of the berm in 15 profiles implies that average berm retreat is computed for 33 profiles only.

Figure 7 demonstrates the morphologic evolution of a profile with berm (São Rafael beach, n. 7 in Figure 5) for both SLR scenarios. Here, a berm retreat of more than 4 m in scenario A and 8 m in scenario B is expected.

Table 1 Average values of the morphological parameters analysed and calculated for profiles with a berm in 2011 and in 2100, according to scenarios A and B

	2011	Scenario A	Scenario B
xB	20.6 m	13.0 m	11.1 m
hB	3.0 m	-	-
tanβ	0.12	-	-
R*	-	7.6 m	9.5 m
RF**	-	2.0 m	11.8 m

xB – berm width; *hB* – berm elevation; *tanβ* – beach face slope; *R* – berm retreat; *RF – beach face retreat; * The berm retreat does not include profiles experiencing total erosion of the berm; ** The beach face retreat was calculated only for profiles where total erosion of the berm is predicted.*

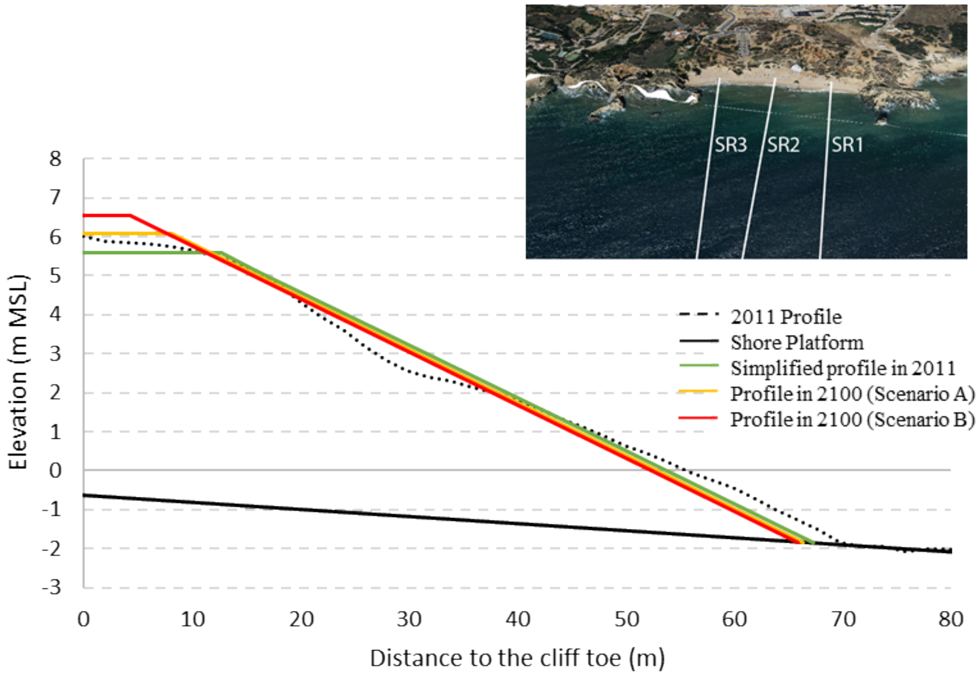

Figure 7 Morphological evolution of a profile with berm (SR2) in São Rafael Beach and 3D view of the beach

An average increase in beach face slope from 012 to 0.15 is expected for berm-less profiles under scenario A while the average width of the beach at MSL will be reduced by 5.8 m (Table 2). According to scenario B the average beach face slope will increase from 0.12 to 0.19 in 2100, accompanied by an average reduction in the width of the beach at MSL of 9.6 m

Some of the beach slope values predicted using the new model are considered to be out of equilibrium with the local sediment and wave forcing characteristics. According to the original profiles analysed in this study, the beach face slope ranges between 0.04 and 0.20, considering both types of profiles. This suggests that beach slope values higher than 0.20 are unlikely to be reached in this area, with modelled beach face slopes steeper than 0.20 considered as out of equilibrium. Beach face slope will increase to values higher than 0.20 in only one profile for scenario A, while under scenario B a total of 11 profiles will reach beach face slopes in excess of 0.20. These profiles could then be considered to potentially suffer submersion.

