

Hazard assessment in Galé – Olhos de Água sea cliffs: a tool for coastal management

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Abstract

Coastal hazards are a function of the interaction between human activities and naturally induced coastal processes. The conflicts arising from this interaction require new approaches that integrate the complex geodynamic environment of rocky coasts. Aiming to develop a method for assessing hazard in sea cliffs suitable for coastal management, the research presented combines the assessment of sea cliff evolution forcing mechanisms along with protection factors. The method considers wave exposure, mass movements and cliff face lithology and profile as factors of increased susceptibility to erosion in sea cliffs, while the presence of beaches and shore platforms protects cliffs from erosion. The method combines digital photogrammetry techniques and GIS analysis, based on a weighted factors approach, attributing weights according to different classes within each factor, in order to obtain a final hazard index that aggregates all factors. The method was applied to the rocky sea cliffs between Galé and Olhos de Água (Algarve, Portugal). High and very high hazard are dominant along the study area, representing more than 90% of the coastline studied. They occur predominantly in the absence of protective beaches and shore platforms. Moderate and low hazard have reduced expression but, even where they have been reported, hazard is not inexistent. The method presents cliff erosion hazards along the study area, being a suitable tool for cliff hazard assessment and useful for coastal management.

Keywords: Coastal hazard, Sea cliffs, Digital photogrammetry, GIS, Coastal management, Algarve, Portugal

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Abbreviations

CIACOMAR – Centro de Investigação dos Ambientes Marinho e Costeiros (Coastal and Marine Environments Research Centre)

CIMA – Centro de Investigação Marinha e Ambiental (Centre for Marine and Environmental Research)

CPZ – Cliff Protection Zone

DEM – Digital Elevation Model

DGPS – Differential Global Positioning System

GCP – Ground Control Points

GIS – Geographic Information System

HWL – High Water Line

ICZM – Integrated Coastal Zone Management

IGEOE – Instituto Geográfico do Exército (Geographical Institute of the Portuguese Army)

IGP – Instituto Geográfico Português (Portuguese Geographical Institute)

INAG – Instituto da Água (Water National Institute)

LPS – Leica Photogrammetry Suite

PDOP – Position Dilution of Precision

POOC – Plano de Ordenamento da Orla Costeira (Coastal Zone Management Plan)

RMSE – Root Mean Square Error

1. Introduction

Rocky cliffed coasts compose around 80% of the world's coastline (Trenhaile, 1987). Notwithstanding, these coasts have not been as extensively studied as beaches or coastal wetlands, probably because the mean evolution of a rocky coast is rather slower in a human scale. Nevertheless, rocky coasts have very specific evolution patterns that make the erosion of cliffs an irreversible process that causes the loss of land and endangers human use of the coast (Colantoni *et al.*, 2004). For a long time, rocky cliffed areas have been apart from spatial planning concerns, since the reduced occupation of cliffs did not bring considerable risks to the populations. This situation has been inverted, since the development of tourism in coastal zones has brought a growing number of people to the coast. With the population increase, buildings and infrastructures have multiplied, usually without concern for correct land planning and even less consideration regarding the potential hazard resulting from the geomorphological dynamics of the coast. The conflict between the increasing occupation and the inherent geomorphological instability of the coast has become a problem of rising magnitude (Moore & Griggs, 2002), which requires new approaches that can evaluate the geodynamics of rocky cliffs accurately for supporting effective coastal management.

Hazard, as defined by Varnes (1984), is the *probability of occurrence of a potential damaging phenomenon within a specified period of time and within a given area*. Hazard is, thus, a function of temporal and spatial probabilities (Van Western *et al.*, 2006). Nevertheless, since the temporal probability is particularly difficult to obtain, most hazard assessments only consider the differentiation of the spatial probability, presenting information on the susceptibility of a certain area to the occurrence of damaging events (Mantovani *et al.*, 1996; Van Western *et al.*, 2006). Remarkably, the disregard of the temporal probability in hazard assessments was reported by Mantovani *et al.*, in 1996 but, after a decade, Van Western *et al.* (2006) still recognize its effective integration as one of the main challenges for the future in hazard assessments.

The coastal area between Galé and Olhos de Água, in the southern coast of Portugal, is composed of rocky sea cliffs, whose evolution rates were studied by Marques (1997), based on mass movements identified using aerial photography interpretation. Hazard evaluation in this area is limited to the study of Teixeira (2006), also supported by mass movements'

identification and their quantitative analysis. Both studies are, therefore, biased towards mass movements that, although being unquestionably dominant in the evolution of sea cliffs, are a result and not a controlling factor. Mass movements correspond to the final response of a cliff evolution cycle. Considering that the result of cliff evolution has already been characterized, this study presents a complementary approach, proposing a hazard assessment that integrates both forcing mechanisms and protection factors in the evolution of sea cliffs. This new approach integrates photogrammetric techniques and Geographical Information Systems (GIS), aiming to evaluate hazard in sea cliffs as a tool to support coastal management in the southern Algarve coast. The objectives of this study are thus to appraise if a suitable assessment of hazard in sea cliffs can be obtained by considering different forcing mechanisms and protection factors of sea cliff evolution. Subsequently, the validity of the results obtained and the methods used will be evaluated in terms of their effectiveness for supporting coastal management in rocky cliffed areas.

The first chapter of the dissertation presents information about the research theme, the aim of this study and its objectives. It is followed by an overview of the study area. A revision of the research being done in the subjects presently under study, focusing particularly in the study area is presented in chapter three, together with a review of the approaches to coastal management undertaken in the region. The fourth chapter details the methodology of the research project, including the field and laboratory procedures for photogrammetric restitution of aerial photographs as well as the methods selected for GIS analysis of the datasets. The results are presented individually for each factor considered for hazard assessment, followed by a description of the hazard index generated by their aggregated consideration. The discussion centres on the calculation of the hazard index, specifically around processing of the chosen factors and their respective weightings, along with the limitations of the method and recommendations for further research. The conclusions of the study are presented in the last chapter.

2. Study Area

2.1 Location

Located in the south-western part of Europe, the Algarve (Figure 2.1a) is the southernmost region of Portugal. It is positioned between 37°35' and 36°58' N and between 7°25' and 9°00' W. It is bounded by the Guadiana River to the east, which constitutes the natural border with Spain, the Atlantic Ocean to the south and east, and the Baixo Alentejo region to the north (Figure 2.1b). On its' *circa* 200 km of coastline, a great majority composed by rocky coasts, the Algarve has a large diversity, divided in three different zones, the *Costa Oeste*, the *Barlavento* and the *Sotavento*. The area presently under study is the cliffed coast between Galé and Olhos de Água (Figure 2.1c). This approximately 13 km long coastline follows a general NW-SE direction on the west part, turning to SW-NE between Ponta do Castelo and Albufeira, since then and until Olhos de Água it follows a rudely E-W direction.

2.2 Climate

The Algarve region has been classified in many different climatic types according to several authors. Alcoforado *et al.* (1982) have defined a Mediterranean climate zone in southern Portugal that includes the central and eastern coasts of Algarve, covering the area under study, whereas Daveau (1988) presented this area has having a maritime climate. Recently INAG (2000) has characterized the area as having a semiarid to dry sub-humid climate. Despite such classification differences, the regional climate is characterized by a warm summer season (average of 22.3 °C) and a mild winter (average of 12.7 °C), average annual precipitation values between 350 and 600 mm, concentrated in the winter months, and five to six dry months (Ribeiro, 1988; IM, 2004).

Precipitation is a very important factor in cliff slope evolution, since it can function as a triggering mechanism for mass movements or induce sub-aerial erosion, creating rills and gullies. Average precipitation values for the Algarve region present a clear distinction between summer and winter seasons and have a high inter-annual variability (Ventura, 1994). According to the values recorded in Faro meteorological station for the 1965-1990 period,

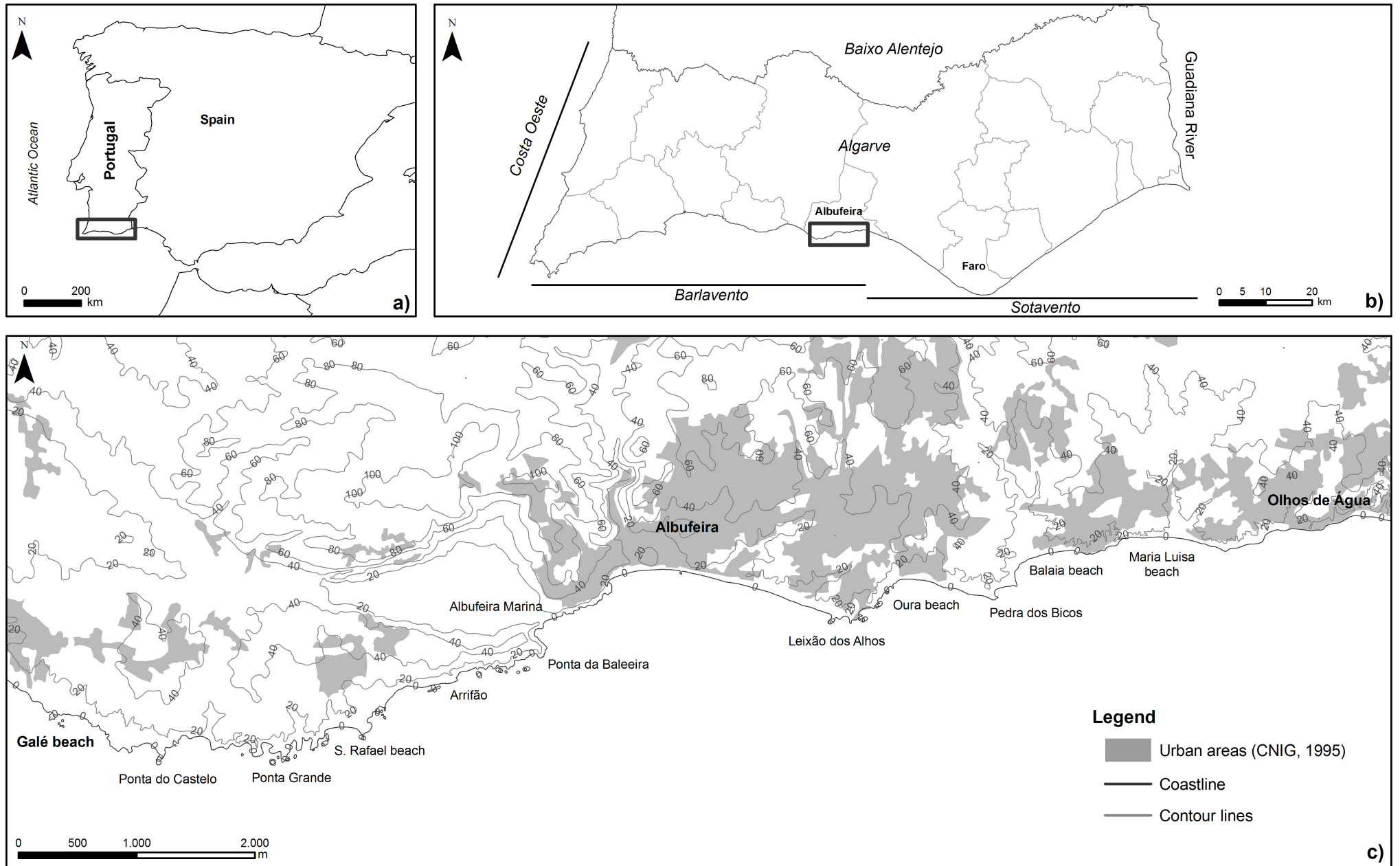


Figure 2.1 - Geographical location of the study area (contour lines and coastline redrawn from IGEOE, 2005): a) Iberian Peninsula, b) Algarve region, c) coastal zone between Galé and Olhos de Agua.

precipitation, mainly in the form of rainfall, but also as drizzle and downpour, is concentrated between November and February and almost absent between May and September (IM, 2004). The highest monthly average precipitation occurs in December with 94 mm and, opposing to it, July presents the lowest average monthly precipitation with only 1 mm (IM, 2004). Considering daily precipitation values equal or higher than 1 mm, there are normally 310 rainless days during one year, meaning that significant rainfall occurs only in 55 days. If the analysis is further narrowed to days with precipitation equal or higher than 10 mm, such situation only occurs, in average, around 16.5 days in a whole year and these are concentrated in the winter and autumn months (IM, 2004).

Extreme precipitation events have considerable interest due to the changes they imprint in the landscape and the damages they can cause to human activities (Ventura, 1994). Daily and hourly maximum precipitation recorded between 2001 and 2006 in two automatic stations located near the study area (Paderne and Algoz), allowed to identify extreme precipitation events that took place in the last years (available in Water Resources National Information Service at <http://snirh.inag.pt>). In terms of daily maximum precipitation, there have been 9 events where the value of 40 mm has been exceeded, being the maximum 71 mm in a single day. Regarding hourly values, the maximum registered is 40.4 mm, although the remaining values are considerably lower, not exceeding 22 mm. Hourly precipitation higher than 2 mm only account for 0.7% of the occurrences, taking place mostly (82%) in autumn and winter.

Research carried out by Marques (1997) reported the increase in the annual precipitation in Faro between 1895 and 1993, followed by a slight decrease thereafter. This increase was accompanied by an enhanced contrast between dry and wet years, mostly due to variations in the wetter months, suggesting that this irregular pattern is consistent with the progressive torrential regime of precipitation in the region (Marques, 1997; Santos *et al.*, 2002). Such regime, concentrating in a few months the majority of the rainfall, together with the most intense precipitation events, is a factor of increased slope vulnerability and of great meaning for cliff hazard assessment.

2.3 Wave Climate

Of great importance for the study of sea cliff evolution and, therefore, in sea cliffs hazard assessment is the wave climate. There are two prevailing wave directions acting on this coast, W-SW and SE, with prevalence to the first, which accounts for 71% of the occurrences, while waves reaching the coast from SE occur during 23% of the time (Costa *et al.*, 2001).

Significant wave heights in this area are generally lower than 1 m (68% occurrence), being the mean significant wave height exactly 1 m. Values higher than 3 m occur less than 2% of the time, essentially during winter. Waves approaching the southern Algarve coast have an average peak period of 8.2 s, being the wave peak period lower than 11 s 78% of the time (Costa *et al.*, 2001).

The southern Algarve coast is protected from NW waves, which are dominant in the western coast of Portugal, but is exposed to the waves coming from SE that are generated by local winds, termed *Levante*. These SE winds usually persist during several days, being responsible for generating particular wave conditions that reflect the small fetch area ascribed to the shape of the Gulf of Cadiz and the proximity of the African continent (Andrade, 1990; Costa *et al.*, 2001). Such conditions generate narrow spectre waves with clear SE direction, significant wave heights between 1 and 2 m and mean wave periods lower than 9 s (Pires, 1998). These are high declivity waves that promote shoreline erosion and are responsible for significant morphological modifications in the coasts exposed to such direction (Andrade, 1990). Nevertheless, it is the W-SW swell that is associated with more extreme wave conditions, responsible for the higher significant wave heights and longer wave periods that reach the southern Algarve coast (Costa *et al.*, 2001).

Extreme wave conditions associated to storms (events with offshore significant wave height higher than 3 m) that affect the southern Algarve coast arrive, mainly, from the SW and SE, occurring respectively 64% and 32% of the time. Stormy wave conditions occur essentially during the maritime winter and usually do not persist more than two days (Costa *et al.*, 2001; IM, 2004). Nevertheless, SW storms can persist for more than two days, although never exceeding five days, and often reaching maximum significant heights higher than 6 m. Significant heights and peak periods for stormy waves range essentially between 3 to 5 m and 7 to 11 s (Pires, 1998; Costa *et al.*, 2001).

Return periods for extreme significant wave heights were calculated by Pires (1998), considering all directions together and SW and SE waves specifically, based on measured data between 1986 and 1994 (Table 2.1). Results indicate that, for the same return periods, SW stormy waves have significant wave heights approximately 2 to 3 m higher than SE waves, while the series without directional considerations presents intermediate values. Also noticeable is the fact that the significant wave height for SE incident waves with a 100 years return period is always smaller than the significant wave heights for the remaining directions, even considering a 5 year return period.

Table 2.1 – Significant wave height (m) for different directions and selected return periods (adapted from Pires, 1998)

Direction	Return period (years)				
	5	10	25	50	100
All directions	5.2	5.7	6.4	6.8	7.3
SW	5.7	6.4	7.4	8.1	8.8
SE	4.4	4.6	4.8	5.0	5.1

2.4 Tides and Sea-Level

Tidal regime in the southern coast of Algarve is semidiurnal, with an average tidal range of 1.2 m for neap tides and 2.8 m for spring tides (IH, 2005), corresponding to a mesotidal coast. Nevertheless, tidal ranges of 3.5 m can be reached, corresponding to a maximum high tide level of about 3.8 m above the hydrographical zero (IH, 2005).

Occasionally, due to the occurrence of storm surges, sea-level can rise above the average conditions. For the southern Algarve coast, the return period for extreme sea-level values has been calculated by Gama *et al.* (1994), which, for a return period of 10 years, has obtained a value of 4.23 m above the hydrographical zero. Considering a 50 year return period, such value rises up to 4.34 m. In terms of sea-level rise in the last century for the Portuguese coast, the observed value is 1.5 mm/yr (Dias & Taborda, 1992).

2.5 Geology

The geology of the Algarve region is quite diverse, comprising formations that range from the Upper Devonian until the Holocene. The study area is located at the Algarve Meso-Cenozoic Algarve Basin, which presents an E-W direction, along which rocks are progressively younger from the west to the east, starting with Jurassic limestones and ending with Quaternary sands (Dias, 1988). In the coastal area from Galé to Olhos de Água it is evident the wide geologic variability of the Algarve coast (Figure 2.2), since in a 13 km long coastline it is possible to identify outcrops from Jurassic, Cretaceous, Miocene and Plio-Pleistocene sedimentary rocks (Manupella, 1992).

