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Hazard assessment in rock cliffs at Central Algarve (Portugal): A tool for coastal management

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ABSTRACT

Coastal hazards are in the interface of human activities with natural coastal processes. The conflicts arising from this relationship require new approaches suitable for coastal management that consider the dynamic of coastal areas. A method to assess hazard in rock cliffs is presented, combining cliff evolution forcing mechanisms along with protection factors, according to a weighted factors system. This method provides a rapid evaluation of vulnerability for cliffed areas, supporting coastal management and hazard mitigation. The method was applied to the rocky cliffs of the densely populated coastal zone between Galé and Olhos de Água (Southern Portugal), where high and very high hazard values were found to be dominant. A method validation was made using the vulnerability areas and the recorded mass movements over a 45 year period in the same area.

1. Introduction

Cliffed and rocky coasts occur along three quarters of the world's coastline [1]. Whilst they have not been as extensively studied as beaches or coastal wetlands, they have very specific evolution patterns causing irreversible loss of land and endangering human uses of the coast [2]. The historically limited human occupation of rocky cliffed coasts has resulted in relatively little attention in spatial planning terms. This situation has been dramatically altered with the advent of mass tourism, with rapid and unsafe development in coastal zones, exposing a growing number of people to the hazards associated with rocky environments. The resulting risks to human activity due to the inherent geomorphological instability of cliffed coasts have become a management problem of increasing magnitude [3], requiring new tools to evaluate the geodynamic of rocky cliffs for supporting effective coastal management.

Hazard studies on rocky coasts are mainly based on calculation of cliff retreat and determination of mass movements as the basis for hazard evaluation. The use of geotechnical monitoring can provide significant data for assessing hazard in rock cliffs. However, such techniques are expensive, time consuming and require high level of expertise, and are not available to most coastal managers. To provide tools that incorporate hazard in management of rock cliffed areas, a basic approach accounting for the main factors that control rock cliff evolution is presented. The use of factors that describe the short-term environmental dynamics, known as geo-indicators [4], can provide simple, semi-quantitative tools for assessing hazard that are valuable for coastal management but also scientifically valid [5]. Like most information concerning coastal environments, the factors involved in hazard assessment for rock cliffs are spatially referenced. Therefore, the geoprocessing capabilities of GIS (Geographical Information Systems), which are increasingly available to coastal managers, can be used to combine factors to produce hazard maps, since these provide a basis for hazard management and mitigation [6].

As a tool to improve coastal management in rock cliffs the method developed pretends to be a complement to historical erosion records or existing field experiments, as a rapid and suitable indicator of vulnerability, as well as a straightforward approach for cliff areas without previous hazard assessments. The method was applied to the coastal stretch Galé – Olhos de Água, in the southern coast of Portugal and, to evaluate results, the vulnerability areas were associated to the location of the recorded mass movements between 1947 and 1992.

2. Study area

The area considered in this research is the cliffed coast between Galé and Olhos de Água (Fig. 1), located in the Algarve, in southern

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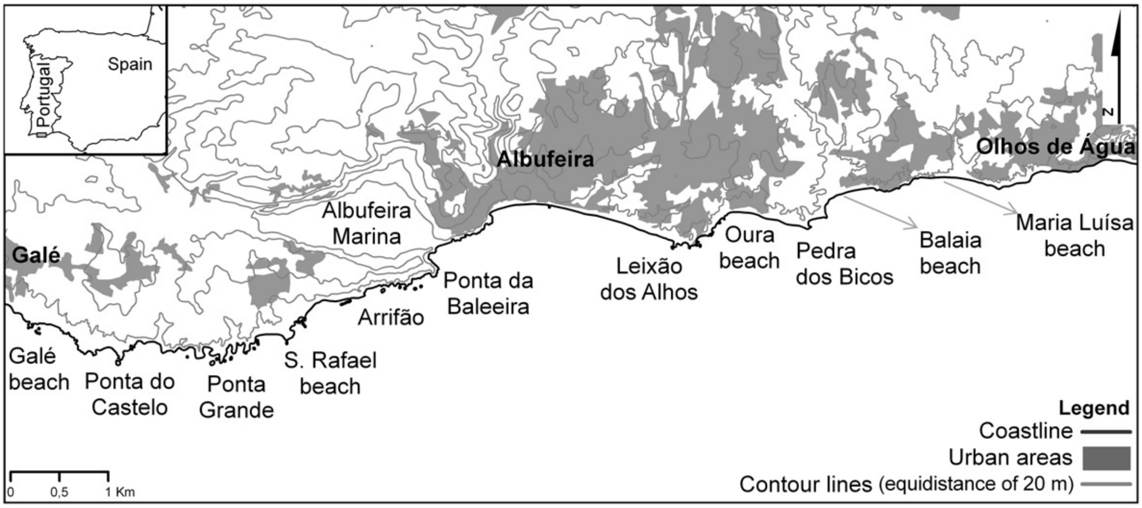

Fig. 1. Location of the study area (urban areas adapted from CNIG [7]).

Portugal. The advent of mass tourism in the 1980s has radically transformed the landscape of the region, resulting in the dense urbanisation of a narrow belt close to the coast and the overwhelming intensification of beach use and occupation [8]. It is estimated that edified areas currently account for 45% of the land within 2 km of the coast [9].

Previous work in this area has identified processes and mechanisms of rocky cliffs' evolution, defining retreat rates based on identification and measurement of mass movements through comparative analysis of aerial photographs between 1947 and 1992 [10]. In addition, Teixeira [8] quantified the relationship between mass movements in the cliffs exposing Miocene calcarenites and intense precipitation during storm events. Hazard evaluation in this area is limited to the study of Teixeira [11], which defined return periods for mass movements through statistical analysis.

2.1. *Physical setting*

Average precipitation values for the Algarve region demonstrate a clear distinction between summer and winter seasons [12], with the highest monthly average precipitation in December with 94 mm [13]. There are 310 rainless days during one year (daily precipitation < 1 mm), and over 10 mm per day only occurs on average 16.5 days per year [13], being one of the reasons for the high tourist demand.