The morphological evolution of a berm-less profile is presented in Figure 8 (Castelo beach, n. 9 in Figure 5), where beach face increases from 0.14 in 2011 to 0.16 or 0.18 according to scenario A or B, respectively. Profiles that undergo a change in profile type under SLR are exemplified in Figure 9 (Maria Luísa beach, n. 2 in Figure 5), where the complete erosion of the berm leads to a transition to a berm-less profile and increase in beach face slope for scenario B.

Table 2 Average values of the morphological parameters analysed and calculated for berm-less profiles in 2011 and in 2100, according to scenarios A and B

	2011	Scenario A	Scenario B
hF	3.1 m	-	-
tanβ	0.12	0.15	0.19
RF	-	5.8 m	9.6 m

hF – beach face elevation; *tanβ* – beach face slope; *RF* – beach face retreat

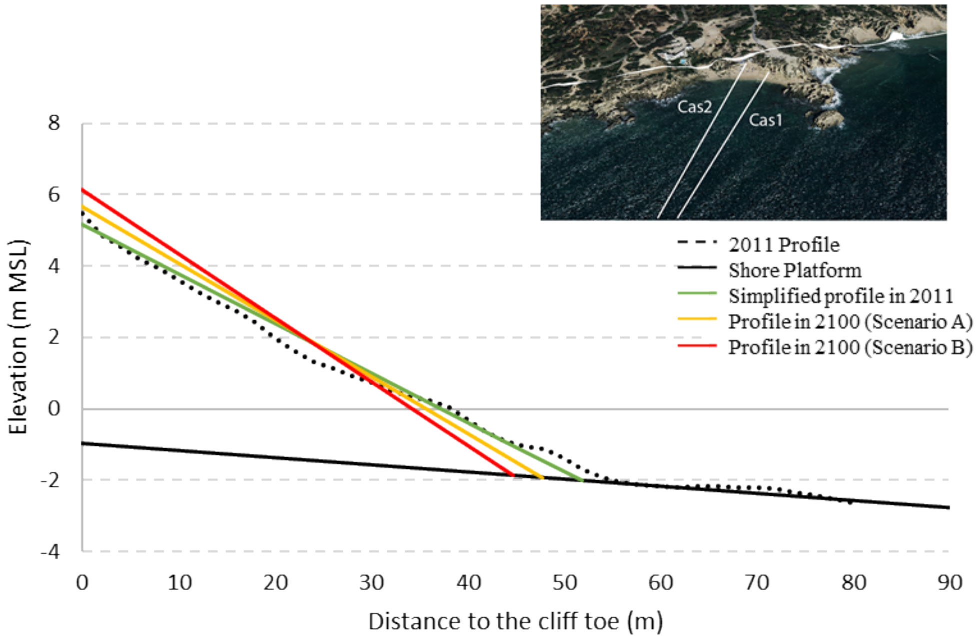

Figure 8 *Morphological evolution of a berm-less profile (Cas1) in Castelo Beach and 3D view of the beach*