The coastal fringe under study is essentially composed by rocky cliffs, carved in intensely faulted, folded and karstified carbonate Miocene limestone included mainly in the Lagos–Portimão carbonated formation. The Miocene rocks are absent from the cliff face between S. Rafael and Albufeira due to the existence of a diapir structure. To the east of Albufeira the

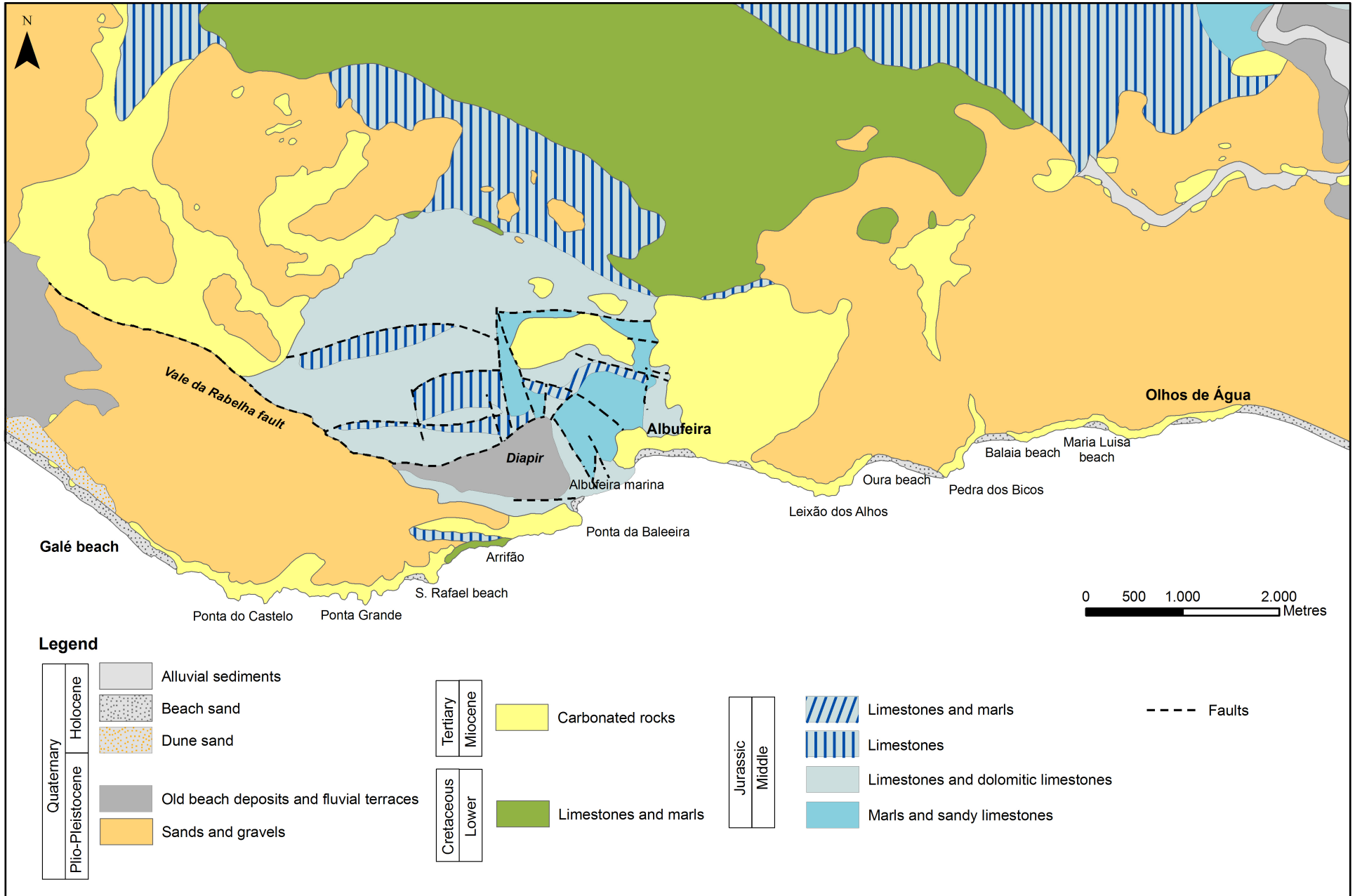


Figure 2.2 - Geology of the study area (redrawn from IGM, 1989 and modified according to Albardeiro, 2004).

cliffs include, in their upper part, the Plio-Pleistocene reddened siliciclastic sand deposits, whose importance increases progressively until Olhos de Água (Moura & Boski, 1999).

Outcrops of Jurassic and Cretaceous rocks in this coastal area are related to the faulting and ascent of plastic materials from the early Mesozoic, as a result of the installation of the Albufeira diapir (Manupella, 1992). Although Jurassic limestone was identified in the coastal slope between Ponta da Baleeira and Arrifão, it was not actually present on the cliff face. The only area where cliffs were composed only by Jurassic rocks, a small stretch north of Baleeira, has become isolated from the sea due to the construction of the Albufeira marina. Such cliffs evolve presently as a regular slope, without the influence of marine processes. The Cretaceous rocks outcrop at the face of the cliff at Arrifão, presenting a clear angular discordance with the Miocene formations, since the latter are horizontally displaced while the Cretaceous ones present a vertical arrangement (Rocha *et al.*, 1989).

The main lithology supporting the rocky cliffs of the study area, as well as the majority of the southern Algarve rocky coast, is the Miocene limestone belonging to the Lagos-Portimão carbonated formation, but also to the Olhos de Água carbonated sandstone (Antunes & Pais, 1992; Moura, 1998). These two units are difficult to separate, since both are composed by Miocene carbonated rocks (Rocha *et al.*, 1989), which led to the classification of the Olhos de Água carbonated sandstone as the upper part of the Lagos-Portimão carbonated formation (Moura, 1998; Dias, 2001). Therefore, Miocene rocks are not homogenous along the coastline, being the cliffs composed mainly by bioclastic limestone and calcarenites that become sandier between Albufeira and Olhos de Água, or even get overlain by siltstones between Galé and Castelo beaches as well as Albufeira and Oura beaches (Rocha *et al.*, 1989; Moura *et al.*, 2006).

Along the coastal slope of the study area, the Miocene carbonated rocks are frequently over imposed by Plio-Pleistocene reddened siliciclastic units, composed by heterometric sands (Moura & Boski, 1999). These sands give shape to the detritic coastal platform between Galé and Olhos de Água (Moura, 1998). In this area, the siliciclastic sands present a variable thickness, seldom exceeding 10 m, although in other areas they can attain values close to 50 m thick, settling indistinctly over older formations. The Plio-Pleistocene units are poorly consolidated and, therefore, are considerably less resistant to erosion than the carbonate rocks (Rocha *et al.*, 1989; Marques, 1997; Moura 1998). They are present in the cliff face in recessed areas adjacent to beaches, namely at Galé, S. Rafael, Balaia and Maria Luísa, or as part of the infilling of the karst features developed in the Miocene limestones (Dias, 1988).

2.6 Tectonics and Neotectonics

General evolution of the area was traced back to the formation and dismantling of the Hercynian chains. After, the sedimentary border of the Algarve was affected by several stages of the Alpine orogenesis that have caused intense and significant tectonic displacement. These events have resulted in an ENE-WSW faulting general direction affecting major tectonic accidents in the area (Dias, 2001). In the study area, the major faulting and still active alignment, the Vale da Rabelha fault, follows this direction. The Albufeira diapir, which is associated to this fault, is possibly the responsible for the most recent tectonic movements (Albardeiro, 2004). Several faults and joints were identified in this area, some of which have an approximate N-S direction and present reduced vertical throw, being identified only by the morphology of the terrain (Albardeiro, 2004). Due to the proximity to the Eurasian plate, near the Azores-Gibraltar transforming plate boundary, the area presents high seismic activity. As expected, the Algarve region is affected daily by several small earthquakes and occasionally by more intensive events with usual epicentres on the continental margin, or even in the mainland (Marques, 1997; Dias, 2001).

2.7 Geomorphology

There are considerable morphological contrasts in the Algarve. Such contrasts are the result of geological structure and geomorphological evolution of the region, which influences vegetation, land-use and settlement (Feio, 1952; Fletcher, 2005). The morphology of the coastal area is conditioned by the lithology and the structure of the Mesozoic and Cenozoic formations (Marques, 1997). It corresponds to a coastal platform developed close to the shore at elevations between 25 and 45 m. This platform extends throughout the study area with various interruptions, mainly due to the Albufeira diapir and also to the incision of the hydrographical network (Figure 2.3). The Albufeira diapir presents a triangular shape with major length along E-W direction, and it is flanked by 40 m height fault scarps developed in Jurassic limestone. To the east of Albufeira the coastal platform presents an elevation around 30 to 40 m, being widely eroded by gullies and rills as result of the low resistance of the Plio-Pleistocene sandy covering. The exhumation of the karst features developed in the Miocene carbonate bedrock also promotes the erosion of the coastal platform (Marques, 1997).

There is a widely developed paleokarst on the Miocene carbonate rocks of the Lagos-Portimão formation, which has been exhumed and filled several times in the past (Dias, 1988;

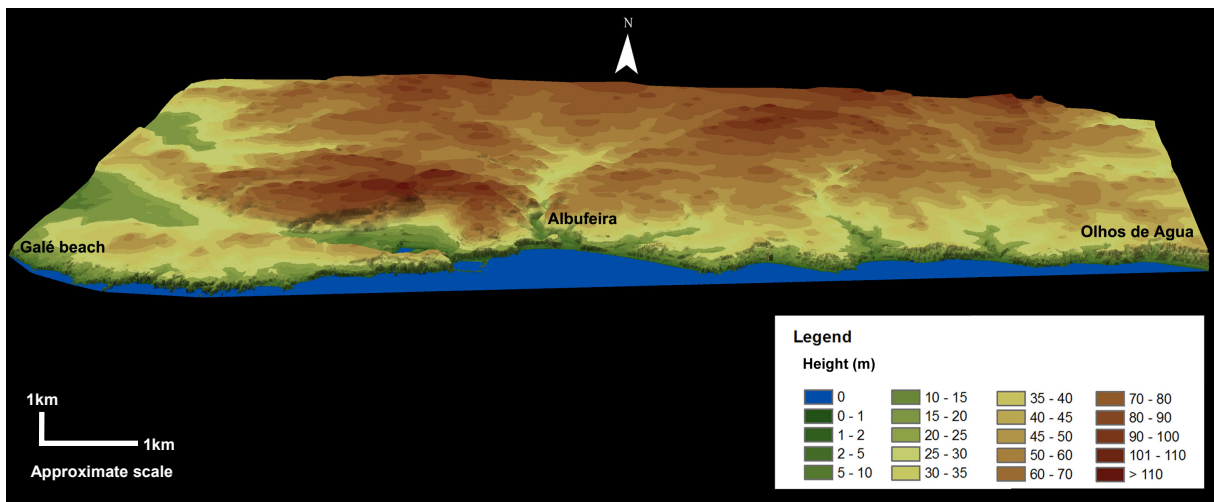


Figure 2.3 – Digital terrain model of the study area (height data from IGEOE, 2005).

Moura, 1998), and is characterized by a large frequency of sinkholes (Marques, 1997). The paleokarst is still frequently filled by the Plio-Pleistocene clastic sediments (Moura *et al.*, 2006), or even Holocene sands (Albardeiro, 2004). These have small resistance to marine and sub-aerial erosion, leading to a rapid evacuation of the infilling material after partial erosion of the Miocene structure, and further collapse of the remaining karst structure. This evolution pattern leads to the abundance of stacks and to the development of a very indented coastline (Dias, 1988; Marques, 1997). The intricate shape of the coastline is also favoured by the presence of shore platforms, the majority of them cut on sub-horizontal Miocene rocks, gently dipping seaward. The origin and evolution of these morphological features is still uncertain (Moura *et al.*, 2006), therefore it is preferable to term them as shore platforms rather than abrasion or wave-cut platforms, since both terms implicate that platforms are exclusively the result of wave abrasion (Griggs & Trenhaile, 1994). Nevertheless, the active shore platforms in the present intertidal zone along the coast of Galé – Olhos de Água have been primarily sculpted by wave attack (Moura *et al.*, 2006), being developed in the lithologic contact between Miocene layers with different rock strength (Albardeiro, 2004). Around Arrifão, an irregular shore platform develops on vertical layers of Cretaceous marls and claystones, cutting the stratification (Moura *et al.*, 2006). Raised platforms, corresponding to sea-level highstands, are present as well along most of the coastline (Albardeiro, 2004; Moura *et al.*, 2006). Coastal morphological features in the study area include also pocket or embayed sandy beaches, with average width between 3 and 50 m.

Like the relief, the hydrographical network is heavily controlled by structure and lithology. Therefore, in the carbonate rocks the drainage network is not very dense, since most water

infiltrates into the rocky massif. Nevertheless, it is possible to verify that streams are preferentially oriented in the NNE-SSW and N-S direction (Moura, 1998; Moura *et al.*, 2006).

2.8 Human Occupation

Since the XIX century fishing had been the main activity in Albufeira area (Cavaco, 1980). However, in the 60's a major socio-economic transformation took place. Tourism came to the region, first on a small scale, which was quickly replaced during the 80's by mass tourism development (INAG, 2000). This rapid increase in tourism industry has led to a sudden intensification of urban areas in a narrow belt near the seacoast, and an overwhelming increase in beach use and occupation (Teixeira, 2002). Nowadays, the Algarve is an important beach tourist destination and tourism related activities are clearly assumed as the leading economic sector in the region, generating an income of approximately 500 million euros solely in lodging establishments, spent by a growing number of tourists, which already exceeds two millions per year (INE, 2003).

The unbalanced relation of the tourist number around the year with the fixed population of the Albufeira municipality creates a considerable demographic pressure. For an area of 140 km², Albufeira had a resident population of 33 019 inhabitants in 2002 (population density of 235 inhabitants per km²), which is clearly surpassed by the total number of guests in hotel establishments that reached 853 566 in 2002 (INE, 2003).

The continuous growth of tourism activities, the influx of foreign and national visitors, as well as settlers, has been so great that it has created several problems, mostly related to water consumption, wastewater treatment, domestic waste production and, above all, land-use. Communities and developments have transferred the pressures and the negative effects to the coastal zone, which was and still is increasingly artificialized. Urban and built-up land comprehends a rather small portion of the Algarve region's area, around 2%. Notwithstanding, it is mainly concentrated along the coast, rendering impermeable the drainage basins of the small and often temporary streams that reach the coastline (INAG, 2000). Considering the zone between the sea and 2000 metres landward, the already edified land occupies 45% of the total area, while 43.3% is subjected to limitations or even interdicted for construction. Moreover, 1% of this zone is reserved for greenways, leaving only 10.7% of free land for new developments (CCDRA, 2006).

3. State of the Art

3.1 Sea Cliffs Natural Dynamics – review of previous research in Algarve

Sea cliffs natural evolution is essentially a result of the interaction between marine and subaerial erosion processes (Davies, 1980). 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, mainly mass movements, are in straight relation with external factors like intense precipitation along with high stormy waves (Trenhaile, 1987). The localized and episodic pattern of mass movements, frequently involving large areas, induces high risks to the human occupation of the sea cliffs. The efficiency of marine and subaerial processes varies as a function of factors like rock resistance, structure of the rocky outcrops, presence of marine abrasion platforms, exposure to the erosive action of waves and even the tide amplitude itself (Sunamura, 1992).

The rocky 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 (Dias, 1984). The different lithology determines different evolution processes (Dias & Neal, 1994; Marques, 1997). The Miocene cliffs evolve mostly by rock falls in periods of heavy rain and by collapse of slices of the entire cliff face after undercutting of the basal support (Marques, 1997). Collapse of the karst features after removal of their sandy infilling is also important, since it may happen not at the cliff face but a few metres inland and, after some time, that collapsed area will be connected to the sea, creating the intricate pattern of the coast in the central Algarve (Dias, 1984). Plio-Pleistocene sandy cliffs evolve predominantly by gullying and through mass movements, mostly slides and slumps (Marques, 1997).

The study of the rocky cliffs of central Algarve is recent. Qualitative studies about the general evolution and shoreline retreat go back to the mid and late 80's on the works of Dias (1984) and Andrade *et al.* (1989). After, Dias & Neal (1992) characterized the rocky coast of Algarve using Emery & Kuhn (1982) cliff profile evolution model, although they have focussed on the soft cliffs of eastern Algarve. In fact, the eastern Algarve soft cliffs have been subjected to more frequent and detailed studies in the past years, mostly concerned with accurate evaluation of cliff top retreat (*e.g.* Correia, 1996; Correia *et al.*, 1996; Catalão *et al.*, 2002;

Oliveira, 2005). As for the harder rocky cliffs of central Algarve, the first detailed study was made by Marques (1991) which quantified cliff evolution rates, as well as evaluated the active processes and mechanisms of cliff behaviour for all the cliffed coast of Algarve, using aerial photography interpretation. This study still is the most extensive one regarding the sea cliffs of Algarve, and almost the only one for some parts of the coast.

In the late 90's hazard evaluation became an issue and Forth *et al.* (1999) presented hazard maps related to karst evolution in the Miocene cliffs of Algarve. However, their test area has not reached the cliffs between Galé and Olhos de Água. Lately Teixeira (2002) has quantified the relationship between slope mass movements in the Miocene cliffs of Algarve and intense precipitation along with stormy wave events. Loureiro & Nunes (2006) have presented a geomorphologic-based risk evaluation for cliffs under different lithologic conditions but, although have incorporated Miocene calcarenites did not include the area under study on this work. Recently, complementary inventories of mass movement in the Miocene cliffs of central Algarve have been used for defining hazard lines and return period for mass movements through statistical analysis (Teixeira, 2006).

3.2 Photogrammetry and GIS Techniques in Cliff Hazard Assessment

Cliff hazard assessment can be approached using diverse methods and techniques (Bird, 1994; Lee & Clark, 2002). When considering specifically the application of photogrammetry and GIS to hazard assessment in coastal zones, where rocky cliffs are the dominant coastal feature, most studies have been dealing with the calculation of shoreline retreat by evaluation of cliff top positions along the time (*e.g.* Catalão *et al.*, 2002; Moore & Griggs, 2002; Lim *et al.*, 2005; Zviely & Klein, 2004). In such studies, photogrammetry has been primarily used to obtain accurate orthophotographs that are integrated into GIS environment for subsequent analysis. GIS main applications have been in the generation of databases with digitized coastal features, to be used for spatial analysis. Such applications have also been developed for assessment and predictive modelling of landslide hazards, mainly in inland mountainous areas (Huabin *et al.*, 2005), but also in rocky coasts where large mass movements are the dominant process of cliff evolution (*e.g.* Fall *et al.*, 2006).