There are two prevailing wave directions acting on the southern Algarve coast, with W-SW and SE waves accounting for 71% and 23% of incident waves respectively. Around 68% of significant wave height (Hs) is lower than 1 m [14]. The waves coming from the SE are generated by local winds, termed *Levante*, having Hs generally between 1 and 2 m [15]. The W-SW swell is associated with the higher significant wave heights [14]. Hs values higher than 3 m are considered as storms and occur less than 2% of the time, essentially during the maritime winter (October to March), and persisting no longer than two days. Wave conditions associated with storms arrive mainly from the SW (64% of the time), while stormy waves from SE account for 32% of the occurrences [13,14]. The tidal regime in the Algarve coast is semi-diurnal, with an average tidal range of 1.2 m for neap tides and 2.8 m for spring tides [16], resulting in a mesotidal coastal environment.

The 13 km coastal stretch between Galé and Olhos de Água exposes several lithologies ranging from limestone to calcarenite (Fig. 2), presenting a set of asymmetrically curved bays linking headlands which are sculpted mostly into horizontally bedded Miocene calcarenites. These lie on the vertical marls from the Cretaceous which are exposed only on the cliffs near Arrifão (Fig. 2). Active faults are responsible for the cropping out of the Cretaceous marls and the Jurassic limestone nearby Albufeira [20,21] (Fig. 2).

Though the main physical support of the area are Miocene calcarenites, they have a heterogenic fabric mainly due to the high content of fossil shells. Eastward from Albufeira the fossil content decreases and the calcarenite becomes sandier [19,22]. By the upper Miocene an intensive phase of karsification was responsible for the development of a karst landscape latter fossilized by siliciclastic sediments along the Pliocene and Pleistocene [23]. However, the low resistance of Plio-Pleistocene sediments to marine and subaerial erosion led to the exhumation of the karst features [10].

The morphology of the study area is controlled by a littoral platform developed close to the shore at elevations between 25 m and 45 m. This platform extends throughout the study area with various interruptions related to the incision of the hydrographical network. To the east of Albufeira the littoral platform presents an elevation around 30 m to 40 m, but widely eroded by gullies and rills. The consequent erosion of the littoral platform and the abundance of stacks resulted in the development of a very indented coastline [10,24]. The indented shape of the coastline (Fig. 1) is also favoured by the presence of active shore platforms, the majority of them cut on sub-horizontal Miocene rocks, gently dipping seaward [22]. Coastal morphological features in the study area also include pocket or embayed sandy beaches.

3. Methodology

3.1. *General approach*

For the present case study, the factors considered for generating the hazard index were divided into two groups: (i) the susceptibility factors (wave exposure, cliff lithology and profile) that add values to the hazard index; (ii) the protection factors (width of a protective beach and/or active shore platform sections) that subtract values from the hazard index. The combination of the weighted values allowed obtaining a composite index with hazard classes that were used to produce a hazard map for the current study area.

3.2. *Remote sensing & GIS*

In this study digital photogrammetry was used to produce a base imagery with high resolution for further analysis. However,

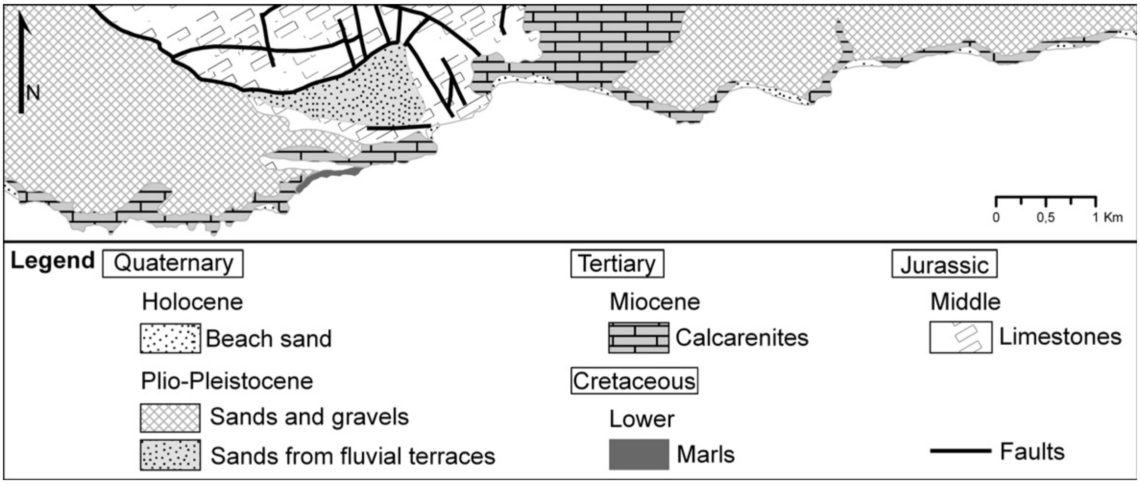

Fig. 2. Geology of the study area (adapted from IGM [17] and modified according to Albardeiro [18]).

nowadays for most coastal areas, accurate and high resolution airborne or satellite imagery can be obtained from mapping agencies and commercial services, without the need for image production, which may not be available to most coastal managers.

Ground Control Points were acquired using a Real-Time Kinematic Differential Global Positioning System. Vertical coloured analogue aerial photographs from 2001 were converted into digital files with a photogrammetric scanner and subsequently imported into Leica Photogrammetry Suite from ERDAS Imagine 8.7 software. The photographs were processed generating a georeferenced mosaicked image which was imported into ESRI ArcGIS 9.1® software to map the features and factors selected to evaluate hazard in rock cliffs. To ease the on screen digitizing tasks, photo-interpretation sketches of the cliff top line, high water line (HWL), active shore platforms and lithology were done using a TOPCON MS-3 mirror stereoscope. Field surveys were carried out to identify and register the main geological and geomorphological features of the area to be later used as ground truth data.

For the purpose of this study the cliff top line refers to the intersection of the cliff face and the undisplaced material adjacent to the cliff face [25]. The cliff top line, as the reference feature, was considered to be the cartographic baseline for the hazard map. Therefore, the weight values of each feature were assigned to that baseline for quantification and for displaying the final hazard map.