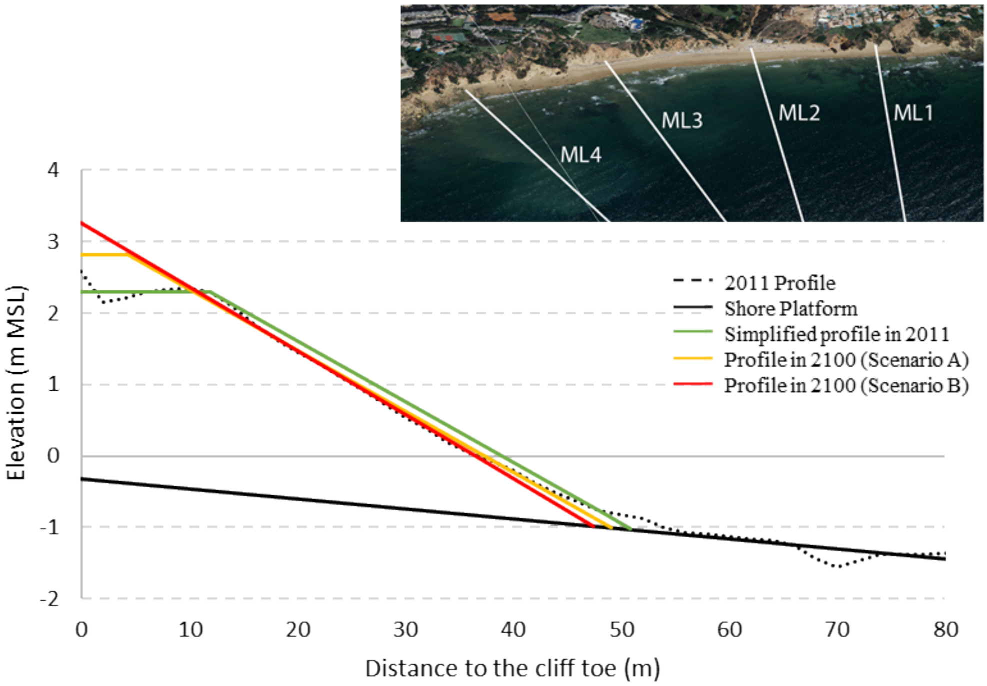

Figure 9 Morphological evolution of a changing berm type profile (ML4) in Maria Luísa Beach and 3D view of the beach

Berm and beach face retreat along the study area for the worst-case scenario are presented in Figure 10 and 11, respectively. No overall spatial pattern can be identified, either in terms of retreat values or the complete berm erosion cases (depicted by the star in Figure 10) or out of equilibrium beach face slopes (depicted by a star in Figure 11).

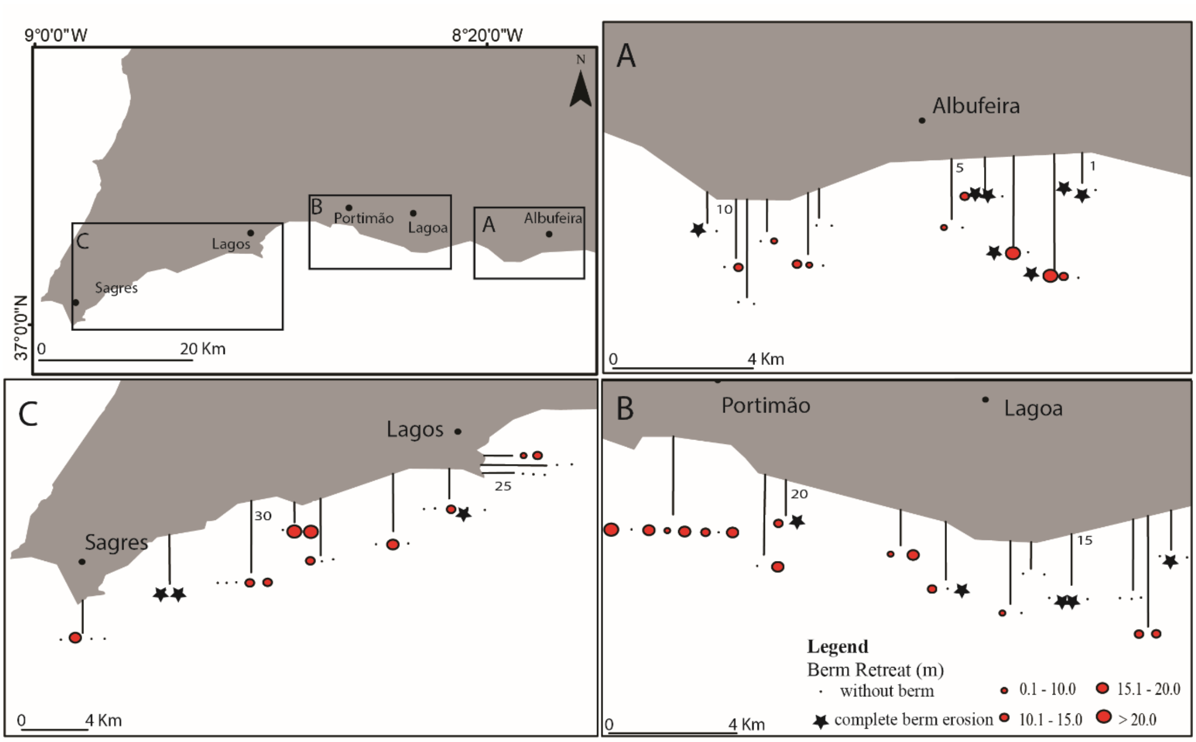

Figure 10 Modelled berm retreat per profile according to scenario B. The numbers represent each beach according to Figure 5