Examples of photogrammetry and GIS combined used in hazard assessment for cliffed coastal areas come from many different locations. In the UK, research funded by Department for Environment, Food and Rural Affairs on cliff erosion has led to the publication of Lee & Clark (2002) review of research being done in the soft rocky cliffs of British coasts (Waters &

Payne, 2006). Studies dealing with cliff hazards in the UK are diverse and numerous, being the majority of them concerned with cliff recession prediction (e.g., Lee *et al.*, 2001; Hall *et al.*, 2002; Lee, 2005). Nevertheless, studies that effectively used photogrammetry or GIS in cliff hazards have also been published (e.g. Boggett *et al.*, 2000; Rosser *et al.*, 2005). In the USA most studies have been driven by the United States Geological Survey and Federal Emergency and Management Agency in the Californian coast (e.g. Moore *et al.*, 1999; Moore & Griggs, 2002, Hampton & Griggs, 2004) and the coast of Hawaii (e.g. Coyne *et al.*, 1999). Recently, in the south-western Spanish coast, Rio & Gracia (2005) presented a cliff erosion vulnerability assessment using photogrammetry and GIS but once again, photogrammetry is mainly used to calculate cliff recession.

In Portuguese coastal areas, and particularly in the Algarve, photogrammetry has also been used for defining accurate rates of cliff top recession, but only in soft cliffs located to the east of Olhos de Água (Correia, 1996; Correia *et al.*, 1996; Catalão *et al.*, 2002; Oliveira, 2005). For the area presently under study the use of photogrammetric techniques or GIS supported hazard assessment has never been done. Studies that relate forms and processes of rocky cliff evolution for hazard assessment are rare, even considering those that are not supported by photogrammetric techniques or GIS. In the Portuguese coast an earlier attempt by Marques & Romariz (1989) evaluated the coastal erosion hazard based on the relations between forms and processes in the rocky coast of Peniche, located on the western coast. However, this study was based on field investigations and geological mapping, not considering photogrammetry or GIS. Likewise, Forth *et al.* (1999) and Loureiro & Nunes (2006) presented hazard maps for part of the Algarve coast, also using a multi-factor approach and defining different weights for each form and process considered. Nevertheless, these studies were mainly focused on karst features and have not considered the combined use of photogrammetry and GIS.

The present study is, therefore, the first attempt to combine the use of photogrammetric techniques, which provide the basis for obtaining accurate data about the forms and processes responsible for the evolution of rocky cliffs, with GIS that supply automated methods to analyze such forms and processes, and latter integrate them in a composite hazard evaluation for sea cliffs in the southern coast of Portugal.

3.3 Coastal Zone Management – instruments and plans in Algarve

A comprehensive approach to coastal zone management, integrating the economic, social, cultural and especially natural dimensions, arrived quite late to the Portuguese political

discourse and even later to the actual practice of planning and management of the coastal area. In fact, nowadays it is still questionable if Portuguese coastal zones are actually managed, since most decisions regarding it are made on the basis of political pressing and lobbying (Dias & Ferreira, 1997; Dias, 2003). Since the early 90's some attempts have been made to set in motion an Integrated Coastal Zone Management (ICZM) strategy for the Portuguese coastal zone. So, in 1993 it was decided that the entire Portuguese littoral should be subjected to Coastal Zone Management Plans, and these would be the next revolution in coastal areas (Gomes & Pinto, 2003). The Coastal Zone Management Plans are widely referred in Portuguese by the acronym POOC, from *Plano de Ordenamento da Orla Costeira*. All POOC's, have an area of intervention of 500 m landward of the coastline and seaward down to the 30 m bathymetric contour.

The area under analysis was integrated into the Burgau-Vilamoura POOC, approved in 1999 for a period of ten years (RCM, 1999). The cliffs on this coast are unstable, but, at the same time, the pressure for tourist development, with the associated occupation of the seaside are probably higher than in any other stretch of the Portuguese coast (Abecasis & Soares, 2000). Such conditions require an uneasy balance between these two contradictory factors, assuring the protection of the cliffs simultaneously to the sustainable use of the coast (Abecasis & Soares, 2000).

The Burgau - Vilamoura POOC does consider the specific character of a coast composed of rocky cliffs with different responses to marine and subaerial induced erosion. This was mostly made by defining the Cliff Protection Zone (CPZ) and also by identifying areas where the cliffs are inactive and, therefore, its use is less conditioned. The landward CPZ was defined according to the expected retreat of the coastline based on the magnitude of singular mass movements. Although such information is unquestionably important, it seems to be a narrow approach to the coast vulnerability and risk induced by the extensive human occupation of the area.

The protection zone was aimed to guarantee the safe use of the coast defining, for the area under analysis, a cliff-top landward strip with 150 m width between Galé and Balaia beaches and 30 m between Balaia and Olhos de Água as CPZ, followed by respectively 25 and 30 m width Additional Protection Zone. It must be noted that a series of high and low density buildings and infrastructures already existed in that protection area and they were not removed. Even more concerning is the fact that some other buildings in that strip were constructed after the CPZ was defined. Such situations are common in Portuguese coastal

areas, since legally there is a ruling concept in terms of land planning that gives prevalence to acquired rights to approved constructions, even though they may have got that approval so far as the 70's, and also the right of building in private land, although this has been increasingly more restricted.

For the cliff-top seaward strip, a protection area with a length corresponding to 1.5 the height of the cliff was defined, aiming to protect beach users from rock falls or cliff collapse into the beach. The reduced width of most of the beaches puts them completely within the CPZ, and therefore dangerous places for beach use. All concrete fixed infrastructures, like restaurants and bars, had to be removed and replaced by wooden mobile structures, but they still remained on the CPZ. The Burgau - Vilamoura POOC, like most of the POOC's for the Portuguese coastal zone, have been criticized for not being real management plans, but just a set of beach infrastructure plans that do not present any effective management strategy. Therefore, the important role they should be having in the restoration of the coast and also in helping to prevent further damage is being questioned (Gomes & Pinto, 2003).

By 1999, INAG (Instituto da Água) has published the Risk Maps for the Portuguese littoral. However, the inexistence of a clear methodology for defining risk areas resulted in a simple confirmation of what the POOC had presented and, as a result, has been of reduced use for coastal management, since no quantitative or qualitative approach to risk classification was presented (INAG, 1999).

Regional and municipal level plans or spatial planning instruments do, as a principle, consider the instability of the cliffs, but its major concern is setting up areas for construction and defining urban perimeters. Coastal management for rocky cliffs between Galé and Olhos de Água has not been effective, since there is not a clear strategy for the area. All the objectives drawn for it are excessively general and it is evident an under consideration of the geodynamic characteristics and evolution of the cliffs.

4. Methodology

Research in coastal areas, particularly related to coastal erosion, is done using a large variety of methods and techniques. From those, photogrammetry has an important role, since it provides spatially accurate data (Wolf & Dewitt, 2000). Photogrammetric techniques have been extensively used as a complement of GIS in mapping purposes (Baily *et al.*, 2003), supplying fundamental data for GIS analysis (Wolf & Dewitt, 2000). In this study, photogrammetry and GIS were combined to evaluate the factors that contribute to hazard in sea cliffs and to generate a hazard map for the area under study. The stages of this integrated analysis are summarized in Figure 4.1.

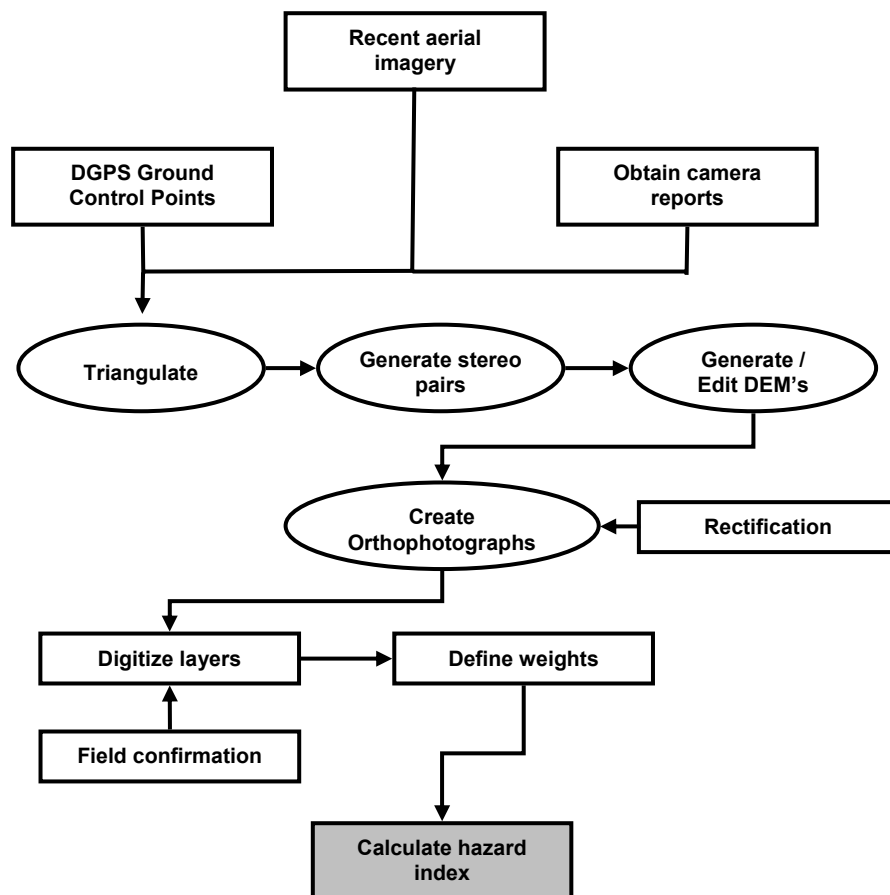


Figure 4.1 - Methodology scheme (modified from Moore & Griggs, 2002).

4.1 Field work and Survey

In order to have a broader knowledge of the study area and identify the main morphological characteristics, a survey was carried out between 27th and 29th of August as well as from 30th of September to the 1st of October, 2005. During this survey, geological and geomorphological features were registered and photographs were taken along the coast to document cliff features (*e.g.* lithology and profile of the cliff face, protection structures). In a later stage of this study, it was necessary to confirm some of these features, therefore, new field surveys were done in the 23rd January and the 29th August, 2006.

For assisting the survey, coloured aerial photographs from 2001 at a scale of 1: 8000 were used. These aerial photographs, flown for the University of Algarve (CIACOMAR/CIMA), also provided the base imagery for this study. Flight lines were shore parallel, therefore, selected photos were cliff top centred with 60 percent overlap between adjacent images. For planning the survey, the aerial photographs were examined and marked for suitable Ground Control Points (GCP), which were distributed along the study area. The GCP selected had to be easily identifiable in at least every stereoscopic pair and, for that reason, with clear outlines. In addition to this, the GCP should not be susceptible of modifications. The collection of GCP took place on the 21st, 28th September and 4th October, 2005.

The GCP were recorded using a Dassault Sercel NP Scorpio 6001 SK/ MK, a Real-Time Kinematic Differential Global Positioning System (RTK-DGPS), involving two receivers, the base station, established at a known point where coordinates are known, and the “rover”, located where GCP coordinates were required. Both receivers should track the same satellites to give accurate relative point positioning. The base station was set up in a street at Albufeira city centre, in a known location, corresponding to the point 1002 (Table 4.1). A second point, 1001, a few metres ahead and across the street, was also used to evaluate the accuracy of the collected GCP, being measured in the beginning and the end of each survey. The antenna height of the rover unit was set up to 2.00 m and the height of the base station was 1.195 m, using a DSNP NAP antenna with support.

Table 4.1 – Coordinates of base station point and accuracy evaluation point.

Point	Eastings	Northings	Z
1001	- 11115.761	-286637.657	57.91
1002	- 11113.153	- 286656.703	54.127

Thirty-two valid GCP (Appendix 1) were collected and recorded using the Transverse Mercator projection, Datum 73, positioned in the geodetic centre of mainland Portugal, Melriça. The recording period in each GCP varied from 2 minutes to 10 minutes, with a minimum number of 5 visible satellites, enabling higher accuracy. To support the recognition of each GCP exact location during the photogrammetric process, location sketches and photographic registers of each GCP collected were also made.

After the surveys it was necessary to post-process the data, *i.e.*, data collected at both the base unit and the rover were logged in real time and then processed at CIACOMAR using GNSS Studio software from Thales Navigation. In the 4th October, the last day of survey, there was a major problem with the GPS raw data collected from 15:30 onwards. The base station did not record properly the GCP, which meant that there were no GCP for the westernmost part of the study area. Nevertheless, the remaining 32 valid GCP were used to successfully orthorectify the aerial photographs.

4.2 Digital Photogrammetric Processing

The aerial photographs taken in 2001 for the University of Algarve (CIACOMAR/CIMA) were used as base imagery for the present study. Since these photographs were in analogue format, in order to produce orthorectified images it was necessary to convert the 22 previously selected photographs and convert them into digital files. With the purpose of preserving the quality of the analogue images and minimize distortion, the original photographs were scanned at a resolution of 20 microns (1270 dpi) using the Vexcel Ultrascan 5000 photogrammetric scanner from the Photogrammetric Laboratory of the Geography Department (University of Portsmouth).

Afterwards, the scanned images were imported into ERDAS Imagine 8.7 software. Using the ERDAS Imagine 8.7 Leica Photogrammetry Suite (LPS) module, it was necessary to create two block files of images (strips of overlapping stereo aerial photographs) due to the existence of two different flight course directions in the selected images. The use of block files facilitates the photogrammetric processing, allowing to carry out the tasks at one time for the entire strip of photos contained inside each block (Leica Geosystems, 2003a).

Aerial photographs contain inherent errors caused by camera orientation, film and lens distortion, terrain relief, and also scale variations due to the inconsistent flight altitudes and attitude of the airplane along a flight line (Moore & Griggs, 2002; Leica Geosystems, 2003a). The orthorectification begins with aerial triangulation (Moore & Griggs, 2002), a procedure

that establishes a relation between the images, the camera and the ground coordinates (Leica Geosystems, 2003a). Aerial triangulation includes interior orientation and exterior orientation. Interior orientation determines the internal geometry of the camera (Leica Geosystems, 2003a), and is performed through the digitizing of fiducial marks and the insertion of camera calibration data (lens characteristics, focal length, radial distortion and location of fiducial marks). Exterior orientation establishes the relationship between the image and the ground coordinate system and is performed through the introduction of the geographic coordinates for GCP and their accurate digitizing on the aerial photographs. Additionally, tie points were both manually and automatically scattered over each photograph. With the information needed to perform aerial triangulation, bundle block adjustment determines the position and orientation of each image as it existed at the time of capture, the ground coordinates for tie points, as well as the reduction of the errors associated with the imagery (Leica Geosystems, 2003a).

Once the aerial triangulation has been performed, a summary is displayed with the results that determine the quality of the overall solution. The errors of this process are then calculated using the residuals of all points' coordinates, which provide significant results such as the total Root Mean Square Error (RMSE) of the rectified image, or even the RMSE for the GCP in the X, Y and Z directions. RMSE is reported in pixels (Leica Geosystems, 2003a), therefore, in order to have an accurate rectification, RMSE should be lower than the value for 1 pixel (Leica Geosystems, 2003b). Considering that pixel size for the present project is 0.21 m, RMSE values lower than 1 mean that the displacement from the real location is less than 0.21 m and that even a RMSE value of 2 represents a displacement of less than 0.5 m. The two block files have different total image unit-weight RMSE values (Table 4.2), with the second block value being significantly higher. Such results indicate that the residuals within the network of points have been minimized more effectively in the first block than in the second one. On the contrary, the higher error value for the second block denotes that the

Table 4.2 – RMSE values for image blocks and control points directions

	Direction	Block 1	Block 2
Control Point RMSE	Ground X	0.1653	0.3614
	Ground Y	0.1094	0.2907
	Ground Z	0.9670	5.7069
Total Image Unit-Weight RMSE		0.3566	1.7090

estimated unknown parameters in the triangulation process do not conform entirely to the original GCP. RMSE values are also higher in the Z direction, being even higher than 1m in the second image block.

With the acceptance of the aerial triangulation solution, transformation equations were computed for each photograph, removing distortions and displacements. Digital stereopairs were then created for every overlapping image, and subsequently used to generate a Digital Elevation Model (DEM), *i.e.* a three-dimensional representation of the surface, with the LH Systems Socet Set digital photogrammetric software. The DEM enables to remove the effect of topographic relief displacement and reduce further distortion (Moore & Griggs, 2002). Back in the ERDAS Imagine 8.7 LPS module, the DEM and the triangulation equations are associated with the digital images to produce the orthorectified image for 2001.

As previously mentioned, the GCP collected for the westernmost part of the study area were unavailable. Nevertheless, since it was important to incorporate this area in the mosaic, the aerial photographs without GCP were georectified through geometric correction using a 2nd order polynomial equation. This procedure allowed rectifying the aerial photographs with reference to the mosaic, selecting points from the orthorectified mosaic and matching them with points on the photograph without GCP. Since there were three aerial photographs in this situation, it was necessary to repeat this process twice, using as reference the last aerial photograph merged with the mosaic. From these points a transformation is performed and upon ortho resampling the images without GCP are georeferenced. This process brings a new source of error and decreases the accuracy of the mosaic each time an aerial photograph is added. Ultimately, the final mosaic is created and the orthorectified image possesses geometric fidelity that enables mapping procedures and quantitative analyses.

4.3 GIS Mapping and Analysis

Rocky coasts are complex systems and, because of that, in order to assess hazard at a regional scale in such environments, it is necessary to evaluate a selected number of influencing factors. For the present study, the factors considered for generating the hazard index were: wave exposure, lithology and cliff face profile, observed mass movements and also width of a protective beach and/or shore platform.