3.3. *Hazard factors*

3.3.1. *Susceptibility factors*

The knowledge of wave conditions is essential in coastal studies and, for cliff hazard assessment, the characterization of coastline exposure to wave action is paramount. To assess the contribution of wave exposure to hazard in the rock cliffs of the study area, the cliff top line was divided into segments exposed to a similar incident wave direction. Wave data concerns the offshore incident wave at Faro buoy, split by directions and presented in percentage of occurrence along with the mean wave height for each direction [14,26] (Table 1).

The weight values were obtained directly from the multiplication between the occurrence percentage for each direction and the respective mean wave height (Table 1).

The azimuth of each coastal segment was obtained with ArcGIS script *FindPolylineAngle* [27]. Values of 45°, 90°, 135° and 180° were added to all segment's azimuth (Fig. 3), to obtain the exposition along a 180° semi-circle offshore and verified in which octant interval the wave exposure is observed (Table 1). The sum of the weight values of each direction according to the segment's exposure (Fig. 3) results in the total weighting of wave exposure. This value is then imported into the cartographic baseline (cliff top line) to allow the hazard index calculation.

The nature and cohesiveness of rock cliffs are decisive factors in their erosion susceptibility [28]. With reference to this and the fact that cliffs' profile are mostly the product of marine erosion and subaerial processes [29], led to the consideration of a joint evaluation of cliff face lithology and profile. Cliff nature is characterized for each coastline segment according to the lithologic composition. These lithologies (Fig. 2) were correlated to the cliff profile matrix adapted from Emery and Kuhn [30], to take into account the cliff shape as a result of marine versus subaerial erosion (Fig. 4). The Jurassic cliffs have not been considered as they are presently protected by a marina and not influenced by marine action.

Cliff profile categorization was supported by photographs and records. Based on the adjusted matrix, the weighting values were assigned to each class in a scale from 0.1 to 1, according to their resistance to erosion (Fig. 4). Thus, the more resistant and

Table 1
Wave climate at Faro [14,26] and weight values.

Direction	Degrees (°)	Occurrence (%)	Mean wave height (m)	Occurrence × mean wave height	Weight value
N	337.5–22.5°	–	–	–	–
NE	22.5–67.5°	0.4	0.6	0.24	0.002
E	67.5–112.5°	3.5	1.0	3.5	0.035
SE	112.5–157.5°	23.2	1.2	27.84	0.278
S	157.5–202.5°	2	1.0	2	0.02
SW	202.5–247.5°	18.3	1.0	18.3	0.183
W	247.5–292.5°	52.3	0.8	41.84	0.418
NW	292.5–337.5°	0.2	0.8	0.16	0.002

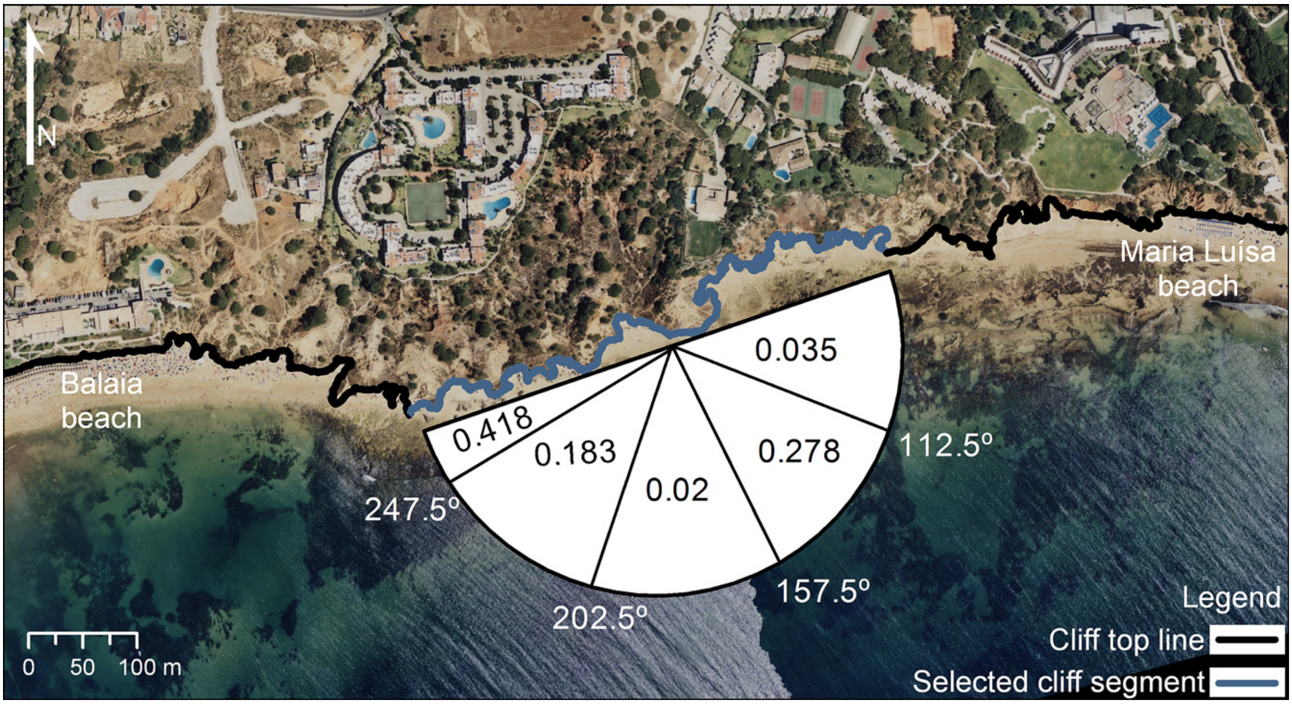

Fig. 3. Example of a segment exposed from 71° to 251° and respective weight values.

homogenous materials with dominant subaerial erosion have lower weighting, while the less resistant, heterogeneous materials, exposed to marine erosion have the highest values. The combined code and weight value of cliff lithology and profile for each coastal segment was imported to the cartographic baseline.

3.3.2. Protection factors

The existence of a beach, permanent or seasonal, offers a valuable cliff defence from marine erosion [29]. Beaches dissipate the wave energy along the foreshore and consequently reduce considerable cliff susceptibility to erosion [31]. Although subjected to the tidal regime and wave climate, Everts (1991) cited in [25] reported that, in California, a beach width of 20 m to 30 m provided considerable protection to cliffs, while a beach width of 60 m offered complete protection to the direct wave's attack onto the cliffs.