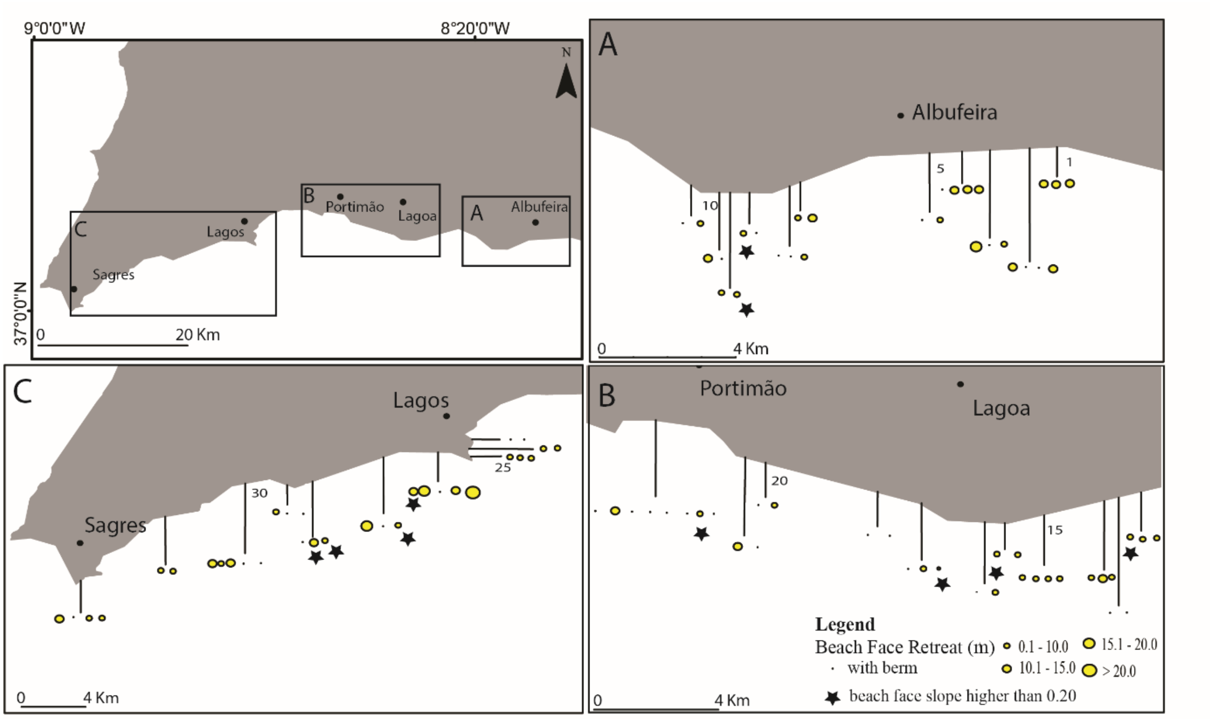

Figure 11 Modelled beach face retreat per profile according to scenario B. The numbers represent each beach according to Figure 5

3.4. Changes to carrying capacity and nourishment cost-effectiveness

Parameters for calculation of beach carrying capacity and nourishment costs for the southern Portuguese coast were based on published information from the regional and national environmental authorities. According to the current coastal management plans for the region, detailed in Teixeira (2016), the carrying capacity unit area, or area of beach that each individual requires, is defined as 15 m^2. In terms of beach nourishment costs, a recent national assessment indicates a value of EUR 6 per m^3 of sand (Santos, *et al.*, 2014).

The cost-effectiveness analysis was performed considering two scenarios: i) total loss (TL), considering that tourists move to another region, with a potential economic loss of EUR 136 per person per day, based on average daily expenditure per tourist (Correia and Águas, 2017); ii) local loss (LL), considering that tourists sleep in the same area but transfer their expenditure to activities away from beach areas. Based on this assumption, expenses related to accommodation (40% of the total expenditure according to Correia and Águas (2017)) are maintained, but not the expenditure related to travelling and other activities (food, shops, beach facilities, etc.). In this scenario, we assume a potential economic local loss of EUR 82 per person per day. The first scenario (TL) assumes a complete economic loss to the region and local economy (the tourist prefers other areas), while the second scenario (LL) assumes only a local loss for beach related activities (the tourist remains at the area but travels to other less crowded beaches/locations). Equations 7, 8, 9, 10, 11 12 and 13, and results from Equations 8 and 13 were used to compute the loss of daily users and consequent potential economic loss.

Changes to beach carrying capacity were computed only for the peak summer months in southern Portugal (July and August), under the assumption that these beaches are fully occupied during this period and there are no other bathing beaches with available space nearby to where beach users can move.