According to the scale and factors considered, the use of GIS provides an approach that enables to analyse and georeference factors of different nature so they can be combined and

evaluated together. After being digitized, the selected factors were categorized by classes and a weight value was attributed to each class within each factor, expressing their relative importance. The combination of these weighted values allowed the quantification of each feature contribution, achieving, as a result, a composite hazard index that displays distinct hazard classes in a map for the study area. Although not considered for the hazard index, the build-up area and coastal protection structures were also digitized in order to evaluate qualitatively their relation with the hazard values obtained.

The factors selected for hazard assessment have been divided into two groups: the susceptibility factors (wave exposure, lithology and cliff face profile, mass movements) that add weight values to the hazard index, each one with a minimum weight value of 0.1 and a maximum of 1; and the protection factors (presence of protective beach and/or platform) that subtract weight values to the hazard index, with a minimum weight value of -0.1 and a maximum of -1. Although there were actually two protection factors, *i.e.* beaches and shore platforms, in practice they were evaluated as only one factor in terms of weight value, since the study area includes sites with both protection features that, if assessed separately, would total up -2, offering an excessive protection value.

Following the digital photogrammetric process, the orthorectified image was imported into ESRI ArcGIS 9.1 software where, via on screen digitizing, it was possible to map the features and factors selected to assess hazard in sea cliffs, which were digitized as vector data and stored as shapefiles. The on screen digitizing was performed at a 1:800 scale, approximately, and the shapefiles were referenced to the same coordinate system as the orthorectified image.

In order to support the digitizing tasks in ArcGIS and, most of all, to increase the accuracy in the recognition of coastal features, sketches of the cliff top line, high water line (HWL), shore platforms, lithology and protection structures were done in transparencies, through aerial photography interpretation using a TOPCON MS-3 mirror stereoscope at the University of Algarve. During this stage it was necessary to perform field surveys to confirm and register photographically some of the features, especially cliff top position, lithology and cliff face profile, as well as identify new protection structures.

The cliff top line was the primary feature to be digitized, and it was considered to correspond to the intersection of the cliff face and the undisplaced material adjacent to the cliff face (Lee & Clark, 2002). The cliff top line is interrupted in areas where cliffs are absent, like exclusively sandy areas or where constructions, like the Albufeira marina, have isolated the cliffs from marine processes. In certain areas, the seaward edge of some raised shore

platforms has been digitized as cliff top line, since the cliff is located far inland and is only affected by spray action (Moura *et al.*, 2006), leaving the edge of the raised shore platforms subjected to direct marine action.

The cliff top line, as reference feature, was considered to be the cartographic baseline for the hazard map. Therefore, the weight values of each feature were assigned to the baseline for quantification and for displaying the final hazard map.

4.3.1 Wave exposure

The knowledge of wave conditions is essential in coastal studies and, for cliff hazard assessment, the characterization of coastline exposure to wave action is determinant. Even in low-energy coastal environments, mechanical wave action is an important erosional mechanism as source of energy for transporting weathered material (Griggs & Trenhaile, 1994). In order to assess the contribution of wave exposition to hazard in the rocky cliffs of the study area, it was required to divide the cliff top line in segments exposed to a similar main incident wave direction. Due to the intricate shape of the coast, with several bays and headlands, these segments had to be considerably large and irregular, with lengths ranging from 300 to 5000 m. Wave data used to perform this analysis was obtained in Costa *et al.* (2001), and concerns the offshore incident wave at Faro buoy, recorded by octant and presented in percentage of occurrence (Table 4.3).

Table 4.3 – Wave climate at Faro (from Costa *et al.*, 2001)

Octants	N	NE	E	SE	S	SW	W	NW
(^o)	337.5-22.5	22.5-67.5	67.5-112.5	112.5-157.5	157.5-202.5	202.5-247.5	247.5-292.5	292.5-337.5
Wave Climate (%)	–	0.4	3.5	23.2	2	18.3	52.3	0.2

Using the ArcGIS script *FindPolylineAngle*, developed by J. Zakula, the azimuth of each coastal segment was obtained. However, the azimuth alone does not provide significant information regarding the exposure of a segment to incident waves. To accomplish that, it was necessary to obtain the exposure directions of each segment along the 180° semi-circle, defining the octants that each segment is in fact exposed as a function of its azimuth (Figure 4.2). This was done by adding to each segment’s azimuth the values of 45°, 90°, 135° and 180° (see example at Table 4.4), and verifying in which octant interval (Table 4.3) the exposure is observed (see example at Figure 4.2).

Table 4.4 – Example of the angles obtained for the exposed octants of segment 12

Segment Id	Azimuth	+45°	+90°	+135°	+180°
12	71°	116°	161°	206°	251°



Figure 4.2 – Example of a segment from 71° to 251°

The statistical program MINITAB was then used to assign weight values automatically according to segments' exposure. In this study the weight values were obtained directly from the wave climate data (Table 4.5), using the percentage of occurrence for each octant as reference.

Table 4.5 – Wave climate at Faro and respective weight values according to each octant.

Octants	Angles	Occurrence (%)	Weight values
N	–	–	–
NE	22.5° – 67.5°	0.4	0.004
E	67.5° – 112.5°	3.5	0.035
SE	112.5° – 157.5°	23.2	0.232
S	157.5° – 202.5°	2	0.02
SW	202.5° – 247.5°	18.3	0.183
W	247.5° – 292.5°	52.3	0.523
NW	292.5° – 337.5°	0.2	0.002

The total weight results from the sum of the weight values of each octant according to the segment's exposure (see example at Table 4.6). This value will then be imported to the baseline attribute table using the *join data* tool.

Table 4.6 – Example of octant weight values and the resulting segment total weight value

Segment Id	Azimuth	45°	90°	135°	180°	Total weight
12	(71°)	(116°)	(161°)	(206°)	(251°)	0.993
	0.035	0.232	0.02	0.183	0.523	

4.3.2 Mass movements

Mass movements were considered to be a crucial factor for assessing cliff susceptibility and, in this case, they were evaluated through the calculation of rate coastline affected by mass movements in each segment. This analysis was based on the mass movements identified by Marques (1997) between 1947 and 1992, using aerial photography interpretation. Mass movements were on screen digitized in ArcGIS as point features (see example at Figure 4.3) directly from the 1:25.000 scale location maps available in Marques (1997). For practical issues, the segments used in this analysis were the same as the ones used for wave exposition



Figure 4.3 – Example of mass movements mapping

analysis. Therefore, after computing the length of each segment, it was necessary to know the length of the segment that has been affected by mass movements. This was done using the *select by location* tool, which allowed selecting mass movements associated with each segment and then, using the attribute table statistics calculate their total length. Such length, as described by Marques (1997), was measured horizontally and parallel to the cliff top. With the length of each segment and the total length of mass movements in each segment computed, it was then possible to obtain the rate of coastline affected by mass movements per segment by dividing these two values and multiplying the result by 100. Afterwards, five classes were created aiming to attain an equitable number of occurrences per class (Figure 4.4), whereas the weight values ascribed to each class reflect the relative importance in terms of hazard evaluation (Table 4.7), with the highest rates representing the higher hazard values.

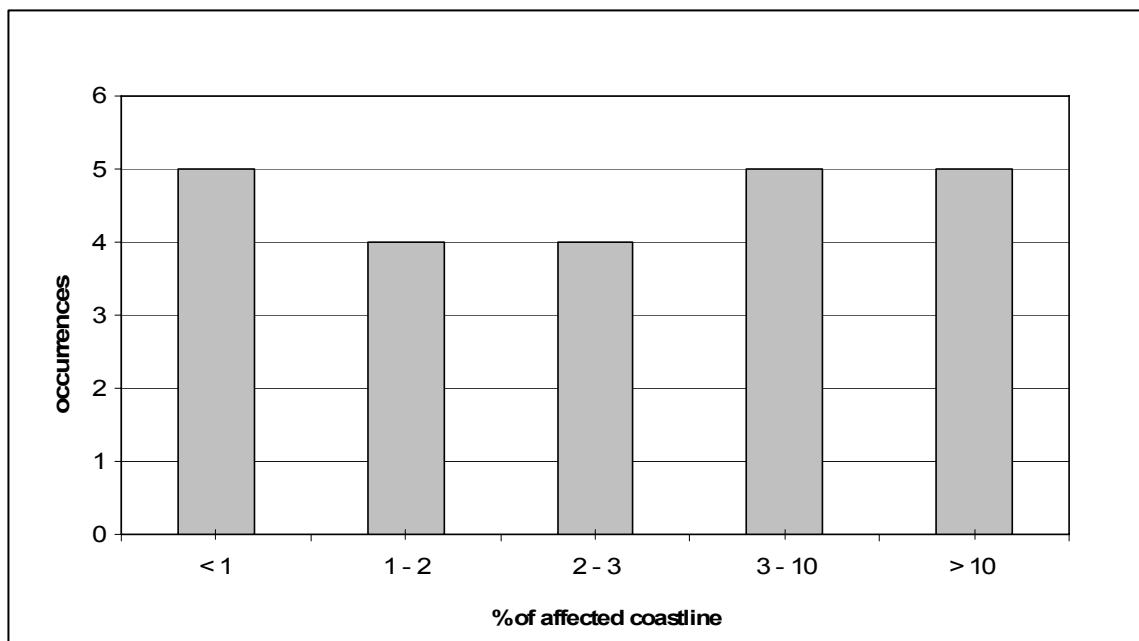


Figure 4.4 – Distribution of mass movements per classes of affected rate

MINITAB was then used to assign weight values to each segment according to the classes of affected rate. With the *join data* tool, the segments' weight values were imported to the baseline attribute table.

The < 1% class includes segments where no mass movements were registered. Nevertheless, even to such segments a weight value of 0.1 has been attributed, since the inexistence of mass movements can result from the segments partition and no segment is absent of mass movement hazard. On the other hand, since the inventory compiled by Marques (1997) is incomplete, ceasing in 1992 and comprehending only mass movements visible in aerial

photographs, it is most likely that small mass movements have occurred in such segments but have not been registered.

Table 4.7 – Classes of affected coastline rate (%) by mass movements, occurrences and respective weight values.

Classes	Occurrences	Weight value
< 1	5	0.1
1 – 2	4	0.25
2 – 3	4	0.5
3 – 10	5	0.75
> 10	5	1

4.3.3 Cliff face lithology and profile

The nature and cohesiveness is a decisive factor in the erosion of rocky cliffs, determining considerably its scale (Sunamura, 1992). Awareness of this and that cliffs are mostly the product of marine erosion and sub-aerial processes (Griggs & Trenhaile, 1994), have lead to a joint evaluation of cliff face lithology and profile.

Cliff lithology characterization was supported by sketches previously done, where coastline segments were displayed according to their lithologic composition, ranging between segments with Miocene rocks at the base and Plio-Pleistocene at the top and segments with Miocene or Cretaceous rocks only. Subsequently, these lithologies were adjusted to the sea cliff profile matrix presented by Emery & Kuhn (1982), in order to take into account the shape of the cliff face as a result of marine versus subaerial erosion (Figure 4.5). Only the profiles suitable for the study area geomorphology were chosen from the original matrix of Emery & Kuhn (1982). Cliff face profile categorization was supported by photographs and recordings taken during field surveys.

Combined mapping of cliff face lithology and profile for each segment of the coast was performed using polygon features. This was done by creating a 5 m buffer around the cliff top line, which was crossed by lines drawn on the limits of each segment considered. The buffer polygon was then partitioned according to the limit lines using the *intersection* tool, generating polygons for each segment (Figure 4.6). The code that identifies the profile and lithology of each segment and respective weight value was introduced in the attribute table.

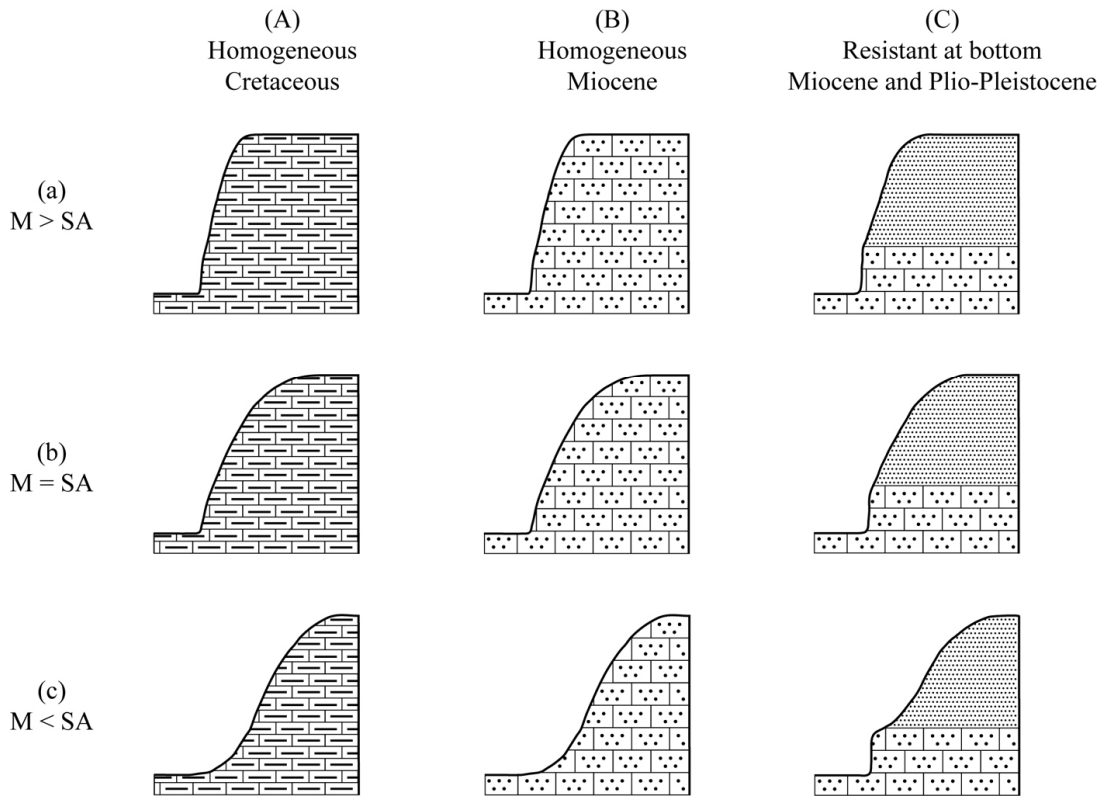


Figure 4.5 – Matrix of cliff face lithology and profile (adapted from Emery and Kuhn, 1982): M – marine erosion; SA – subaerial erosion



Figure 4.6 – Example of cliff face lithology and profile mapping

Based on the adjusted matrix, the weight values were assigned to each class in a scale from 0.1 to 1, according to their resistance to erosion (Table 4.8). This is expressed in the weight values, where the more resistant and homogeneous materials have lower hazard values, adapted according to the type of erosion they are exposed to. Cretaceous rocks are more resistant than Miocene rocks and, therefore, the later are more susceptible to erosion.

The third lithology class considered, formed by resistant Miocene rocks at the base and soft Plio-Pleistocene deposits at the top, represents the less resistant cliff lithology. It allows a faster erosion and coastline retreat and, for that reason, has higher weight values. In Miocene and Cretaceous cliffs, marine erosion is more efficient than subaerial processes (Dias, 1984), with strong erosion at the base followed by the weakening of the remaining cliff profile. In contrast, subaerial processes are more effective in unconsolidated material, as Plio-Pleistocene deposits, overlying Miocene rocks.

Table 4.8 – Weight values for lithology and profile classes

	A Cretaceous	B Miocene	C Miocene & Plio-Pleistocene
a (M>SA)	0.2	0.6	1
b (M=SA)	0.15	0.55	0.9
c (M<SA)	0.1	0.4	0.8

4.3.4 Beach width

Regarding the protection of cliffs, the existence of a beach, permanent or seasonal, offers a valuable defence from marine erosion (Griggs & Trenhaile, 1994). Beaches dissipate the wave energy along the foreshore and, consequently reduce considerable cliff susceptibility to erosion (Coyne *et al.*, 1999). Although subject to site specific conditions, Everts (1991 in Lee & Clark, 2002) reported, in California, that a beach width of 20 to 30 m provide considerable protection to cliffs, while a beach width of 60 m offers complete protection to 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 seaward limit of the beach, while the landward limit was the cliff line. The HWL was selected since it is the evidence of the landward limit of the high tide and, therefore, was established as the suitable marker for the land-water interface (Crowell *et al.*, 1991). Although the aerial photographs used in this study

were not captured all in the same day, they are from the same season – summer, which maintains a reasonable criterion, since beach width oscillates on a seasonal basis (Crowell *et al.*, 1991).

The HWL of each beach was digitized on screen as a polyline feature in ArcGIS using the tonal contrast wet/dry line on the sand. To support the identification of this line, the HWL sketches done by photo-interpretation were also used. According to the general direction of the coast and at an approximated distance of 10 to 15 m, a series of perpendicular lines were drawn from the HWL to the cliff line in order to calculate the average beach width (Figure 4.7). The length of these lines was automatically obtained using the Visual Basic Script code for calculating length in the ArcGIS *Field Calculator*. Subsequently, the lines corresponding to each beach were selected and their average length, which corresponds to the average beach width, was obtained automatically using the *Statistics* tool in the attribute table.

To identify beaches' landward influence area and, therefore, assign the respective protection value to the baseline, a 50 m buffer with flat end type and to the HWL left side only was generated for every beach, using the *buffer* tool from ArcToolbox (Figure 4.7). However, due to the lacework shape of the coastline, it was compulsory to manually correct some buffers since, even with flat end type, some buffers intercept other areas, like headlands or bays, which are not actually protected by a beach.



Figure 4.7 – Example of average beach width mapping

The classes of beach protection were obtained by computing the cumulative frequency of average beach width values. According to it, 6 classes with the same percentage were identified, each one with around 17% of the occurrences (Figure 4.8).