To support the calculation of average beach width and, consequently, the degree of protection, the HWL was considered as reference feature for the dry beach limit. The cliff top line was used as the landward limit of the dry beach in alternative of the cliff foot line, since it was impossible to distinguish it from vertical aerial photographs. The HWL was selected as the suitable marker for the land-water interface [32] since it is the evidence of the landward limit of high tide combined with wave action. The aerial photographs used in this study were taken on the 23rd and 24th of July, 2001, which maintains a reasonable criterion for width calculation, since beach width and high tide oscillations are minimised.

The HWL of each beach was digitized on screen in ArcGIS using the tonal contrast wet/dry line on the sand (Fig. 5), supported also by the HWL sketches created from photo-interpretation. According to the general direction of the coast and at an approximate distance of 10–20 m, perpendicular lines were drawn from the HWL to the cliff line in order to calculate the average beach width.

The classes of beach protection were obtained by computing the cumulative frequency of average beach width generating a total of

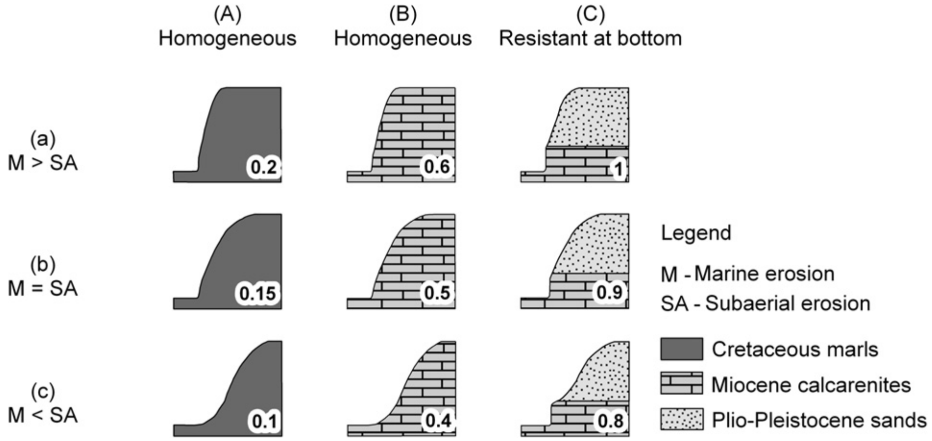

Fig. 4. Matrix of cliff face lithology and profile for the study area (adapted from Emery and Kuhn [30]). Weight values are indicated in the figure.

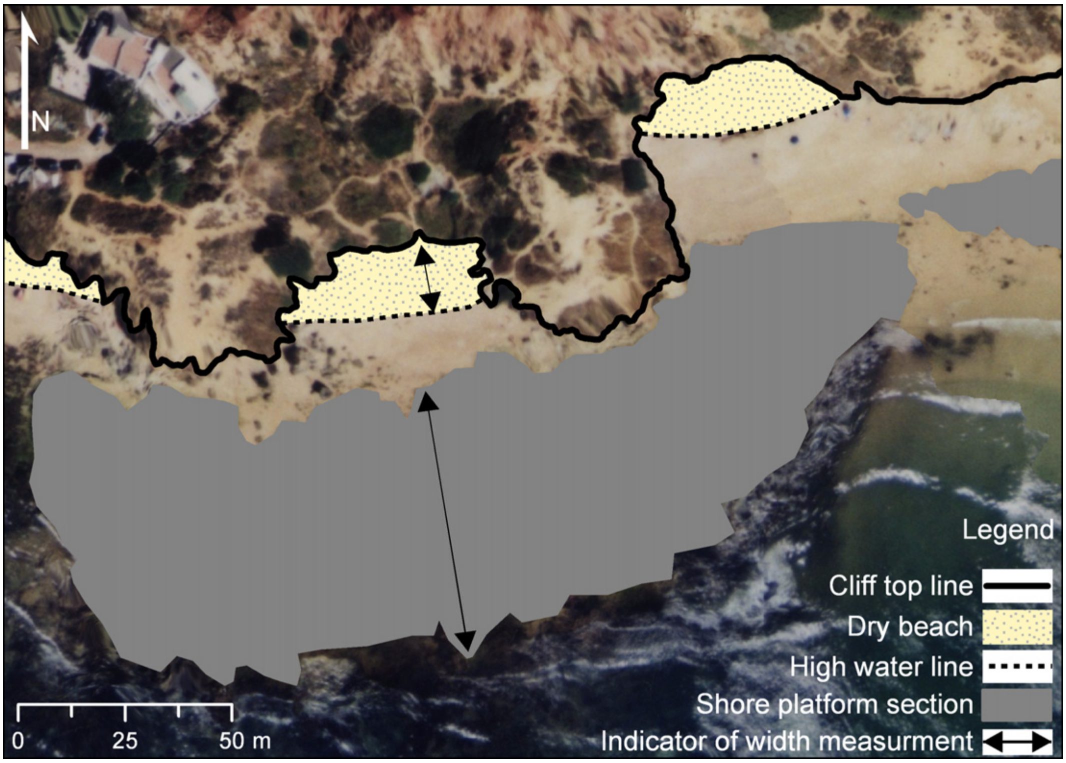

Fig. 5. Example of average beach width and shore platform width mapping.

six classes with around 17% of occurrences (8–10 occurrences in a total of 57 beaches). Since beaches reduce the cliff vulnerability to erosion, they have a negative weighting. Average beach width weighting values were assigned to each class, with the lowest protection value being −0.1 and the highest value of −0.6 being obtained in beaches that have more than 17.8 m (Table 2).

Resistant shore platforms provide protection to cliffs since they dissipate wave energy and force waves to break further offshore, thereby reducing the number and energy of waves that reach the cliff base [25]. To determine the average width of each active shore platform section, a procedure similar to the one applied for average beach width calculation was used. Only the sections of active shore platform visible above water level, as determined from photo-interpretation, were used in order to maintain a common criterion for platform delineation. Perpendicular lines to the general orientation of the coast were drawn within each platform section at an approximate distance of 10–20 m (Fig. 5). The length of these lines was used to compute the average width of each active shore platform section.