Using the carrying capacity unit area (15 m^2/person; Teixeira, 2016) the total carrying capacity for all the considered beaches, in 2011, is 32826 users/day. A reduction of 2619 daily users (8% of the users of all beaches in 2011) along the study area is expected for scenario A, which implies a potential LL of almost EUR 215,000 per day and a TL of more than EUR 356,000 per day, corresponding to a total of EUR 12.9 M and EUR 21.4 M per year, respectively, considering only the two occupation peak summer months at prices from 2016. Under scenario B, the reduction on beach area would lead to a loss of 4129 users per day (13% of the users of all beaches in 2011), representing a potential LL of more than EUR 338,000 and a TL of more than EUR 561,000 per day and EUR 20.3 M or EUR 33.7 M per year, respectively, again considering only the impact on July and August. Figure 12 presents the percentage of reduction in daily users per beach for each SLR scenario analysed.

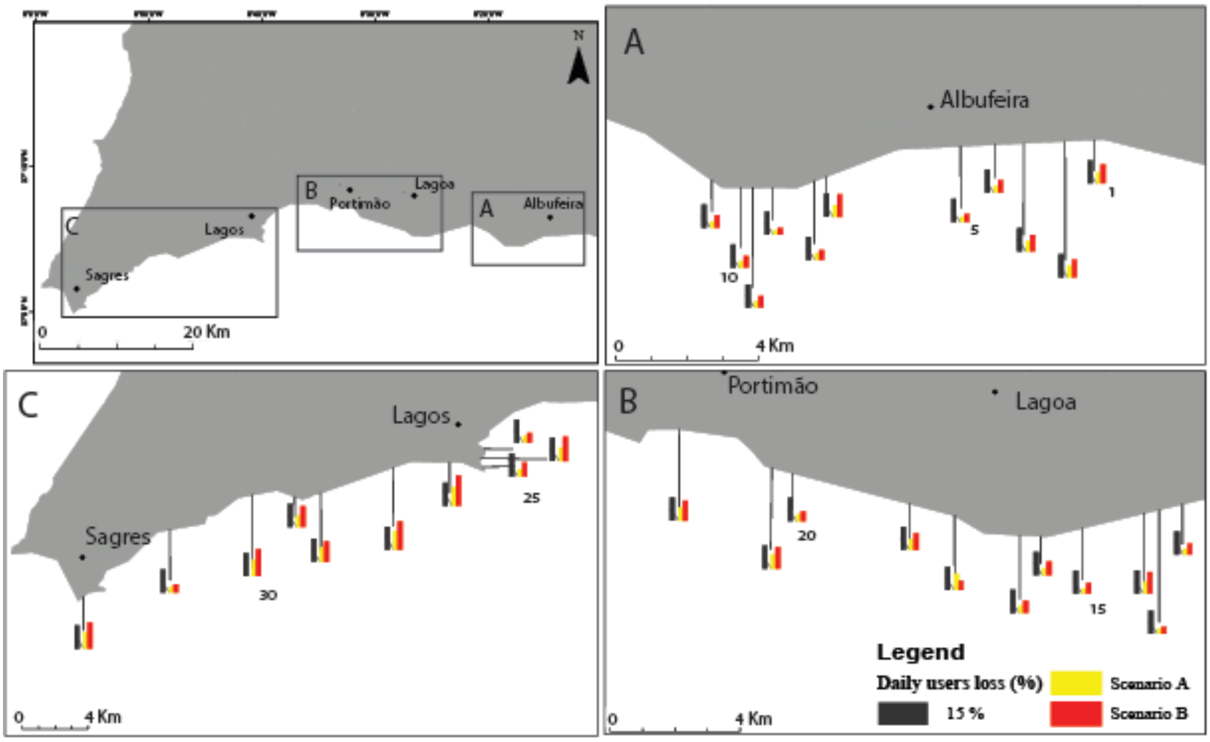

Figure 12 Reduction (%) of the daily users per beach for each scenario of SLR. The black bar represents 15% of reduction of daily users. The numbers represent each beach according to Figure 5.

The nourishment volumes required to mitigate the effects of SLR, based on maintaining the beach width and bathing area to the 2011 values, amounts to approximately 335,000 m^3 of sediment for scenario A and 644,000 m^3 for scenario B, representing costs of EUR 2 M and EUR 4 M respectively. The regional distribution of sediment requirements per beach (Figure 13) suggests that more sediment will be necessary for the westernmost section of the coast, as beaches in this area are generally wider and longer.