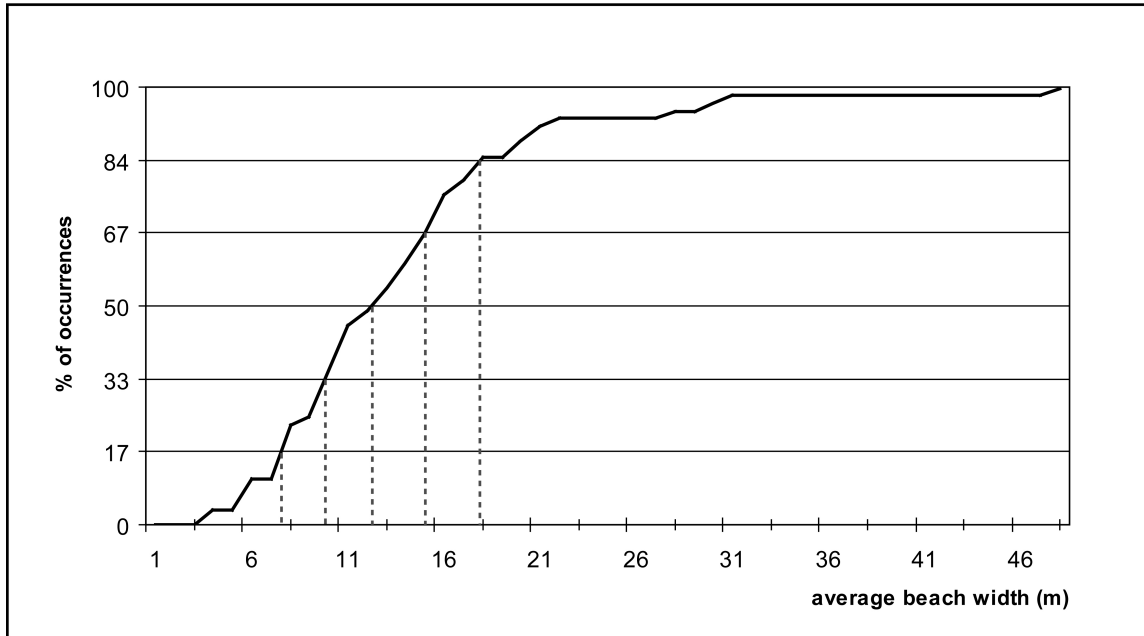


Figure 4.8 – Cumulative distribution chart of average beach width (dashed lines represent the obtained class limits)

In relation to shore platforms, beaches have a higher impact in cliff protection, since they have been recognized to be one of the most important buffers for cliff erosion. Since both shore platforms and beaches offer protection to the cliffs, they have a negative value, withdrawing weight value to the hazard index. Average beach width weight values were assigned gradually to each class, with the lowest value being -0.1 and the highest -0.6, obtained in beaches that have between 17.8 and 48 m wide (Table 4.9).

Table 4.9 – Average beach width classes, occurrences and respective weight values.

Classes	Occurrences	Weight value
< 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

Again, MINITAB was used to assign weight values to each beach segment according to the classes of average beach width. Using the *identity* tool in ArcToolbox, the weight values of each beach were related to the respective baseline segments.

4.3.5 Shore platform width

Resilient shore platforms provide protection to cliffs since they dissipate wave energy and force waves to break further offshore, therefore reducing the number of waves that reach the cliff base (Lee & Clark, 2002). Wider platforms provide, therefore, higher protection to cliffs in relation to narrow platforms.

In order to determine the average width of each shore platform, a procedure similar to the one applied for average beach width was applied. As mentioned before, the aerial photographs used were not captured all in the same day, however, they all have been captured during low tide. To maintain a common criterion in the platforms delimitation, both platform sketches and digitized platform polygons contemplate only the platforms visible above water level or, in some cases, just part of them, even if it was possible to identify the rest of the platform below water level. Perpendicular lines were drawn within each platform at an approximate distance of 10 to 20 m, with respect to the general orientation of the coast (see example at Figure 4.9). The length of these lines enabled to compute the average width of each shore platform.

In order to relate the average platform widths to the baseline, it was necessary to use buffers in the same way as in beach width. However, it is not possible to generate a buffer from a polygon feature respecting the same criteria used in beach width, flat end and left side type, as a way of restricting the influence area of each platform. It was then necessary to draw a parallel line seaward of each platform (platform line) and along its full extension, following the general orientation of the coastline. From this line a 300 m wide buffer, with flat end and to the left side only of the platform line, was created. Such buffer allowed identifying the areas and the segments of the baseline over which the shore platforms exert protection.

As in beach buffers, some platform line buffers had to be adjusted manually in order to eliminate overlapping that otherwise would duplicate the protection. To assign weight values to each platform, the cumulative frequency of average platform width values was calculated, establishing 4 classes, with 25% of the occurrences each (Figure 4.10).

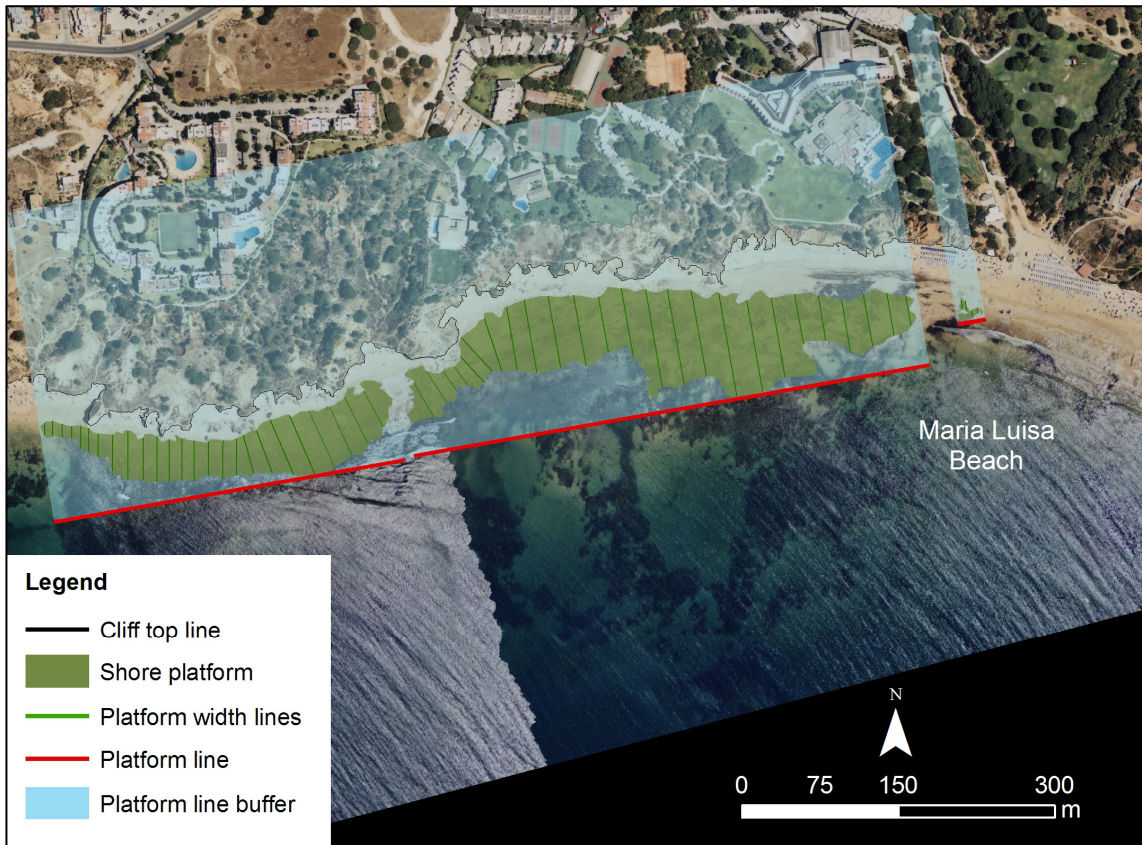


Figure 4.9 – Example of shore platform width mapping

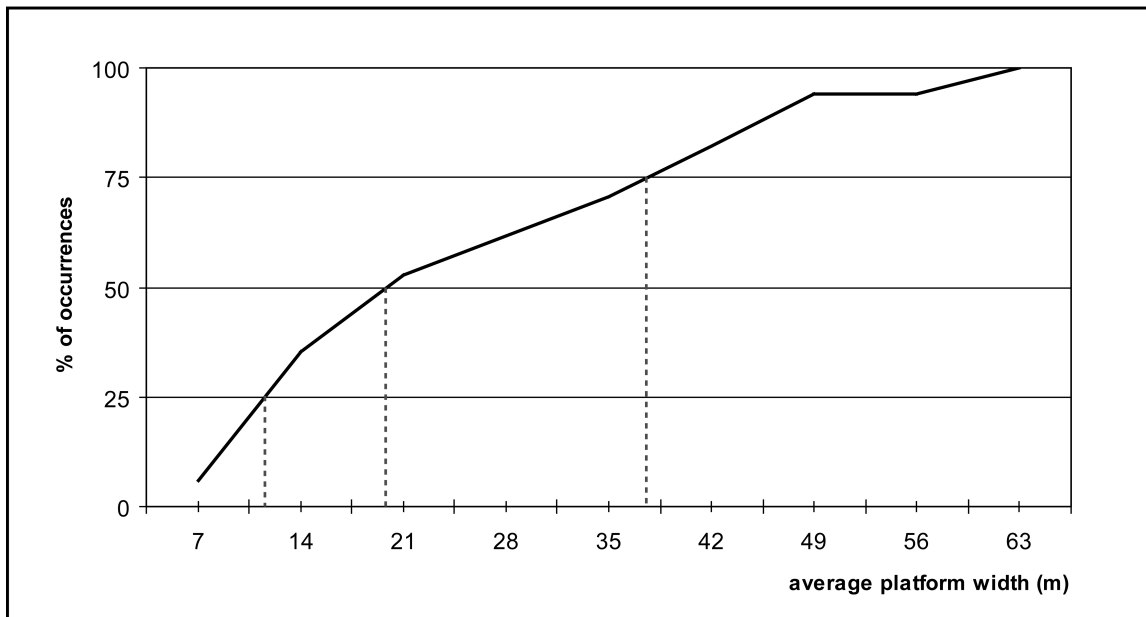


Figure 4.10 – Cumulative distribution chart of average platform width (dashed lines represent the obtained class limits)

With a minor protection role for sea cliffs, the weight values were assigned gradually from -0.1 to -0.4 (Table 4.10) completing, with beaches, one protection factor. Wider platforms in this area, with a higher protection value, attain average widths close to 60 m. MINITAB and the ArcToolbox *identity* tool were used to assign weight values to each platform and to allocate them to their respective baseline segments.

Table 4.10 – Average platform width classes, occurrences and respective weight values.

Classes	Occurrences	Weight value
< 11.6	9	-0.1
11.6 – 20.0	9	-0.2
20.0 - 37.6	9	-0.3
> 37.6	7	-0.4

4.3.6 Hazard index

In order to represent the degree of hazard encountered along the cliffs between Galé and Olhos de Água, a final index was calculated. This hazard index combines the factors considered in this study, as they reveal the resistance or exposure of sea cliffs to erosion and also the protection that coastal features can offer to that same cliff erosion.

The hazard index was calculated for each segment of the baseline according to

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

where *WE*, *MM*, *CFLP*, *BW* and *PW* are the weighted values of *wave exposure*, *rate of cliff top line affected by mass movements*, *cliff face lithology and profile*, *average beach width* and *average platform width*, respectively. For example, if a segment has a *WE* of 0.96, a *MM* of 0.75, a *CFLP* of 0.55, a *BW* of -0.4 and a *PW* of -0.2, then:

$$\text{Hazard} = \sum (0.96; 0.75; 0.55; -0.4; -0.2)$$

$$\text{Hazard} = 1.66$$

Since three susceptibility factors and one protection factor were considered, the hazard index values range between -1 and 3, originating four hazard classes with equal intervals, presenting *low*, *moderate*, *high* and *very high* hazard (Table 4.11).

Table 4.11 – Hazard index classes and respective values.

Classes	Hazard value
LOW	-1 : 0
MODERATE	0 : 1
HIGH	1 : 2
VERY HIGH	2 : 3

4.3.7 Built-up areas and coastal protection structures

Built-up areas and protection structures, even though they were not contemplated for the present hazard index, are recognized to be important in the evaluation of erosion hazard in rocky cliffs (Forth *et al.*, 1999). Therefore, such features have been digitized in order to evaluate their significance in the study area and also to identify relationships with the hazard values obtained.

Built-up areas within a 150 m wide protection zone along the coastline were digitized as polygon features (Figure 4.11). The width of this protection zone was defined according to the

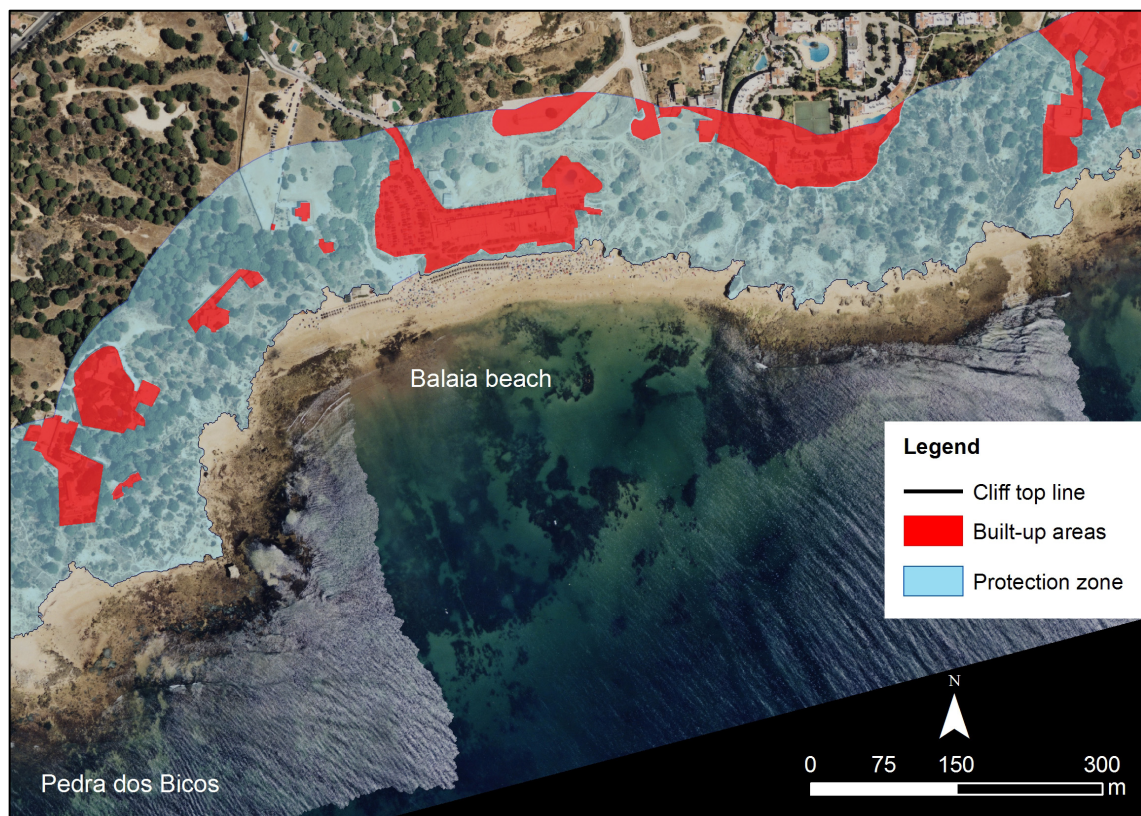


Figure 4.11 – Example of built-up areas in the protection zone mapping

maximum landward limit of the CPZ defined by the POOC for the study area. This protection zone was obtained by creating a 150 m buffer of the cliff top line with flat end type and to its left side. As build-up area were considered all concrete constructions, all buildings and every impermeable surface, like roads, car parks, tennis-courts, swimming pools, as well as gardens or lawns. These structures or land uses occupy a considerable portion along the protection zone, increasing the pressure in cliff materials and contributing to cliff instability.

A few parts along the cliffed coast presently under study have been protected by engineering structures. Although they have been constructed with the same purpose of providing stability to the cliffs, these structures are made of different materials, suggesting different objectives and durability. The protection structures have been digitized in ArcGIS as polygon features, comprising structures as walls in the cliff base, cemented cliffs, metallic nets covering the cliff face and filling of cavities in the cliff base with stone (Figure 4.12).

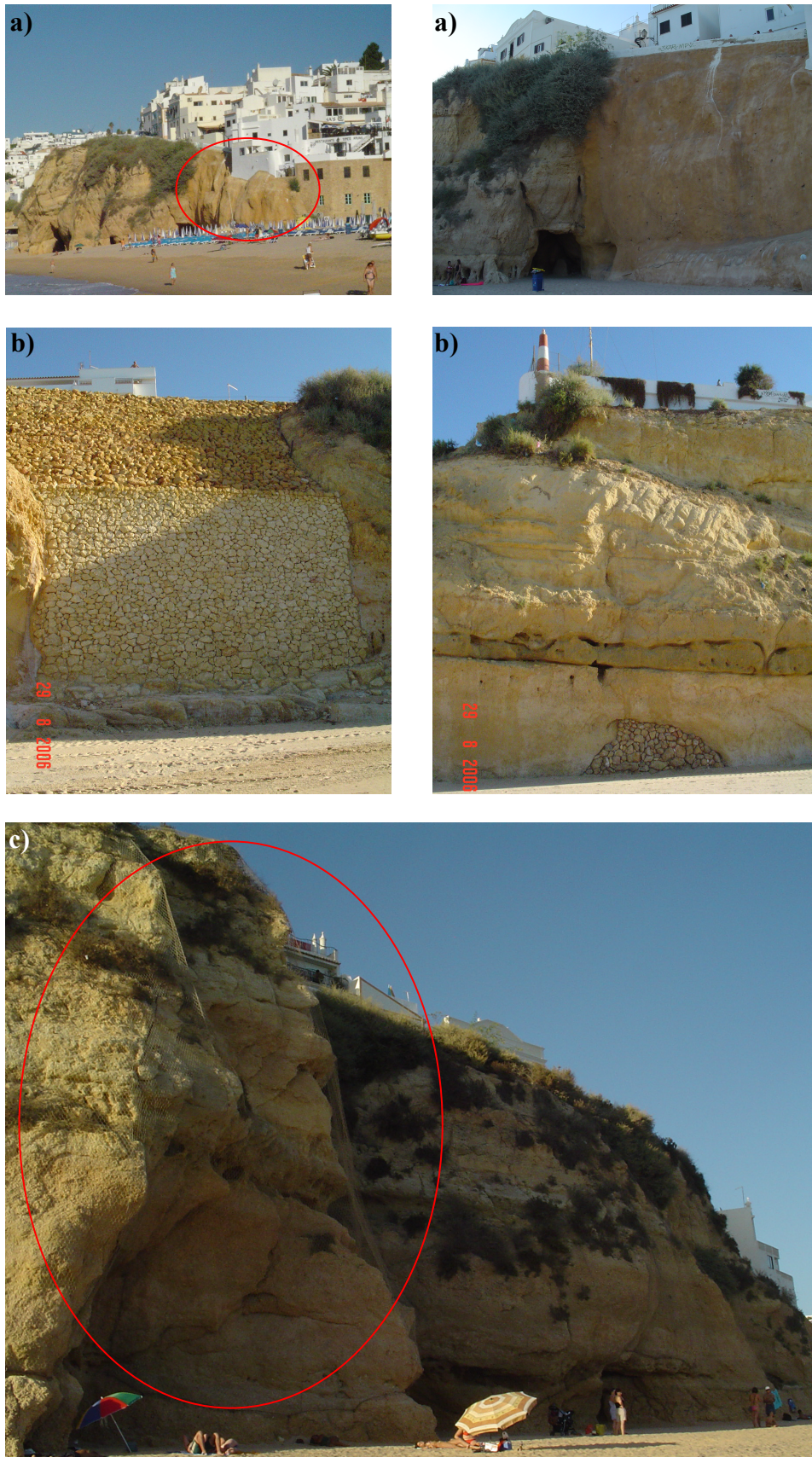


Figure 4.12 – Examples of protection structures made in: a) cement; b) stone; c) metallic net.