The cumulative frequency of average platform section width was calculated, establishing 4 classes, each with about 25% of occurrences (7–9 occurrences in a total of 34 active shore platform sections). The weighting values were assigned gradually from −0.1 to −0.4 (Table 3).

Table 2
Average beach width classes, occurrences and weight values.

Classes	Occurrences	Weight value
No beach	–	0
<7.6	10	−0.1
7.6–9.8	10	−0.2
9.8–12.2	8	−0.3
12.2–15.1	10	−0.4
15.1–17.8	9	−0.5
>17.8	10	−0.6

The wider active platform sections in this area, with a higher protection value, attain average widths close to 60 m. In what concerns weighting, beaches and active shore platform sections were combined because the study area include areas with both protection features. Therefore, protection values can range from 0 (no platform and no beach) to −1 (wide platform and wide dry beach).

3.4. Hazard index

To represent the degree of hazard encountered along the cliffs between Galé and Olhos de Água, the final index was calculated. The hazard index combines the factors considered in this study case, as they reveal in a simple approach the resistance or exposure of rock cliffs to erosion and also the protection that coastal features can offer to that same cliff erosion. The hazard index was calculated for each resulting segment of the baseline according to:

$$\text{Hazard} = \sum(\text{WE}; \text{CLP}; \text{BW}; \text{PW})$$

where WE, CLP, BW and PW are respectively the weighted values of wave exposure, cliff lithology and profile, average beach width and average active shore platform section width.

Table 3
Average platform section width classes, occurrences and weight values.

Classes	Occurrences	Weight value
No platform	–	0
<11.6	9	−0.1
11.6–20.0	9	−0.2
20.0–37.6	9	−0.3
>37.6	7	−0.4

3.5. Method validation

Mass movements result from a combination of specific processes and occur after long periods of apparent stability [29]. Therefore, registered mass movements were considered essential as a spatial indicator of cliff susceptibility areas and were used for validation of the proposed method. Records of mass movements between 1947 and 1992 collected by Marques [10] through stereoscopic analogue aerial photo-interpretation were used. The location of these mass movements was digitized on screen in ArcGIS from the 1:25 000 scale location maps available in Marques [10]. Additionally, the length of coastline affected by mass movements, measured horizontally and parallel to the cliff top as described by Marques [10], was also considered.

4. Results

4.1. Susceptibility factors

It should be noticed that, although the coastal stretch presently under analysis has a straight length of circa 13 km, the cliff top line over which the analysis is made has a total length of circa 25 km. This large difference is due to the indented pattern of the cliff top line of the study area.

The wave direction segments that the coast was divided into were found to fall into three exposure groups: the segments exposed to NE-E-SE-S-SW; the segments exposed to SE-S-SW-W-NW, and finally the ones exposed to E-SE-S-SW-W. As a result of the general E-W orientation of the southern Algarve coast a significant part of the coastline (61.1%) between Galé and Olhos de Água is exposed to waves approaching from E to W wave direction group. A further 14.5% of the coastline is exposed to waves from SE to NW group, whilst the remaining 24.4% of the coastline is exposed to waves arriving from NE to SW group (Fig. 6a).

Using the weighting for wave direction illustrated in Table 1, the coastlines belonging to the exposure group NE-SW are associated with the lowest weighting of 0.518. The other coastline stretches being exposed to the most frequently occurring W waves [14], are consequently associated with higher weighting values. It is therefore clear that the exposure to the W direction is determinant in terms of hazard for the coast presently studied.

The analysis of cliff lithology and profile (Fig. 6b), indicates that 88.4% of the active cliffs in the study area are carved exclusively in calcarenites with the aB class being clearly dominant (65.7%), corresponding to the intermediate susceptibility classes of lithology. A significant part of the profiles are indicative of the dominance of marine erosion, as recognized by Dias [33] and Marques [10]. Profiles typical of higher effectiveness of marine erosion, classes aA and aB, are present in 69.8% of the study area, while only 5.9% of the cliffs are actually primarily shaped by subaerial erosion, classes cB and cC. The remaining 24.3% of the cliffs in classes bB and bC exhibit an intermediate profile reflecting the combination of marine and subaerial erosion, with neither process being noticeably dominant. Cliffs sculpted on marls, class aA, have the lower weight values and are present in only one sector, located near Arrifão.

4.2. Protection factors

The coastal area between Galé and Olhos de Água is generally constrained by rocky headlands, with long beaches in between. Protective beaches at the front of the cliffs are commonly present in the study area, with 49.2% of the coastline being fronted by beaches of variable width affording differing degrees of protection. In this area an increase in the average dry beach width is usually

