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Morphological and economic impacts of rising sea levels on cliff-backed platform 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 subaerial 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.

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. Cazenave & Llovel, 2010; Church et al., 2013; FitzGerald, Fenster, Argow, & Buynevich, 2008; Gornitz & Lebedeff, 1987; Solomon et al., 2007; 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

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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, Rahmstorf, Engelhart, & Kempe, 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, Garcin, Yates, Idier, & Meyssignac, 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. Davidson-Arnott, 2005; El-Raey, Frihy, Nasr, & Dewidar, 1999; Ferreira, Garcia, Matias, Taborda, & Dias, 2006; Hands, 1983; Leatherman, 1991). The Bruun rule has been widely criticised within the scientific community (c.f. Cooper & Pilkey, 2004; Pilkey & 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 & 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, Dias, and Taborda (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 & Milkins, 2015). Platform beaches, also known as perched beach (e.g. Gallop, Bosserelle, Eliot, & Pattiaratchi, 2012), are generally limited landward by a cliff (Taborda & Ribeiro, 2015) and laterally by rocky headlands (Loureiro, Ferreira, & Cooper, 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

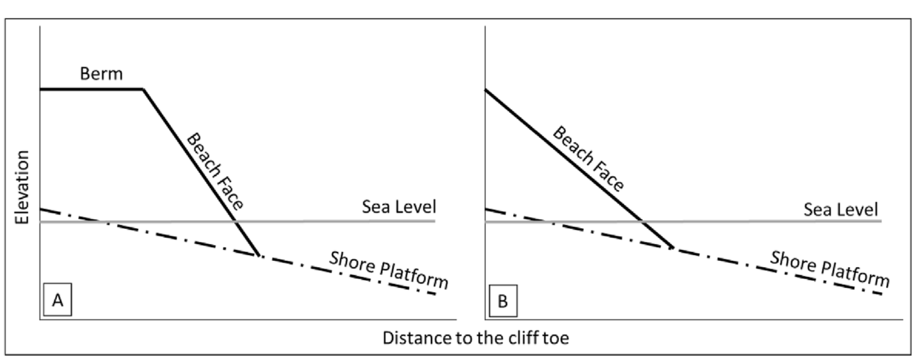

Fig. 1. Schematization of the different profile types. A – profile with a berm; B – profile without a berm (berm-less profile). The profiles are backed by a rocky-cliff.