5. Results

The application of the methods described to the coastal area between Galé and Olhos de Água has resulted in the characterization of five primary layers, comprehending the factors identified as the principal contributors for assessing hazard in sea cliffs. The aggregation of such factors enabled the definition of a hazard index, which is analysed in conjunction with the built-up areas along a 150 m wide coastal protection zone. Exploratory analysis of the results was mostly based on multiple and composite queries made to the shapefiles' attribute tables, especially to the Hazard Index shapefile table, using the *Select by Attributes* and *Select by Location* tools available in ArcGIS.

It should be noticed that, although the coastal stretch presently under analysis has a 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 intricate pattern of the cliff top line used in this study.

5.1 Wave exposure

The majority of the coastline (61%) between Galé and Olhos de Água is exposed to the waves arriving from E to W directions (Figure 5.1), which is in agreement with the general orientation of the southern Algarve coast. Nevertheless, exposure to waves arriving from the NE to SW and also SE to NW octants is also significant, occurring respectively in 24.4% and 14.5% of the coastline (Table 5.1).

Considering the weight values for each exposure group and the contribution of each octant in particular (Table 4.5), it is possible to identify that, for the NE-SW exposure group, the main contributions are from waves approaching from the SE and SW octants, with values of 0.232

Table 5.1 – Length, relative distribution of the coastline exposition to prevailing wave directions and weight value per group

Exposure group	Length (m)	% of the coastline	Weight value
NE – SW	6113	24.4	0.474
SE – NW	3626	14.5	0.960
E – W	15297	61.1	0.993



Figure 5.1 - Weight values for the wave exposure groups

and 0.183, respectively. This means that, alone, these two octants represent 88% of the weight value for the NE-SW exposure group. The E-W and SE-NW exposure groups present very similar weight values, 0.993 and 0.960, respectively. In both, the main contributors are the SE (0.232), SW (0.183) and W (0.523) octants.

Since the relative frequency of mean direction associated with the peak period corresponding to the W octant represents more than half of the observations (Costa *et al.*, 2001) and, considering that the weight values have been attributed directly in relation to such parameter, it is clearly noticeable that the exposure groups that integrate the W octant are the ones with higher weight values, being the waves approaching from this octant determinant in terms of hazard for the coast presently under study.

5.2 Mass Movements

The average rate of cliff top line affected by observed mass movement at the study area is 5.0%, corresponding to a total length of 1261 m. In general, the highest rates were registered in the eastern part, between Pedra dos Bicos and Olhos de Água, while the central area and western areas present lower values, always below 10% (Figure 5.2). Values of cliff top line affected by mass movements lower than 3% occur in 67.7% of the entire area (Table 5.2). As expected mass movements occur primarily in cliffs composed only by Miocene rocks (Table 5.3), since this is the dominant lithology on the study area. Mass movements occurring in cliffs composed by Miocene and Plio-Pleistocene rocks have a reduced frequency, since only 14 have been registered. However, they are responsible for a considerable portion (36.9%) of the cliff top line affected by mass movements, indicating that these events may be rare, but have a strong impact on the coastline morphology (Table 5.3).

Table 5.2 – Length, relative distribution of classes of cliff top line affected by mass movements and weight value per class

Affected rate classes (%)	Length (m)	% of the coastline	Weight value
< 1	3870	15.5	0.1
1 – 2	3808	15.2	0.25
2 – 3	9273	37.0	0.5
3 – 10	4424	17.7	0.75
> 10	3661	14.6	1

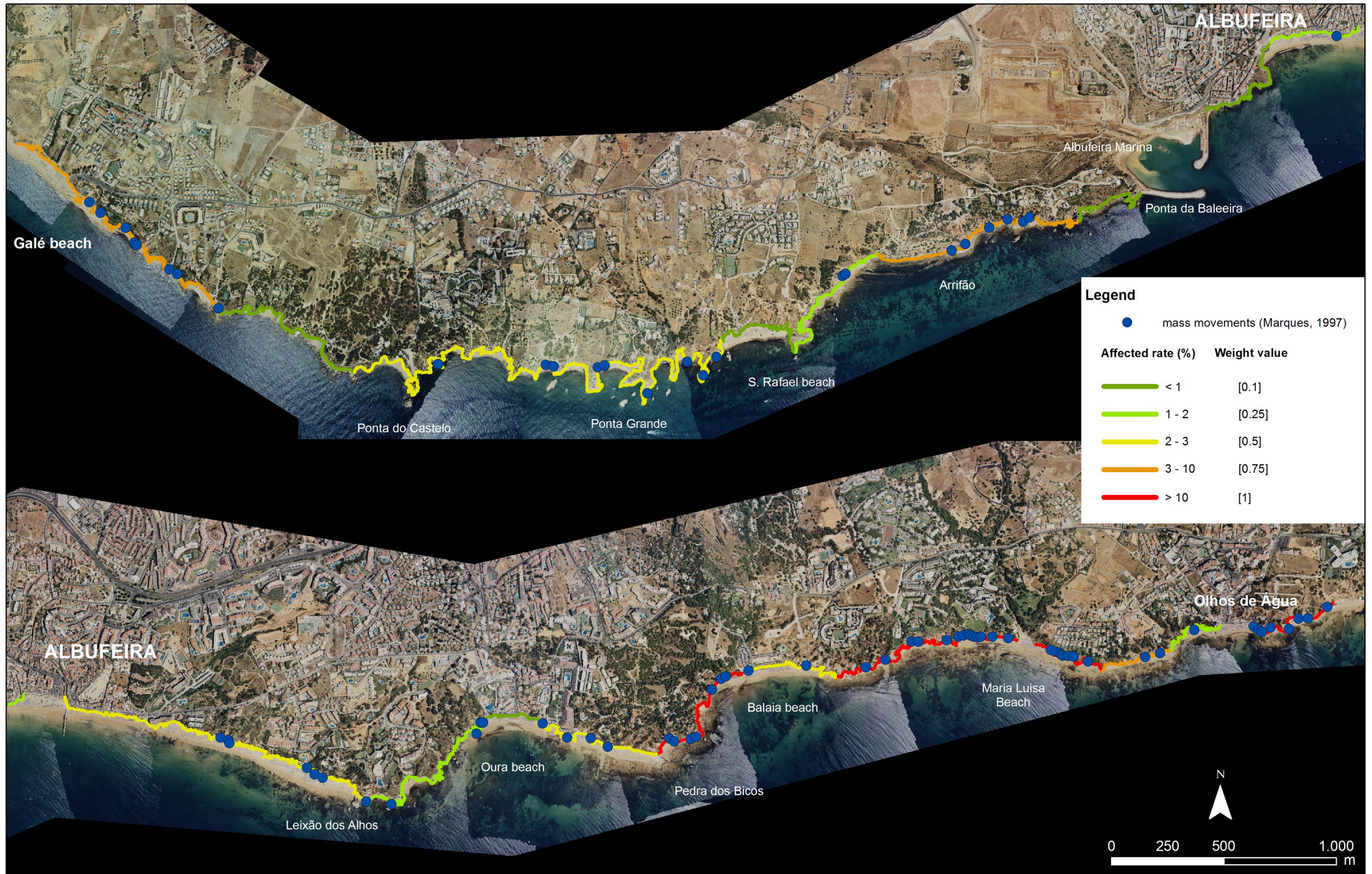


Figure 5.2 - Weight values for the rate of cliff top line affected by mass movements

Table 5.3 – Number, relative distribution of mass movements according to lithology classes and respective affected length

Lithology classes	mass movements		affected length	
	number	%	m	%
Cretaceous	3	3.5	59	4.7
Miocene	68	80.0	737	58.4
Miocene and Plio-Pleistocene	14	16.5	465	36.9

Mass movements distribution according to wave exposure groups allows to recognize that the majority of these events occur in the E-W exposure group (Table 5.4). Since this exposure group represents 61.1% of the coastline (Table 5.1), such dominance is not surprising. Nevertheless, when considering the length of the cliff top line affected by mass movements, the dominance is even more pronounced, with 80.8% of the affected length recorded in areas exposed to waves approaching from octants between E and W.

Table 5.4 – Number, relative distribution of mass movements according to exposure groups and respective affected length

Exposure group	mass movements		affected length	
	number	%	m	%
NE – SW	17	20	168	14.3
SE – NW	10	11.8	74	5.9
E – W	58	68.2	1019	80.8

5.3 Cliff face lithology and profile

The combined analysis of the cliff face lithology and profile (Figure 5.3), according to the classes defined, allowed to recognize that 88.4% of the active cliffs in the area presently under study are carved in Miocene rocks (Table 5.5), having the majority of them a profile indicative of a more effective marine erosion in relation to subaerial processes, as already recognized by Dias (1984) and Marques (1997). In fact, profiles typical of higher effectiveness of marine erosion are present in 69.8% of the study area, while only 5.9% of the cliffs are actually being primarily shaped by subaerial erosion (Table 5.5). The remaining 24% have an intermediate profile that does not enable to identify clearly the dominance of either marine or subaerial erosion. Cretaceous cliffs have the lower weight values and are



Figure 5.3 - Weight values for the cliff face lithology and profile classes

present in only one sector, located near Arrifão, being the less representative lithology in the study area. Classes of cliff face lithology and profile with weight values lower than 0.5 and higher than 0.7, only occur in 7.3% and 7.5% of the study area, respectively. The most hazardous classes present a reduced relative distribution, being the classes of intermediate weight values the most representative.

Table 5.5 – Length, relative distribution of cliff face lithology-profile classes and weight value per class

Classes	Length (m)	% of the cliffs	Weight value
aA (Cretaceous / M > SA)	1026	4.1	0.2
cB (Miocene / M < SA)	807	3.2	0.4
bB (Miocene / M = SA)	4876	19.5	0.55
aB (Miocene / M > SA)	16455	65.7	0.6
cC (Miocene and Plio-Pleistocene / M < SA)	671	2.7	0.8
bC (Miocene and Plio-Pleistocene / M = SA)	1200	4.8	0.9

5.4 Beach width

Protective beaches at the front of the cliffs are frequent in the area presently under study. In fact, 49% of the coastline is protected from the direct action of the waves by a total of 57 beaches with variable width and, therefore, different degrees of protection. An increase in the average beach width is usually associated to an increase in its length. As a result, wider beaches are also longer, leading, in this study, to a higher percentage of the coastline protected by beaches whose average width exceeds 17.8 m (Table 5.6). These are the cases of Galé, S. Rafael, Oura and Balaia beaches, as well as the beach between Albufeira and Leixão dos Alhos (Figure 5.4).

Table 5.6 – Length, relative distribution of classes of average beach width and weight value per class

Classes	Length (m)	%	Weight value
< 7.6	680.9	5.5	-0.1
7.6 – 9.8	707.2	5.7	-0.2
9.8 – 12.2	780.1	6.3	-0.3
12.2 – 15.1	1709.2	14.0	-0.4
15.1 – 17.8	2776.3	22.5	-0.5
> 17.8	5674.3	46.0	-0.6

The beaches between Galé and Olhos de Água are generally bounded by rocky headlands, with the longer ones developing in the larger embayments (Galé, Albufeira – Leixão dos Alhos, Oura, Balaia and Maria Luísa). These beaches are larger in the eastern flank of the embayments which, considering that the accumulation of sand is essentially made in the downdrift flank of the embayment's, indicates that sediment drift in this area is mostly from W to the E, driven by W-SW waves. In the small pocket beaches between Galé beach and Arrifão such behaviour is not evident.

5.5 Shore platform width

Emerged shore platforms offer protection to 45% of the coastline between Galé and Olhos de Água. From the 34 shore platforms identified, the larger ones are located in the eastern area, between Oura beach and Olhos de Água (Figure 5.5), presenting average widths close to 50 m. Such average width value is exceeded in the case of the shore platforms adjacent to Pedra dos Bicos and west of Maria Luísa beach. In the central and western parts of the study area, shore platforms are generally narrower and shorter, except in front of Arrifão, where they attain average widths higher than 40 m and are continuous for close to 1100 m.

As in the average beach width, it was also noted for the average shore platform width that the wider shore platforms are also the longer, resulting in a considerably higher proportion of the coast protected by shore platforms larger than 37.6 m (Table 5.7). The narrower shore platforms, whose average width does not exceed 11.6 metres, give rise to a very limited protection in extremely restricted areas. Shore platforms with average widths comprised between 11.6 and 37.6 m, account for 43.6% of the coastline protected by these morphological features.

Table 5.7 – Length, relative distribution of classes of average platform width and weight value per class

Classes	Length (m)	%	Weight value
< 11.6	867.4	7.7	-0.1
11.6 – 20.0	1720.7	15.3	-0.2
20.0 – 37.6	3181.7	28.3	-0.3
> 37.6	5476.2	48.7	-0.4

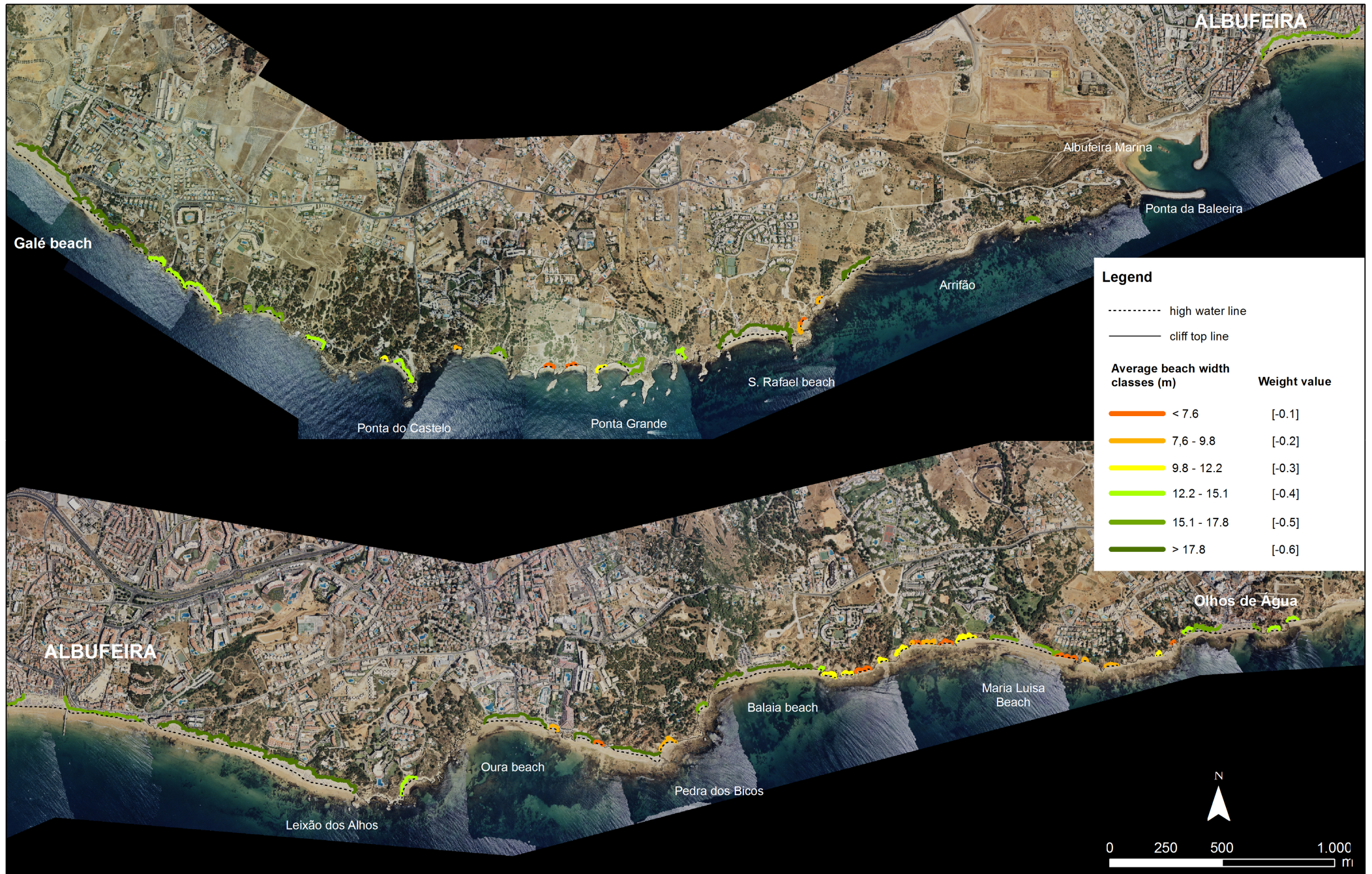


Figure 5.4 - Weight values for the classes of average beach width



Figure 5.5 - Weight values for the classes of average shore platform width

Shore platforms are all carved in Miocene calcarenites, with the sole exception being the shore platform in front of Arrifão, developed in Cretaceous marls. Nevertheless, lithologic composition does not seem to present any significant influence on the shore platforms average width for the area presently under study.