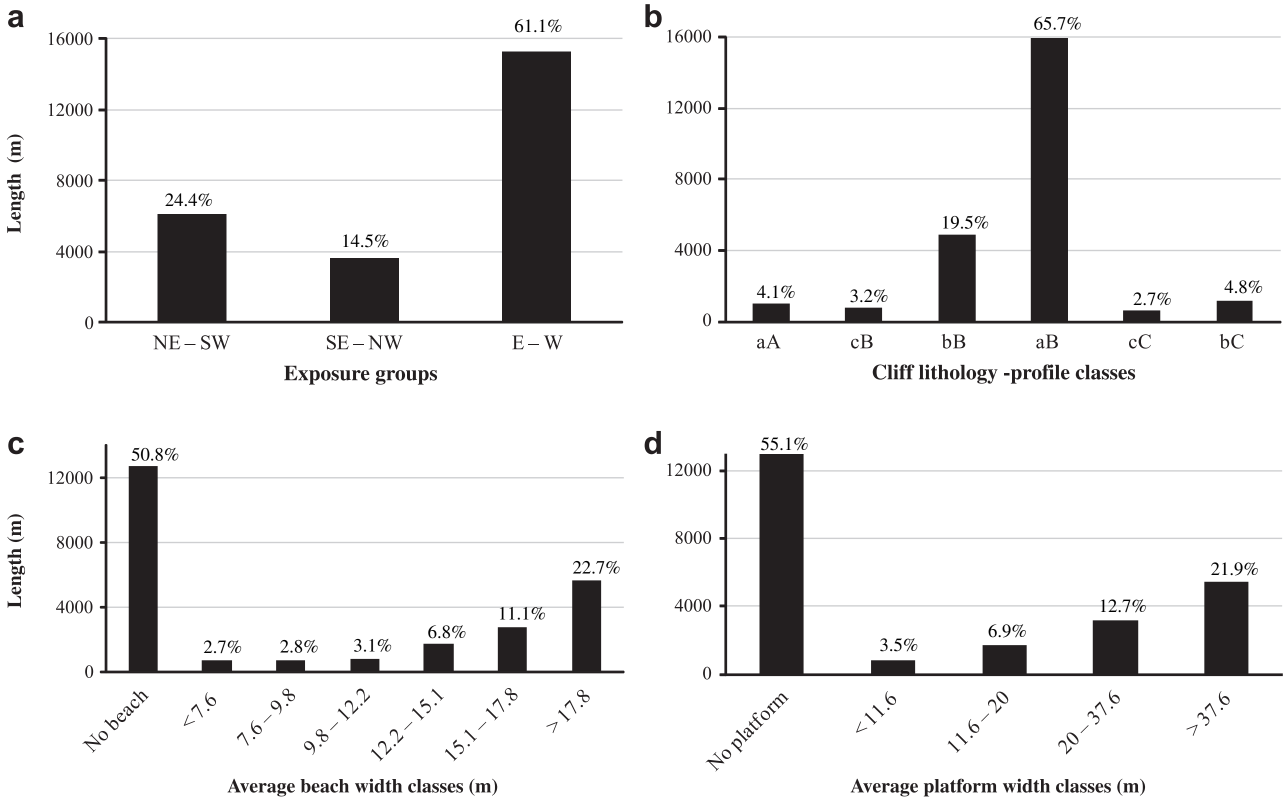

Fig. 6. Distribution of factor classes. (a) Wave exposure; (b) cliff lithology profile; (c) average beach width; (d) average platform width.

Table 4
Hazard index classes, weight values and distribution by hazard index classes.

Hazard classes		Length (m)	%
Low	≤0.2	334.04	1.3
Moderate	0.2–0.7	2291.43	9.2
High	0.7–1.2	15388.65	61.5
Very high	≥1.2	7021.72	28.0

associated to an increase in its length, leading to a considerable percentage of the coastline protected by beaches whose average width exceeds 17.8 m (Fig. 6c). These are the cases of Galé, S. Rafael, Oura and Balaia beaches, as well as the beach between Albufeira and Leixão dos Alhos (Fig. 1).

Emerged shore platform sections offer protection to 45% of the coastline between Galé and Olhos de Água (Fig. 6d). On the 2001 aerial photographs it was possible to identify active shore platforms in 34 sites, the larger sections emerged being located in the eastern area, between Oura beach and Olhos de Água, with average widths close to 50 m. In the central and western parts of the study area, active shore platform sections are generally narrow, except in front of Arrifão, where they attain average widths higher than 40 m and are continuous for about 1100 m parallel to the shore. The narrowest active shore platform sections, whose average width does not exceed 11.6 m, provide a very limited protection and in extremely restricted areas (3.5%). Active shore platform sections with average widths comprised between 11.6 and 37.6 m, accounted for 19.6% of the coastline protected by these morphological features.

Protection in the form of beaches or active shore platforms sections, or even by both features, is present along 72.7% of the coastline, despite the different degrees of protection, leaving the remaining 27.3% of the coastline unprotected. However, most of such protection concerns beaches and active shore platforms sections with reduced average widths, being thus associated to the lower protection classes and weighting.

4.3. *Hazard index*

The determined hazard indexes can range between −0.38 and 1.94, resulting in four hazard classes termed *low*, *moderate*, *high* and *very high* (Table 4).

High and very high hazard values are clearly dominant, accounting for 89.5% of the coastline between Galé and Olhos de Água, which point out the relatively low degree of existent protection. The very high hazard class accounts for 28% of the coastline, occurring mostly west of S. Rafael beach, close to Ponta da Baleeira, and also west of Maria Luísa beach (Fig. 7).

The high hazard category represents 61.5% with a fairly widespread distribution, with a greater dominance between Albufeira beach and Balaia beach (Fig. 7). The moderate hazard class occurs in 9.2% of the coastline east of Pedra dos Bicos (Fig. 7). The low hazard class covers just over 1.3% of the coastline in two areas located west of Arrifão and in Pedra dos Bicos (Fig. 7).

The dominance of high and very high hazard classes is related with the conjunction of two factors: (i) prevailing exposure of the study area to waves coming from the W to the E (61.1%); (ii) prevalence of cliffs carved in calcarenites with a profile indicative of more effective marine erosion (65.7%).