To compute the cost-effectiveness index (Eq. 14), nourishment lifetimes of 1 year (a highly unlikely situation of complete erosion of the nourished sediment after one year) and of 10 years (a reasonable estimate based on previous nourishments along the southern Portuguese coast) were considered. Yearly or decadal potential economic implications were also considered in the calculation of the cost-effectiveness index. Sediment nourishment is found to be cost-effective for most scenarios and lifetimes (Table 3), with the effectiveness index ranging from 0.48 (scenario B, 1 year lifetime, LL) to 23.53 (scenario A, 10 years lifetime, TT). Nourishment is not cost effective only for scenario B (higher sea level rise), if a 1 year lifetime and both scenario of potential economic losses are considered. Considering the more likely 10 years lifetime beach nourishment is 4.79 to 23.53 times more cost-effective than no-action.

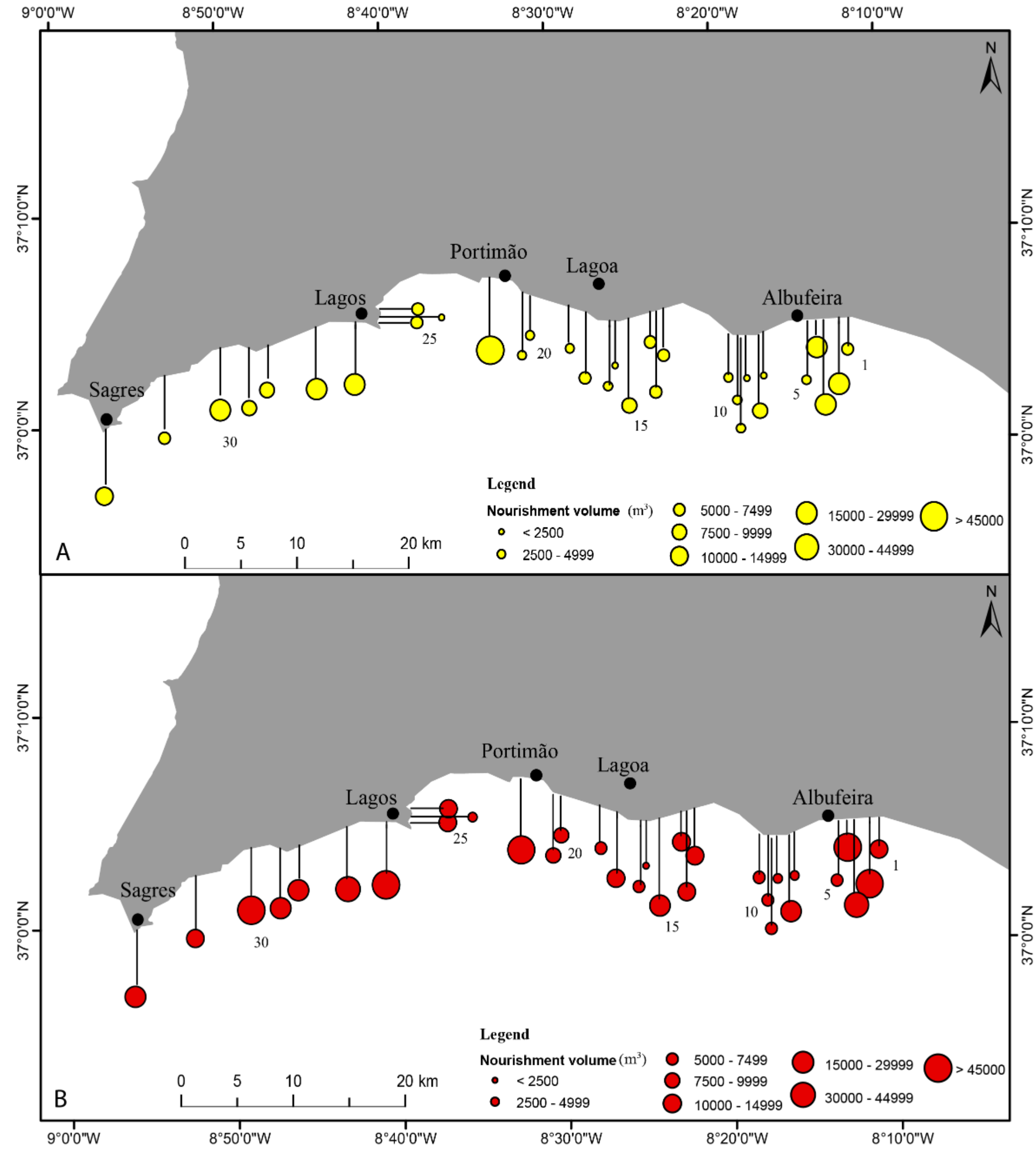

Figure 13 Nourishment volume per beach according to SLR scenario A (A) and B (B). The numbers represent each beach according to Figure 5.