5.6 Hazard index

Aggregated consideration of the forcing mechanisms and protection factor previously presented allowed the definition of a composite hazard index. According to it, high and very high hazard values are clearly dominant, accounting for 91.5% of the coastline between Galé and Olhos de Água (Table 5.8). Very high hazard accounts for 27.0% of the coastline, occurring mostly in the western and eastern parts, between Ponta do Castelo and S. Rafael beach, and also east of Balaia beach (Figure 5.6). High hazard accounts for 64.5% of the coastline, being the more representative hazard class. Such high frequency results in a fairly widespread distribution, without distinctive spatial arrangement. Moderate hazard is considerably less representative, occurring in 7.3% of the coastline. Representative stretches of moderate hazard occur west of S. Rafael beach and Leixão dos Alhos, as well as east of Pedra dos Bicos and Olhos de Água. Low hazard values have very reduced expression, being identifiable in only one location, slightly west of Arrifão, extending for merely 308.6 m, which represents 1.2% of the coastline.

Table 5.8 – Length, relative distribution of hazard index classes and respective values

Classes	Length (m)	%	Hazard value
Low	308.6	1.2	[-1.00 – 0.00]
Moderate	1823.7	7.3	[0.01 – 1.00]
High	16141.3	64.5	[1.01 – 2.00]
Very high	6762.3	27.0	[2.01 – 3.00]

Considering specifically the hazard forcing factors, *i.e.* the factors that contribute positively to the hazard index increase, the majority of the coastline presents a very high hazard value (Table 5.9). Long stretches of coastline with hazard values between 2.01 and 3.00 are well distributed along the study area (Figure 5.7). High hazard values are present in 35.2% of the coastline, almost half of the value obtained when considering all the hazard factors. The



Figure 5.6 - Hazard index classes and values



Figure 5.7 - Hazard classes for the combined effect of all factors that contribute to increase the hazard index

western part of the study area, between Galé beach and Albufeira, concentrates most of the coastline stretches with high hazard values. As for the moderate hazard values, they are present in only one location, slightly west of Arrifão, and account for 2% of the coastline.

Table 5.9 – Length, relative distribution of hazard classes considering only the hazard forcing factors and hazard value per class

Classes	Length (m)	%	Hazard value
Moderate	488.3	2.0	[0.01 – 1.00]
High	8820.4	35.2	[1.01 – 2.00]
Very high	15727.1	62.8	[2.01 – 3.00]

Considering only the hazard forcing factors, a large part of the coastline is displaced to the immediately higher hazard class. This is indicative of the importance that the protection factors have for the combined hazard assessment, since they lower considerably the hazard index in many stretches of the coastline. Actually, in more than 18 km of the cliffs between Galé and Olhos de Água there is some degree of protection, which accounts for 72.7% of the coastline (Table 5.10). Most of the coast (44.3%) presents a high protection, with values between -1.00 and -0.50, while moderate protection accounts for 28.4% of the coastline. The remaining 27.3% are not protected by shore platforms and/or beaches. Unprotected stretches of the coastline are located mostly to the west of Albufeira, with a large portion being headlands (Figure 5.8).

Table 5.10 – Length, relative distribution of protection classes and protection value per class

Classes	Length (m)	%	Protection value
High	11084.3	44.3	[-1.00 – -0.50]
Moderate	7122.4	28.4	[-0.49 – -0.01]
No protection	6829.1	27.3	[0]

In terms of relative distribution of each or both protection features (Table 5.11), beaches alone offer protection to a wider extent of the coast (27.8%), followed by shore platforms alone (23.5%) and by both beaches and shore platforms (21.4%).



Figure 5.8 - Classes of protection factors that contribute to decrease the hazard index

Table 5.11 – Length and relative distribution of coastline protection features

Feature	Length (m)	%
Shore platforms	5878.7	23.5
Beaches	6960.8	27.8
Shore platforms and beaches	5367.2	21.4
No protection	6829.1	27.3

Regarding the relative distribution of each feature according to each hazard class (Table 5.12), some relationships were found. Low hazard, since it occurs in one single location, is always referenced to only one class within each factor. Invariably, such classes are in the extremes, with the lower values of hazard in the hazard forcing factors and the higher values of protection in the protection factor. Moderate hazard occurs mostly in stretches of the coastline exposed to the NE-SW exposure group. In fact, it is evident that lower hazard values occur mostly where the coast is exposed to NE-SW, since this is the less hazardous exposure group, while the higher hazard values occur dominantly where the coast is exposed to E-W, which is the most hazardous one. The majority (65,7%) of the cliffs between Galé and Olhos de Água are carved in Miocene rocks and present a profile indicative of more effective marine erosion, corresponding to the cliff face lithology and profile class aB (Table 5.5). Such dominance is registered in the moderate, high and very high hazard classes, with the aB class representing more than 50% in every one of them. In all hazard classes the most representative rates of cliff line affected by mass movements are lower than 3%. Nevertheless, a rate higher than 10% is also frequent where very high hazard was registered, accounting for 33.4% of this hazard class.

Considering the factors that offer some degree of protection to the coastline, very high and high hazard values occur predominantly where the coastline has neither a beach nor a shore platform protecting it. The absence of a protecting beach or a shore platform in front of the cliffs was registered in respectively 83% and 69.6% of the coastline with very high hazard. Concerning high hazard values, the non-existence of a beach or a shore platform is also dominant, but not as representative as in the very high hazard class. Moderate hazard occurs mostly where there is a large shore platform protecting the cliffs. Notwithstanding, the same strong association could not be found regarding average beach width, since most of the stretches where moderate hazard was found are not protected by a beach.

Table 5.12 – Length and relative distribution of the hazard index factors according to the hazard classes (shaded values represent dominant factors for each hazard class)

Factors and classes		Hazard classes							
		LOW		MODERATE		HIGH		VERY HIGH	
		Length (m)	%	Length (m)	%	Length (m)	%	Length (m)	%
Exposure Group	NE-SW	308.6	100	1380.7	75.7	4423.5	27.4		
	SE-NW			140.7	7.7	3265.6	20.2	219.6	3.2
	E-W			302.3	16.6	8452.1	52.4	6542.8	96.8
Cliff face lithology and profile	aA	308.6	100	179.7	9.9	538.0	3.3		
	cB			327.8	18.0	476.3	3.0	3.1	0.1
	bB			396.9	21.8	3758.9	23.3	720.6	10.7
	aB			919.3	50.4	10437.4	64.7	5098.1	75.4
	cC					671.4	4.2		
	bC					259.2	1.6	940.6	13.9
	< 1					230.2	12.6	3639.6	22.5
Rate of cliff top affected by mass movements	1 – 2	308.6	100	1265.7	69.4	2234.1	13.8		
	2 – 3			302.3	16.6	5093.9	31.6	3877.3	57.3
	3 – 10					3795.7	23.5	628.0	9.3
	> 10					25.5	1.4	1377.9	8.5
								2257.1	33.4
Average beach width	no beach			617,6	33,9	6475,3	40,1	5615,0	83,0
	< 7.6			32,4	1,8	245,6	1,5	403,0	6,0
	7.6 - 9.80			57,3	3,1	447,3	2,8	202,6	3,0
	9.81 - 12.20					527,6	3,3	252,4	3,7
	12.21 - 15.10			295,2	16,2	1414,0	8,8		
	15.11 - 17.80			463,4	25,4	2023,6	12,5	289,4	4,3
	> 17.80	308.6	100	357,8	19,6	5007,9	31,0		
Average shore platform width	no platform			119,6	6,6	8960,5	55,5	4709,9	69,6
	< 11.55					776,3	4,8	91,1	1,3
	11.55 - 19.95			104,0	5,7	1608,7	10,0	8,0	0,1
	19.96 - 37.60			491,7	27,0	1959,6	12,1	730,3	10,8
	> 37.60	308.6	100	1108,5	60,8	2836,2	17,6	1223,0	18,1

5.7 Built-up areas in the cliff protection zone

The presence of buildings and urban infrastructures, like roads, parking areas and lawns, in the 150 m cliff protection zone is fairly different considering the areas west and east of Albufeira (Figure 5.9). Built-up areas in the western part, between Galé and Ponta da

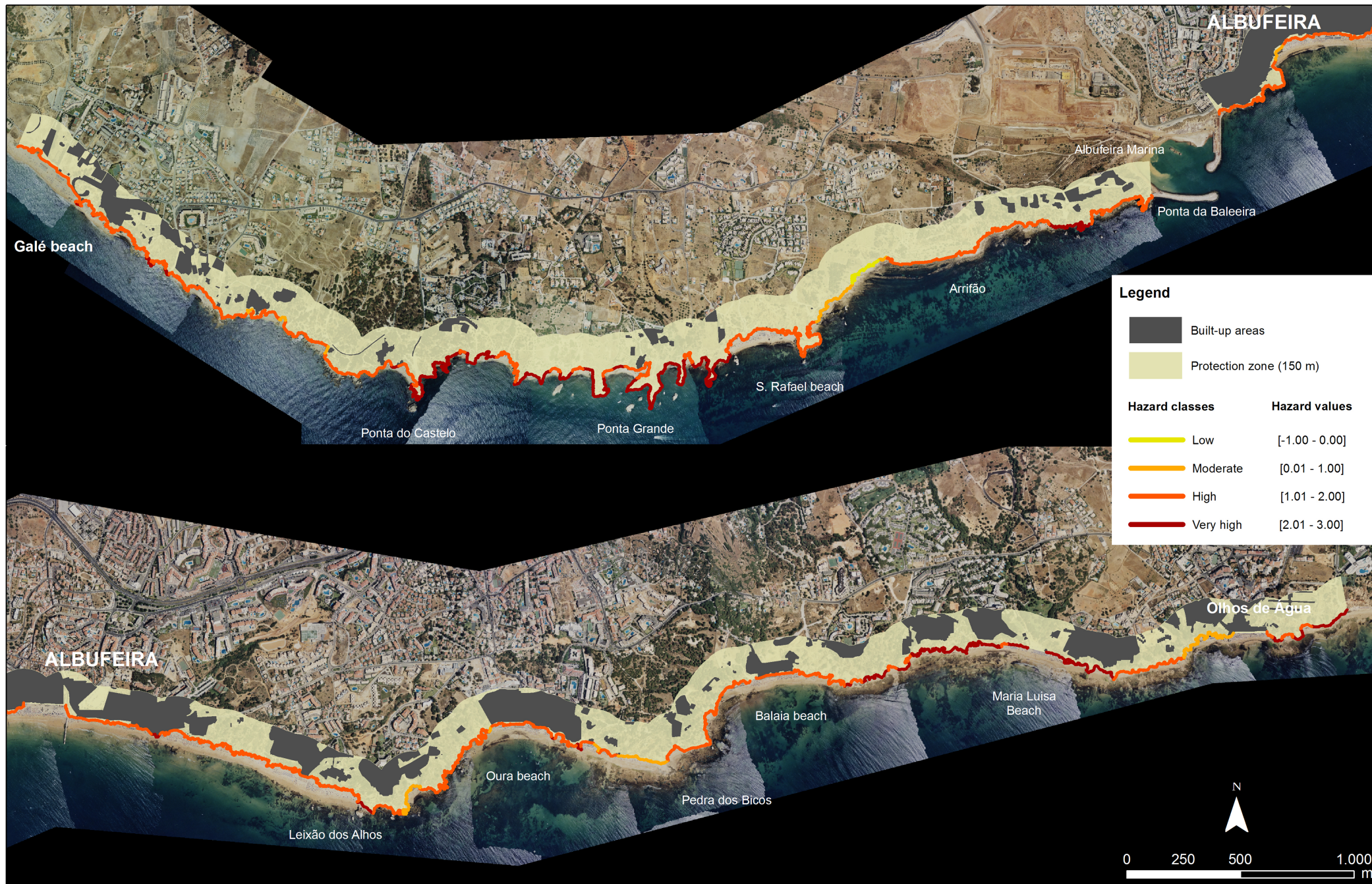


Figure 5.9 - Hazard index classes and values and built-up areas in the 150 m cliff protection zone

Baleeira, account for 12.8% of the cliff protection zone and are dispersed along the coast. The only exception is the area around Galé beach, where there is a higher density of built-up areas. In the eastern part, between Albufeira and Olhos de Água, built-up areas are more significant, occupying 45.9% of the total area of the cliff protection zone. High density areas are frequent in this part, not only Albufeira, but also Oura beach or Maria Luísa beach. It should be noticed that this analysis reports the situation as it was in 2001 when the aerial photographs were taken and, since then, numerous buildings and infrastructures have been constructed in the cliff protection zone, especially in the eastern part.

The higher density and occupation of the cliff protection zone by built-up areas in the eastern part can be related to the existence of wider and longer beaches, to the height of the cliffs, which are lower in this part, and, as a result, to the existence of better and more frequent access roads and paths. On the other side, the western part has higher cliffs and the beaches are often very small and difficult to get to.

Hazard values for the stretches of the coastline located in front of the built-up areas vary between moderate and very high. Since high hazard occurs in 64.5% of the coastline, built-up areas are mostly located near stretches with high hazard. Nevertheless, no spatial relationship could be found between built-up areas and the hazard values of the coastline.

6. Discussion

6.1 Data accuracy

The benefit of complementing digital photogrammetry with GIS is the considerable amount of data that can be collected, analysed and quantified using interoperable systems. Apart from the lengthy processes involved, the methods used in the present work made possible some tasks automation, along with standard data management since acquisition to the production of the final map. Nevertheless, it is expected that various difficulties arise when using aerial photography from coastal areas (Baily & Novell, 1996). This is the case not only in photogrammetry, but also when working with GIS, since the problems of subjectivity and uncertainty will always be present, depending their degree partly on the author's experience.

Being one of the tools available for coastal research, digital photogrammetry is used in this study due to its capability of producing accurate digital data suitable for hazard assessment. Although user friendly, digital photogrammetry still requires expert knowledge, as well as good imagery, precision scanners and accurate GCP (Baily *et al.*, 2003), in order to provide the desired quality mosaics for subsequent analyses. The quality of an orthorectification procedure is, first of all, assessed by the accuracy of the GCP used, which is evaluated during post-processing using the Position Dilution of Precision (PDOP) value. This value describes the strength of the satellite configuration when a GCP is collected and should ideally be lower than 4. However, in this study, a few GCP exceeded this value (Appendix 1), what could be due to the presence of obstructions in the skyline, since some GCP had to be surveyed in a very dense urbanized area, which limits the use of all satellites available at the collection moment. Such GCP influenced the triangulation result (Table 4.2), whose values are indicative of error that can be ascribed to mismeasured GCP, data entry error, or even poor quality GCP (Leica Geosystems, 2003a), once the surrounding buildings interfere with the DGPS visibility. Nevertheless, it is preferable to have points in their real positions, even if they have a higher error, than move them falsely to reduce the error (Baily *et al.*, 2003). According to the objectives of the study, the RMSE values obtained are quite low, with both blocks having RMSE values lower than 0.5 m, indicating a highly accurate rectification comparing with other studies using similar methods (*e.g.* RMSE of 1.6 m in Moore & Griggs,

2002). Although RMSE values for Z are slightly higher, 0.9670 for Block 1 and 5.7069 for block 2, they are irrelevant considering the aim of the study, which does not require as high accuracy as in cliff retreat positioning. Therefore, RMSE values for Z had no significant influence in this hazard assessment. To compensate for the impossibility of having GCP for the western part of the study area, some aerial photographs were only rectified, decreasing the overall accuracy each time another aerial photograph was tied to the mosaic. Despite this, the final mosaic has the required accuracy for the accomplishment of the study aim.

According to Fletcher *et al.* (2003), it is possible to distinguish two fonts of uncertainty that affect the accuracy in this kind of study, *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 on screen delineation. Even though the on screen digitizing was done with support of photo-interpretation sketches, which were accompanied by field surveys, allowing increased accuracy, it still involves a certain degree of uncertainty. For example, due to the angle of capture, some aerial photographs do not allow a clear distinction of the cliff top or other features, making its delineation on screen inexact. On the other side, several aspects may represent an increased difficulty in the identification of a feature's position, like the presence of vegetation or the colour similarity between the cliff-forming materials and sand, which makes delineation even more difficult in this particular area where cliffs present frequent indentations in different elevation levels due to the presence of gullies.

6.2 Hazard assessment

The approach to hazard assessment presented here intends to be a quantitative evaluation with a deterministic basis, without however take into account the hazard temporal and probabilistic dimension. It considers the geodynamic environment of rocky cliffs, as well as historical records along with observational processes. Cliff-forming materials and the physical processes to which cliffs are exposed to are emphasized by Griggs & Trenhaile (1994) 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. Additionally, mass movements have been incorporated as indicative of cliff evolution. Beaches and shore platforms were considered as coastal features that condition cliff erosion by granting 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 (Sunamura, 1992). In order to better assess coastline exposure to prevailing wave directions along the study area, the cliff top line should be preferably divided in small segments, since there are numerous bays and headlands whose sides are exposed to different incident wave directions. However, due to such coastline shape complexity, as well as its dimension, it was necessary to consider larger segments. This forced to evaluate wave exposure in a larger scale, rather than in small segments. Nevertheless, it must be recognized that different results could arise if considering a more detailed scale analysis. On the other hand, the ArcGIS script used to obtain the azimuth considers the segments as a straight line between the first point and the last point. This means that there are parts of those segments that are registered as being exposed to waves from a certain direction, that in reality are not. However, the contemplation of such small scale indentations would turn the analysis and results interpretation unfeasible. The ArcGIS script automates the process of obtaining an indicator angle for wave exposure, but it does not provide the remaining directions that a segment of the coast is actually exposed. The solution found of adding 45°, 90°, 135° and 180° degrees to the azimuth value and consider the classes where those values are comprised, leads to an overrate of the extreme values of +0° (azimuth) and +180°, which are comprised in classes with an exaggeration. For instance, a segment with an azimuth value of 107° is comprised in the classes of 67.5° to 112.5° and 247.5° to 292.5°, according to its +0° and +180° values respectively. This results in a 45° overrating of this segment, since there is no wave exposure before 107° and after 287°. A way of avoiding such error could be to subdivide the existent wave direction classes. However, this would require a wave data desegregation that is inexistent.