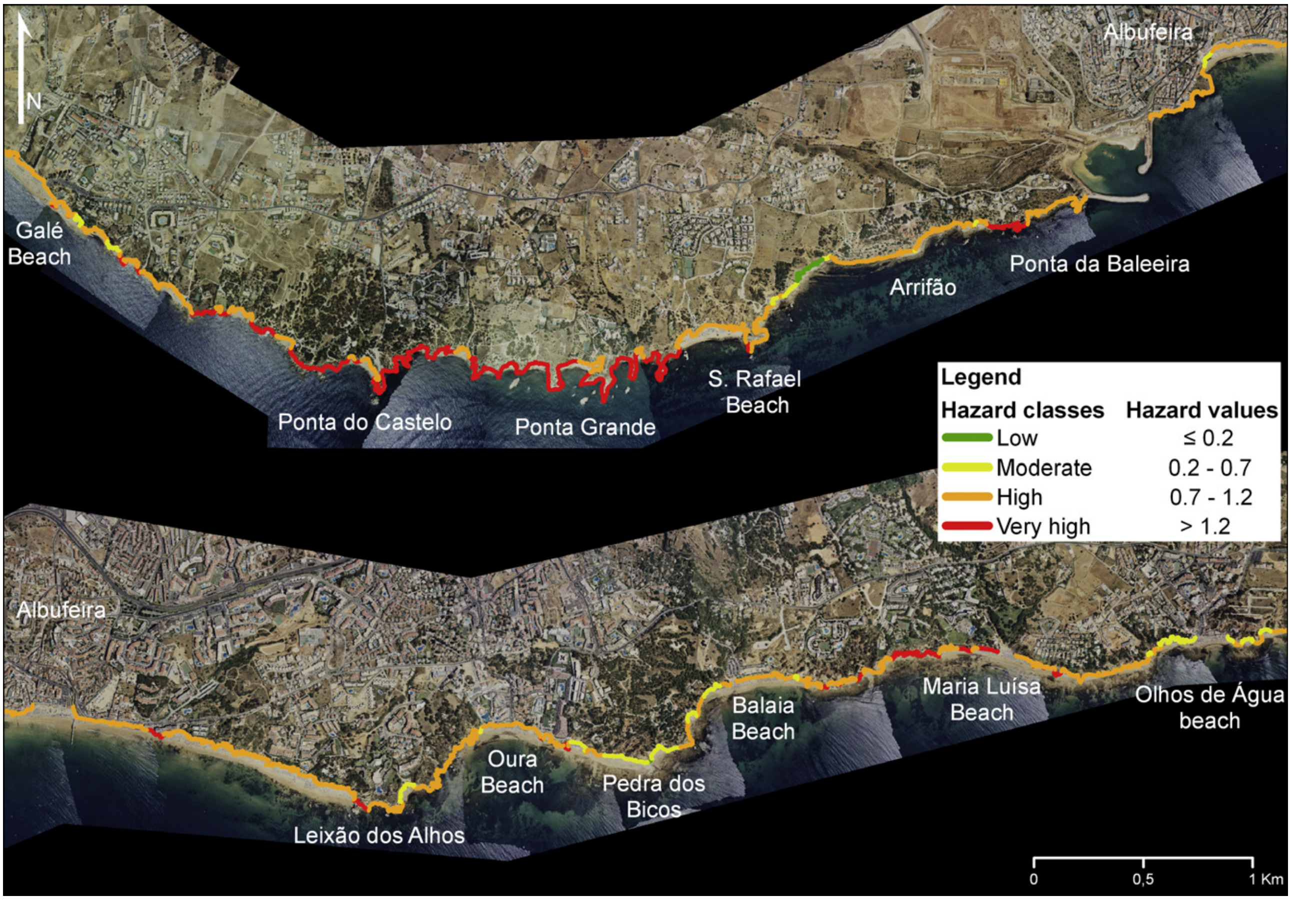

Fig. 7. Distribution of the hazard index along the study area.

5. Discussion

5.1. Data management and accuracy

The benefit of complementing accurate imagery with GIS is the considerable amount of data that can be collected with great precision, combined and analysed in a fairly rapid and effective way for coastal management purposes. Nevertheless, it is expected that various difficulties arise when using aerial photography from coastal areas [34], since the problems of subjectivity and uncertainty are always present. Although user friendly, digital photogrammetry still requires expert knowledge [35]. According to Fletcher et al. [36], it is possible to distinguish two types of uncertainty that affect the accuracy in this kind of method, *positional*, which refers to the characteristics that difficult the recognition of the exact feature position, and *measurement*, which refers directly to the orthorectification error and the subsequent mapping. Even though the on screen digitizing was done with support of photo-interpretation, which was accompanied by field surveys, allowing increased accuracy, this still involved a certain degree of uncertainty. For example, due to the vertical angle of capture, some aerial photographs do not allow a clear distinction of the cliff top or other features. The presence of vegetation or the colour similarity between the cliff-forming materials and sand, represents an increased difficulty in the features delineation. As in every similar cliff studies, this is aggravated at areas where cliffs present frequent indentations and different elevations due to the presence of gullies.

5.2. Hazard assessment

Hazard, as defined by Varnes [37], is the *probability of occurrence of a potential damaging phenomenon within a specified period of time and within a given area*. However, due to the complexity of the time element definition, most research only consider the differentiation of the spatial probability, presenting information on the susceptibility of a certain area to the occurrence of damaging events [38,39]. The hazard assessment approach presented here intends to be a semi-quantitative evaluation suitable for coastal management, based on a snapshot analysis of the study area without taking into account the probabilistic dimension of hazards. Whilst designed as an approach for general application in the hazard assessment of rock cliffed coasts, it is also imperative the method adaptation to the specific features of each area.

Cliff-forming materials and the physical processes to which cliffs are exposed are emphasized by Griggs and Trenhaile [29] as the main factors that affect the scale of coastal cliff erosion. Therefore, wave exposure and cliff lithology, along with the analysis of cliff profile, have been selected for evaluation in this study. Beaches and active shore platform sections were considered as coastal features that condition cliff erosion by affording some degree of protection. The erosion at the cliff base caused by wave action creates instability along the cliff profile, which can lead to mass movements of various types [28]. The attribution of a direct value from the relation between percentage of occurrence for each wave direction and the respective mean wave height was considered to be the most appropriate way of assigning a weight value. It directly gives the importance of each wave direction affecting the study area, and also considers the variable magnitude according to wave height, reducing the weighting subjectivity. Ideally, the cliff top line should be divided in smaller segments, since there are numerous bays and headlands whose sides are exposed to different incident wave directions. This means that there are parts of those segments exposed to some directions that were not possible to take into account and some other parts that have been considered to be exposed and, in fact, are not entirely. It should, therefore, be recognized that different results could arise if the analysis was conducted at a more detailed scale with the decomposition of a larger segment, with one average hazard value, into several smaller segments with different hazard values. However, the use of such small scale approach would immensely increase the working time and would largely increase the complexity on the analysis and interpretation of results. The ArcGIS script automates the process of obtaining an indicator angle for wave exposure, but it does not provide the remaining directions to which a coastal stretch is also exposed. The solution of adding 45°, 90°, 135° and 180° degrees to the azimuth value and considering the resulting classes could lead to overestimation. Subdivide the existent wave direction classes would reduce these potential errors, however, for this study area there is a lack on more detailed wave information. This overrating can justify some of the high hazard values obtained, since most of the segments are exposed to the W direction, which has the higher wave exposure. Thus, the approach to wave exposure appraises a worst case scenario.