Table 3 The cost-effectiveness Index according to the lifetime and SRL scenarios

Life-Time	***Scenario A***		***Scenario B***	
	TL	*LL*	*TL*	*LL*
1 year	2.35	1.42	0.79	0.48
10 Years	23.53	14.18	7.94	4.79

4. Discussion

4.1. Modelling of profile response to SLR in platform beaches

The morphologic response of pocket or embayed beaches to SLR was studied by several authors (e.g. Trenhaile, 2004, 2018; Brunel and Sabatier, 2007). Embayed beaches with strong geological control, i.e. backed by a cliff, laterally controlled by headlands and with a limited amount of sand over an underlying platform, do not comply with the Bruun rule assumptions and proposed morphological evolution. These are (practically) closed sedimentary systems, controlled by hard rock boundaries with sedimentary exchanges contained within the beach and nearshore areas (a closed sedimentary balance). The model proposed by Taborda and Ribeiro (2015), specifically designed for embayed or pocket platform beaches, was applied to investigate the SLR-driven morphologic evolution of beach profiles with a well-developed berm. However, for beaches without a berm Taborda and Ribeiro (2015) model simply assumes the submersion of the beach without any morphologic change of the profile, which is characterized by a linear to sub-linear beach face directly connecting the underlying shore platform and the cliff base. To study berm-less profiles or profiles undergoing total erosion of the berm after a given SLR, a new model is proposed. Both models, Taborda and Ribeiro (2015) for profiles with berm and the new proposed model for berm-less beach profiles, consider a closed sediment budget within each beach system. This implies that morphological changes at the upper section of the beach face must be counteracted by a morphological adjustment on the lower section of the beach face. Aagaard and Hughes (2017, p. 392) considered that *"on steeply sloping inner shelves/shoreface less attenuation of incoming waves occurs compared to gently sloping cases and thus the former experience relatively larger wave impact on the seabed, which may cause winnowing of fine sediment such that only the coarse sediment fractions remain on the steeper parts of the profile"*. Such changes in grain size across the beach profile provide support for the increase of the beach face slope on the model developed in this paper, since in constrained beaches with a fixed available sediment volume the beach profile will face a higher wave energy after SLR, due to lower wave attenuation in the nearshore.

Exposure to wave action along the southern coast of Portugal is highly influenced by geological control, with embayments exposed to significantly lower energy than headland (Bezerra *et al.*, 2011). This contributes to the compartmentalization of the coastline, providing support to the assumption that beaches along this coast are closed sedimentary systems and sedimentary exchanges amongst them is negligible. Beaches with low indentation ratios or with some degree of interconnectivity were not considered for analysis, or alternatively assumed as one single beach (e.g. the TCVB beach includes different beaches, as Três Castelo, Cariano, Vau and Barranco das Canas). Work by Loureiro *et al.* (2012) suggests that embayed beaches in southern Portugal generally maintain their sedimentary volume, with sediment exchanges within the different parts of the same beach. The closed sediment balance approach, although adequate for the studied beaches in a long-term context, exclude relevant sediment pathways (for southern Portugal or any other coastal area), since even embayed beaches may have sedimentary inputs (even if small) during episodic floods and/or due to cliff erosion (e.g. Nunes *et al.*, 2011). Sediment losses can also occur during extreme storms that have been found to drive sediment offshore, beyond the boundaries imposed by headlands (as suggested for the southwestern coast of Portugal by Loureiro *et al.* (2012b) and for southwest coast of England by Scott *et al.*, (2016)). The effects of these high-energy, low-frequency events were not considered in our study.