Weighting is a subjective process, intended to express the relative importance of different classes. In order to overcome such subjectivity, the attribution of a direct value from incident wave occurrence percentage was considered to be the most correct way of assigning a weight value, since it corresponds precisely to the importance of each direction affecting the study area. Along with the factor overestimation, this option may justify the high hazard values obtained, since most of the segments are exposed to the W octant, which has the higher wave exposure. Moreover, it was not possible to consider the protection effect of distant headlands, which refract incident waves and, therefore affect the energy of the waves that approach the different segments. This approach to wave exposure appraises a worst case scenario, since it considers the potential hazard to coastal segments.

Historical records of mass movements' location between 1947 and 1992 collected by Marques (1997) provide information on the final stage of a cliff evolution cycle. Mass movements' on screen digitizing was done directly from the location map in Marques (1997), presented on a 1:25.000 scale. Therefore, it is clear that mass movements' position may not be accurate, possibly containing errors arising from the difficulty in recognizing the exact location where mass movement actually took place. Despite this, the results from the rate of coastline affected by mass movements remain realistic and accurate since mass movements were considered per segment, and minor dislocations do not interfere with the final result for each segment. These values provide information on the spatial frequency and intensity of mass movements between different cliff segments, but their distribution is exceptionally irregular. Among the 23 segments with values from 0% to 33%, 5 segments have values of 0%, 18 segments have values below 9% and the remaining 5 segments have values of 11% to 33%. To quantify hazard in these segments following a common criterion, the option was to have classes with approximately the same occurrences number. However, facing an irregular distribution, the attribution of weight values became problematic. The weight values assigned do not increase proportionally with the rate of coastline affected by mass movements, they just distinguish the different classes defined. A weight value of 0.1 was attributed even to segments with 0% of coastline affected by mass movements, because the segments analysed have different lengths that may have induced such results, and are always vulnerable to the occurrence of mass movements, even if such vulnerability is reduced. On the other hand, the mass movements' inventory comprises a period of only 45 years. This may not be a representative period to withdraw assumptions on the location of mass movements since, according to Teixeira (2006), even with a 100 year period only circa 20% of the Miocene cliffs of southern Portugal would be affected by mass movements. The low rates of coastline affected by mass movements may then be due to the inventory period and also, as Marques (1997) demonstrated, large mass movements are very scarce in comparison with smaller ones. Despite the simplicity of the method used to evaluate mass movements occurrence, it appears to be efficient, since it was possible to relate higher mass movement occurrence with the hazardous classes from the remaining susceptibility factors, wave exposure and cliff face lithology and profile.

The joint evaluation of cliff face lithology and profile was considered to be a workable approach to assess the resistance of cliff forming materials to erosion. The method does not take into account information on geological structure or geotechnical data, which is important

regarding the study of cliff erosion, but is a suitable approach to characterize the geomorphology of the cliff face at a large scale. The matrix of sea cliff profiles presented by Emery & Kuhn (1982) played a fundamental role in the assessment of this feature, joining the relative effectiveness of marine versus subaerial erosion in different degrees of rock homogeneity. The matrix adaptation to the study area lithology and profile characteristics was based in expert knowledge, obtained through surveys, photos and literature analysis. The classification was performed disregarding some minor variations within each class. Such variations, although visible in the field, were not discernable in the images due to their reduced dimensions and, therefore, become impracticable to analyse in further detail. Nevertheless, it is a useful method because lithology regulates the mechanical strength of the cliff or, in other words, cliff's resistance to waves (Sunamura, 1992), while the profile represents the processes acting in the evolution of cliffs. Moreover, the results obtained in this study agree with the findings of Dias (1984) and Marques (1997) regarding the predominance of marine erosion over subaerial erosion, complementing them by suggesting that the study area is mostly subjected to a moderate hazard in terms of cliff face lithology and profile.

Beaches and shore platforms as protective features in the erosion of cliffs have been evaluated in terms of their average width. In the case of beaches, this has been supported by the delineation of the HWL and the cliff top line as reference features for beach width measurement. For the HWL the common procedure is to use 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 (Crowell *et al.*, 1991), which can lead to errors on the demarcation of the HWL. Likewise, the identification of HWL can be complicated by a gradual change between wet and dry areas (McBride *et al.*, 1991, in Coyne *et al.*, 1999) or simply by high rates of evaporation in the site (Coyne *et al.*, 1999). All these difficulties in the delineation of the HWL tend to decrease the accuracy in the beach width evaluation. Moreover, aerial photographs are *snapshot images* with information of a certain time and location, which means that they can not demonstrate the mean conditions (Baily & Nowell, 1996). The base imagery for the present study was captured in different days and, most likely, at different hours. This means that the tidal height between different aerial photographs may differ and affect the HWL and platform delineation. However, the pictures were taken during low tide in consecutive days with similar low tide heights, 0.7 and 0.9 m (data obtained using WXTide32 application), which does not affect significantly the results, allowing a good agreement between aerial photographs. Tidal level is relevant

essentially for platform digitizing, since only the emerged ones were considered. Therefore, even if parts of the shore platforms were visible below water level, in most platforms it was impossible to identify their underwater contour due to light reflection, reduced water transparency or even sand covering.

The method used to assess average beach width encloses a significant error because the width lines were drawn from the HWL to the cliff top line, instead of the cliff foot. This line was not drawn because the angle at which the aerial photographs were collected does not allow a clear distinction between cliff top and cliff foot. This has led to an overestimation of average beach width, since part of the cliff was quantified as belonging to the beach. Again, assessing average beach or platform width through the drawing of perpendicular lines is not an accurate process, partly because the equidistance at which those lines are drawn is not precise. Nevertheless, in the absence of an automated process to obtain the average width of an irregular polygon, this method provides a suitable average value to assess the protection offered by these features. Aiming to assign a protection value to the baseline according to the weights of beach and shore platform average width classes, buffers of these features were created. Some manual adjustments had to be done to both beach and shore platform buffers to avoid the assignment of inadequate protection values to some segments. On one hand, this reduces the automation advantages of using GIS approaches; on the other hand, it allows to reduce the error and to improve the results. The buffers were restricted to the limits of their respective features, although the protection they exert may extend further away. Nevertheless, considering the scale and objectives of this study, it would be out of scope to evaluate the complex relations of protection offered by both beaches and shore platforms beyond the areas where there is clearly protection, since it would require consideration of their interactions with waves and sea bottom topography.

Three factors of susceptibility and one factor of protection were evaluated, since beaches and shore platforms, due to their complementarity, were considered jointly as one factor of protection. However, this difference does not mean that a given area will have higher susceptibility than protection, or the opposite, since all factors vary along the study area and it is from their combined analysis that the hazard index is obtained. Results have shown that 91.5% of the coastline presently 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, independently of their dimension. Therefore, these areas may experience frequent small rock or debris falls, rather

than large mass movements, since these have larger return periods (Teixeira, 2006). Although it is impossible to predict when and where such events will take place, it has been demonstrated by Teixeira (2002) that, in the Miocene cliffs of southern Portugal, it will probably occur after large precipitation events associated to stormy waves. Hazard indexes should always be considered with caution. In the present assessment, due to the intricate shape of the coastline, the index results may present wide variations in relatively small areas that are the product of specific features, like a small pocket beach or a headland. In fact, the results show a realistic representation of hazard, specifically concerning headlands (Figure 5.6), since these are included in the very high hazard class, confirming the general assumption that headlands are areas of high vulnerability and exposure to wave attack.

Through the division of susceptibility and protection factors (Figures 5.7 and 5.8), it is possible to evaluate not only the impact of each group on the hazard index, but also their variation along the coast. It is evident that without considering the protection factor, high hazard diminishes while very high hazard increases significantly. It is the association of wider beaches and wider shore platforms that provides the most effective reduction in hazard values and, therefore, the protection of cliffs. Finally, it is important to note that the hazard index results concern only the study area, being limited to the factors involved. For another or larger study area and for a wider range of factors, the index presented would have to be adapted, and afterwards applied.

6.3 Hazard assessment integration in coastal management

The unsuitable relation between natural coastal processes and human activities give rise to increasing coastal hazards (Moore *et al.*, 1999). Buildings and urban development have a known perverse effect on cliff stability, leading to first-time collapse or reactivation of pre-existent mass movements (Lee & Clark, 2002). However, human contributions for cliff recession are not restricted to heavy constructions on cliff top and include also the frequent landscaping vegetation with the necessary irrigation. This, combined with normal precipitation, amplifies the pressure in cliff materials and reduces their strength and accelerates the natural cliff evolution processes (Griggs & Trenhaile, 1994).

The association of hazard, which results from the vulnerability of the coast to erosion, with the occupation of the coast, gives rise to risk situations. Accordingly, as an indirect cause of erosion and a determinant component of risk assessment, the features considered as built-up area occupy a significant portion of the cliff protection zone, 12.8% to the west of Albufeira

and 45.9% to the east. In fact, within the 150 metres protection zone is possible to distinguish large agglomerates composed by hotels, villas and other tourism related facilities. This indicates that coastal hazards have not been properly considered, leading to an overwhelming occupation of an area that, due to its susceptibility to coastal erosion, should not be allowed to be occupied by permanent constructions. Moreover, research carried out by Teixeira (2006) indicates that for mass movements' return period of 100 years, a protection zone with 47 to 67 metres width should be maintained free of buildings, although light land uses may be authorized according to expert evaluation of the risks involved.

In practice, none of these restriction areas have been effective, most of all because of the absence of a systematic planning regarding construction areas. Likewise, protection structures in the study area have been built has a direct response of punctual needs based on lobbying, rather than due to a defined strategy of coastal protection against erosion. Therefore, protection structures are not directly associated with higher hazard or even risk, being mostly related to the intensive use of the cliff top area or the beaches adjacent to the cliffs.

The evidences of ineffective coastal management suggests not only the lack of concern for the obvious risks involved, but also the disregard for tourist interests, leading to a depersonalization and unattractiveness of an area that is economically dependant of the tourism industry. It must be considered that the area under study, part of the Algarve region, has prime tourist sites that are threaten by an excessive development.

An effective coastal zone management should thus integrate a planning system that incorporates the different realities present in the coastal areas. According to this, the presentation of coastal susceptibility to erosion through a hazard map is a useful tool, enhancing the management of rocky cliffs by certifying that a development construction takes in due account potential instability problems (Lee & Clark, 2002). At the same time, it provides information on the suitable or adverse areas for development (Forth *et al.*, 1999), as well as for the need mitigation or recovery measures.

6.4 Limitations and recommendations

Any hazard assessment involves a certain degree of uncertainty and, in this study, the main limitation is the inaccuracy created by the method during the various stages. From the digitizing processes to the weighting of factors, or even their choice, subjectivity is always present, reducing the degree of accuracy. Furthermore, the hazard map classifies the area based on a reduced number of factors and no predictive attempt or temporal analysis has been

made on the hazard development. Even the application of the proposed method to other areas has to be pondered, since it was developed to adjust to this particular area. However, considering the outcomes of the method, it appears to be an adequate approach to large scale cliff hazard assessment. It provides reliable information about the areas of higher susceptibility to erosion, as well as the areas subjected to higher protection, and, because of that, quite useful in coastal management.

To improve the method and consequently obtain more precise results in future research, hazard assessment should include other relevant factors that contribute to the susceptibility of rocky cliffs to erosion, as well as the development of the factors presented here. Mass movements inventory period is relatively short, at least regarding the spatial occurrence of mass movements according to the cliff life time, since regarding frequency and intensity, Teixeira (2006) has demonstrated that this inventory may be considered complete. Therefore, in order to obtain better evaluations on the occurrence of mass movements it is necessary to consider other inventories that extend the analysis period.

It is from the right combination of factors that after years of apparent inexistence of superficial change, mass movements happen (Griggs & Trenhaile, 1994). Regarding the natural factors that contribute to hazard, they're assessment should consider extended interpretation of geomorphological and geological engineering data. The presence of structural discontinuities (bedding, joints, fissures) and karstic forms (caves, sinkholes), together with data on gullies development and rainfall that originates them, may not indicate where mass movements occur, but still presents information about the areas where the susceptibility to erosion is higher, enabling preventing measures.

Even though the built-up area in the cliff protection zone has not been considered in the quantified analysis, it should be integrated in future research, since it is from the interaction between human activities and natural coastal evolution that risk arises. Developments of the method present should incorporate temporal analysis, as well as human occupation in order to present effective risk assessment and generate risk maps. The integration of mass movement return periods in such maps would allow the definition of the potential risk.

7. Conclusion

The evolution of sea cliffs depends on the interaction between various factors caused by terrestrial or marine processes, which turn rocky coast erosion into an episodic and spatially variable event (Moore & Griggs, 2002). Aiming to evaluate hazard in sea cliffs, this study combines cliff evolution forcing mechanisms (wave exposure, cliff face lithology and profile and mass movements) with the existence of protection features to cliff erosion (beaches and shore platforms). The analysis, supported by the integration of digital photogrammetry and GIS techniques, evaluates these factors through a weighted index that translates coastal susceptibility to erosion in the study area.

The application of the method proposed demonstrates that sea cliffs between Galé and Olhos de Água are mostly subjected to high and very high hazard, which are widespread along the study area. Such distribution pattern is probably related to the fact that 61% of the coastline is exposed to the most hazardous wave class, which combines the waves approaching the coast from the E to the W octants. Low hazard occurs in one location only, close to Arrifão, and it is mostly the result of the high resistance of the cliff forming material, since low hazard cliffs are carved in Cretaceous rocks. Miocene rocks are predominant along the study area, comprising 65.7% of the cliffs between Galé and Olhos de Água. In Miocene cliffs marine erosion was found to have higher effectiveness over subaerial erosion, confirming the findings of Dias (1984) and Marques (1997). In what concerns mass movements, 37% of the coastline affected by these events has a rate of 2% to 3%, whereas rates higher than 10% occur in 14.6% of the study area. Protection features have considerable importance, since they lower the hazard index along most of the study area, offering high and moderate protection to 44.3% and 28.4% of the coastline, respectively.

The results obtained by the application of the proposed hazard assessment method allow classifying the area based on a selected number of factors, assigning a hazard value to the coast that can be used as indicator for coastal management options and measures. A hazard map sets up the areas of higher and lower susceptibility to erosion. This allows to identify directions for the management of the coast, based on improved consideration of cliff evolution by the decision makers.

The method proposed involves some subjectivity, especially during the digitizing tasks and weight attribution to the factors' classes. This subjectivity implicates that the extrapolation of this method must be done with adjustments, because the hazard index has been tested and calibrated to this particular study area.

Aiming to improve the proposed method for hazard assessment, future research should complement the factors selected for evaluation, as well as improve the analysis of the current selected factors. Additional factors as engineering geology data, as well as structural and karstic discontinuities evaluation should be considered in further developments of the method. Human activities have a determinant effect on the instability of coastal cliffs, accelerating the natural erosional processes. Built-up areas along the cliff protection zone and the presence of protection structures have to be considered in a future study, at least if the hazard assessment is intended to move forward and quantify the risk posed by sea cliff evolution to human activities.

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Appendices

Appendix 1 – List of valid GCP

Survey date	Point	Eastings	Northings	Z	Time	SVs	PDOP
21st September 2005	1	-11123.443	-286614.607	52.678	03:00.0	7	2
	2	-11316.374	-286609.681	71.583	02:00.0	6	10.3
	3	-11161.809	-287104.816	0.733	02:00.0	7	4.9
	4	-11357.120	-286139.476	70.713	02:00.0	7	3.5
	5	-12724.598	-286729.213	5.813	02:00.0	6	2.8
	6	-12721.827	-286735.348	5.883	02:00.0	6	2.8
	7	-12723.486	-287106.922	47.203	02:00.0	6	2.8
	8	-13237.602	-287537.831	18.834	02:00.0	8	1.7
	9	-13175.327	-287118.508	40.125	02:00.0	8	1.8
	10	-13964.659	-287412.398	45.497	08:20.0	6	3.4
	11	-14373.895	-287701.401	35.790	08:30.0	6	3.6
	12	-15064.471	-286668.070	31.051	09:30.0	7	2.6
28th September 2005	13	-8840.293	-286333.450	31.676	03:00.0	8	1.4
	14	-8658.464	-286097.827	34.375	03:00.0	8	1.7
	15	-8206.707	-286087.620	41.124	03:00.0	6	2.1
	16	-7793.168	-286171.891	35.347	03:00.0	6	2.3
	17	-6900.286	-286049.637	26.954	03:00.0	5	3.3
	18	-5783.551	-285176.589	34.662	03:00.0	6	2.9
	19	-5485.482	-285712.117	27.727	03:00.0	6	2
	20	-5500.194	-285764.942	28.118	03:00.0	7	1.7
	21	-4842.717	-285487.691	26.203	03:00.0	7	1.7
	22	-4752.206	-284909.800	47.516	03:00.0	6	2
4th October 2005	23	-10226.903	-285556.788	57.875	04:00.0	8	1.5
	24	-10067.108	-286096.920	35.509	04:00.0	7	1.8
	25	-9853.540	-286579.488	2.445	04:00.0	7	1.9
	26	-6597.219	-285753.709	30.489	04:00.0	6	1.5
	27	-5751.465	-285650.389	29.694	04:00.0	7	1.6
	28	-4873.945	-285849.141	19.14	04:00.0	5	8.8
	29	-5745.469	-286119.673	23.56	04:00.0	7	2.4
	30	-6471.339	-286125.791	28.185	04:00.0	8	1.6
	31	-8139.604	-286529.695	8.989	04:00.0	6	2.4
	32	-8698.776	-286646.421	27.634	04:00.0	5	3.4