The evolution of rock cliffs is essentially a result of the interaction between marine and subaerial erosion processes [40]. Marine processes are responsible for the cliff's slope increase and for notch formation by basal undercutting, favouring the occurrence of instability phenomena. Subaerial processes are directly related to external factors including intense precipitation and storm conditions [41,28]. The matrix of rock cliff profiles presented by Emery and Kuhn [30] played a fundamental role reflecting the relative effectiveness of marine versus subaerial erosion in different degrees of rock homogeneity. The rock cliffs of the central Algarve are mostly composed of Miocene calcarenites, which are in some areas covered by Plio-Pleistocene sands that also fill the paleokarst features [33]. The classification was based on expert knowledge, obtained through field surveys, photos and literature analysis but disregarding the non-natural areas and some minor variations within each class. Nevertheless, it is a useful method for coastal management because lithology regulates the mechanical strength of the cliff or, in other words, the cliff's resistance to waves [28], while the profile represents the overall processes acting in the evolution of cliffs. The results obtained in this study agree with the findings of Dias [33] and Marques [10] regarding the predominance of marine erosion over subaerial erosion.

Beaches and active shore platform sections as protective features in the erosion of cliffs have been evaluated in terms of their average width. Sallenger et al. [42] found that cliff retreat in the Central California was correlated better to beach width than to beach elevation at the base of a cliff, implicating that beach width can be used as a suitable proxy for evaluating the protective capacity of a beach. Beach width calculation has been supported by the delineation of the HWL and the cliff top line as reference features for beach width measurement. The assessment of average beach width includes potential errors because the width lines were drawn from the HWL to the cliff top line, instead of the cliff foot. This can lead to a probable overestimation of average beach width in some places, since part of the cliff was quantified as belonging to the beach. Nevertheless, in most of the study area cliffs are vertical or near vertical, minimising this error, and the vertical angle of the aerial photographs do not allow a clear distinction between cliff top and cliff foot all along the study area. For the HWL delimitation it is used the tonal contrast wet/dry line on the sand, however, this is not a straightforward process due to the existence of other lines, such as the swash terminus line, debris lines and erosion scarps [32]. The gradual change between wet and dry areas McBride et al. (1991) cited in [31] or high rates of evaporation in the site [31], may also be established as a factor of accuracy decrease.

Aerial photographs as snapshot images cannot demonstrate the mean conditions [34]. To diminish errors only the emerged platforms sections were considered because even if parts of the shore platforms were visible below water level, in most active platform sections it was impossible to identify their underwater contour due to light reflection, reduced water transparency or sand covering.

The protection exerted by beach and active shore platform section can extend further away from the limits of their respective features. However considering the scale and objectives of this study, it was out of scope of this research to evaluate the complex relations of protection offered by both beaches and shore platform sections beyond the areas where there is a direct and obvious protection. That would require consideration of their interactions with waves and with sea bottom topography, which could only be solved with a detailed wave modelling approach.

5.3. Index validation

Results have shown that 89.5% of the coastline under study is subjected to high and very high hazard. Such values mean that this is an area where cliffs are highly or very highly susceptible to erosion, which will most probably occur in the form of mass movements.

As a result of the indented shape of the coast the index results may indicate wide variations in relatively small areas, as the product of specific features like a pocket beach or a headland. The positive relationship between hazard index and conspicuous headlands means that the more exposed an area is the higher vulnerability to erosion it possesses. Traducing the multiple factors acting in the study area, the presented index is considered to produce a realistic representation of hazard.

The distribution of mass movements' occurrences per hazard class (Table 5) is consistent with the outcome length per hazard class (Table 4). On the other hand, the number of mass movements does not have an increasingly correspondence in the higher hazard classes.

However considering the average length of mass movements per hazard class (Table 5) it reveals occurrences with larger affected length. In the very high hazard class the average affected length of a mass movement is 27 m while in the lower hazard class is 8 m (Table 5). The lower hazard classes (low and moderate) have less than 10% of the affected length, whilst the higher hazard classes (high and very high) account for 40–50% of the total affected coastline.

Thus from this data it seems correct to assume that the developed method can be useful as a tool for coastal management to evaluate hazard in rock cliffs. The mass movements inventory available period is relatively short (45 years), regarding the spatial occurrence of mass movements according to the cliff life time [11].

It is however important to note that these hazard results concern only this specific area. The application of the present approach to assess hazard in a different study area involve the necessary adaptation to the specific study area characteristics, which imply adjustment not only of the factors active in those cliffs but also in the different factor classes and weights.

Further refinement of this method should incorporate temporal analysis with mass movement return periods as well as human occupation in order to present effective risk assessment and generate risk maps. The definition of the potential risk for this coastal area will allow the definition of coastal evolution scenarios and the identification of suitable management approaches.

Table 5
Mass movement occurrences per hazard class.

Hazard classes	Mass movements		
	Occurrences	Affected length (m)	Affected length/occurrences
Low	2	16	8
Moderate	13	123	9
High	53	670	13
Very high	17	452	27

6. Conclusion

Research on the erosion of rock cliffs as the result of the interaction between various factors provides important information for coastal management. The present method pretends to be a tool that uses scientific recognized knowledge about rocky coasts, applying simple proxies representative of the main control factors, and presenting, trough mapping, information on which management and decision-making depend to take informed decisions. Cliff evolution forcing mechanisms along with protection factors of cliff erosion were combined to produce a hazard map. The analysis, supported by geographical information, has evaluated these factors through a weighted index that translates a scenario of coastal susceptibility to erosion.

The application of the method demonstrates that rock cliffs between Galé and Olhos de Água are mostly subjected to high and very high hazard, which are widespread along the study area. This distribution pattern is probably related to the fact that 61.1% of the coastline is exposed to the most hazardous wave class. The low hazard category occurs in just two locations and is mostly the result of the high resistance of the cliff-forming material, and presence of protection by both platform sections and beach (Arrifão and Pedra dos Bicos respectively). In calcarenite cliffs marine erosion was found to be more significant than subaerial erosion. The hazard index results were corroborated by comparison with mass movements recorded between 1947 and 1992, revealing a relation between the higher vulnerability areas and the larger mass movement average lengths.

The obtained results are a first step towards an integrated coastal management approach. The final setting of management objectives should involve identification of priority areas, such as urbanised sites located in high and very high hazard areas defined on this study, where a detailed cliff management strategy may be necessary.

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