A limitation of the model developed for berm-less beaches is that beach face slope cannot increase indefinitely with SLR. The increase of the maximum run-up with the increase on SLR, associated to the rise of water level, considered to promote a shift of sediment within the sand wedge based on the beach face pivoting to conserve the sediment balance. Such increase in slope will reach a limiting value regardless of the continuity of SLR, which will be a function of sediment type and wave energy, as investigated by Sunamura (1984). For each sediment type (grain size) and wave conditions there will be a maximum equilibrium slope that cannot be exceeded. Nevertheless, variation in equilibrium slope for each sediment type can occur through reorganization of sediment, with the coarser material displaced to the top of profile and the finer to the lower part of the profile, as suggest by Aagaard and Hughes (2017). After such limiting steepness is reached, it is reasonable to assume that the beach will become progressively submerged as SLR continues. For the southern coast of Portugal the maximum observed beach face slopes are close to 0.20, reflecting the dominant grain size (medium to coarse) and the wave regime (moderate energy). It is then assumed that morphological adjustment to SLR in southern Portugal is limited to beach face slopes lower than 0.20, with submergence as SLR continues on beaches where such value is exceeded. In those cases, and particularly during high tide, the remaining beach carrying capacity will be lost. Beach face steepening to values above 0.20 was modelled for 15 profiles in 11 beaches (34.4%), suggesting that a relevant number of sites are expected to undergo submersion during high tide in 2100.

4.2. Socio-economic impacts

The reduction in the beach carrying capacity presented here is in agreement with studies performed in similar beach types, particularly the Greek islands where Alexandrakis *et al.* (2015), demonstrated that pocket beaches would be eroded due to SLR, thus decreasing their carrying capacity. Beach nourishment has been increasingly considered the best option to mitigate erosion and promote beach widening, including along several sites in the study area (Teixeira, 1999, 2016). These interventions, although aimed primarily at increasing the beach carrying capacity, are rarely evaluated from the point of view of mitigation of the economic losses associated with SLR. In this study, we propose a simple cost-effectiveness analysis that demonstrates that beach nourishment, even for relatively small lifetimes, is a cost-effective option for reducing the potential long-term economic losses. The approach developed is valid only for areas with very high occupation during summer months, where the touristic demand is very high during the peak of the summer season and all beaches are fully occupied. The cost-effectiveness of beach nourishment is naturally dependent on the daily expenditure by each tourist, which differs between locations, as well as the availability and cost of sediment for beach nourishment operations. Absence of suitable source of sand on nearby areas will significantly increase nourishment cost and, therefore, will affect the outcome of a cost-effectiveness analysis. For our case study, beach nourishment is considered a suitable mitigation measure with added value for the region, since the estimated costs are easily recovered through tourism activities. However, it must be noted that aesthetic changes to nourished beach where not considered and these may be relevant for the attractiveness of a beach and reduce its touristic value. Our assumption it that beach nourishment will be performed with sediment of similar characteristics to the original beach, maintaining the overall aesthetic value of the nourished beach.

According to the cost-effectiveness index computed for the southern Portuguese beaches based on two SLR scenarios and nourishment lifetimes, our simple estimates suggest that nourishment is a cost-effective option, even considering that beaches are only full during two months of the year. This is naturally influenced by our assumptions of economic losses, by considering that reduction in beach width and area due to SLR imply a complete change of tourists to other regions or countries (total loss) without adaptation to the new conditions, or at least, a loss of local economic activity.

5. Conclusion

The main objective of this study was to present a new approach for determining the evolution of platform beaches under SLR, including the development of a new morphological evolution model for berm-less platform beaches.

This approach integrates the model developed by Taborda and Ribeiro (2015) for pocket or embayed beaches with berm, our model for berm-less beaches, as well as combination of both models when complete berm erosion occurs during the modelling timeframe. This novel approach was applied to 32 beaches in the highly touristic area of southern Portugal (approximately 100 km-long). Our results indicate that SLR will cause a significant reduction of both berm and beach face width, thus reducing the emerged area of the beaches in southern Portugal. A significant number of beaches (34%) will experience complete berm erosion until 2100, while 28% of beaches (34.4% profiles) will become submerged at high tide, in the worst-case scenario (a SLR of 0.98 m, according to the RCP8.5 IPCC scenario). Consequently, a reduction in the carrying capacity of southern Portugal embayed platform beaches is expected. Beach nourishment was found to be a cost-effective measure to mitigate the projected reduction in beach carrying capacity in southern Portugal, given the significant potential losses for the local economy caused by reductions in available beach area.

The approach proposed is a simple exploratory model that includes several assumptions, and should be considered alongside the limitations highlighted and understood as a worst-case analysis. Application to other coastal areas with similar beach types is fundamental to provide further evaluation and incorporation of improvements and adaptations.

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