Elsevier Editorial System(tm) for Geomorphology
Manuscript Draft

Manuscript Number: GEOMOR-1305R2

Title: Erosion risk assessment of active coastal cliffs in temperate environments

Article Type: Research Paper

Keywords: Risk; hazard; impact; sea cliffs; cliff recession; index.

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Abstract: The potentially negative consequences resulting from cliff recession are a matter of serious concern in many coastal areas worldwide. The assessment of these kind of processes has traditionally been performed by calculating average cliff recession rates and projecting them into the future, without taking into consideration the diverse factors affecting cliff dynamics and stability. In this work a new, practical method is presented to evaluate cliff erosion risk on temperate environments, by analysing the main factors responsible for both the physical and the socioeconomic aspects of erosion, representing cliff loss potential and damage potential respectively. For this purpose an integration of 11 physical variables (such as cliff lithology, beach characteristics or rainfall regime) and 6 socioeconomic variables (such as land use type or population density) is proposed. These variables are weighted and combined into a Hazard Index and an Impact Index, which in turn are merged into a composite Risk Index, where the resulting values are normalized and expressed as a percentage of the maximum theoretical risk. The method is tested and validated by using data about cliff retreat rates and mass movement processes in the coast of Cádiz province (SW Spain). The proposed approach allows the zoning of coastal cliffs according to the risk, hazard and/or impact levels, including the recognition of critical

areas where specific intervention strategies should be adopted. It is believed that the method presented in this work is practical and at the same time scientifically valid, without requiring extensive and detailed surveys of the area where it is to be applied. This way, it constitutes an easy to use, valuable tool for decision-making regarding land use planning and management strategies in active coastal cliffs.

EROSION RISK ASSESSMENT OF ACTIVE COASTAL CLIFFS IN TEMPERATE ENVIRONMENTS

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Abstract

The potentially negative consequences resulting from cliff recession are a matter of serious concern in many coastal areas worldwide. The assessment of such processes has traditionally been performed by calculating average cliff recession rates and projecting them into the future, without taking into consideration the diverse factors affecting cliff dynamics and stability. In this work a new, practical method is presented to evaluate cliff erosion risk in temperate environments, by analysing the main factors responsible for both the physical and the socioeconomic aspects of erosion, representing cliff loss potential and damage potential, respectively. For this purpose an integration of 11 physical variables (such as cliff lithology, beach characteristics or rainfall regime) and 6 socioeconomic variables (such as land use type or population density) is proposed. These variables are weighted and combined into a Hazard Index and an Impact Index, which in turn are merged into a composite Risk Index where the resulting values are normalized and expressed as a percentage of the maximum theoretical risk. The method is tested and validated by using data about cliff retreat rates and mass movement processes in the coast of Cádiz province (SW Spain). The proposed approach allows the zoning of coastal cliffs according to the risk, hazard and/or impact levels, including the recognition of critical areas where specific intervention strategies should be adopted. The method presented in this work is deemed both practical and scientifically valid, without requiring extensive and detailed surveys of the area where it is to be applied. This way, it constitutes an easy to use, valuable tool for decision-making regarding land use planning and management strategies for active coastal cliffs.

Keywords

Risk, hazard, impact, sea cliffs, cliff recession, index

1. Introduction

Diverse types of cliffed and rocky coasts are estimated to represent about 80% of the world's oceanic shorelines (Emery and Kuhn, 1982; Trenhaile, 1987), including plunging sea cliffs, bluffs backing beaches and rocky shore platforms. Increasing population of coastal zones has led to the accelerating occupation of cliff tops and faces by buildings and infrastructure, that in some areas are seriously threatened by shoreline retreat. Moreover, such increasing human pressure has indeed exacerbated these erosion problems at some points. As a consequence, the conflicts between human occupation and the inherent instability of cliffed coasts have become a problem of increasing magnitude (Moore and Griggs, 2002).

In spite of this, most studies on coastal processes have traditionally been focused on beaches and sandy coasts (Trenhaile, 1987; Naylor et al., 2009). The main reason lies in the difficulties of studying sea cliff dynamics, especially regarding the performance of field measurements and the prediction of the future behaviour of cliffs. This is particularly true in the case of risk assessments and erosion hazard studies, due to the complexity of the quantification of retreat rates on rocky coasts (Hapke, 2004). Such complexity is mainly related to the fact that sea cliff retreat is an episodic, site-specific phenomenon: cliffed areas usually recede at very slow rates until a low-frequency, high-energy event causes sudden erosion episodes of much higher magnitude than average retreat (Griggs, 1994; Lee et al., 2001; Trenhaile, 2002), generally in the form of different types of slope mass movement (Dong, 2005; Teixeira, 2006). These episodes are sporadic and unpredictable, thus rendering their observation and measurement difficult.

Besides, risk assessment on sea cliffs has often been based only on the aforementioned quantification of recession rates, thus ignoring the anthropic factor which is inherent to the concept of risk. It is well known that the risk can be generally defined as the potential negative impact that may occur on elements on which there is some kind of interest, including population, human infrastructure and environmental goods, as a consequence of a given hazard (UNDP, 2004). Therefore, an adequate erosion risk assessment must necessarily include the evaluation of the two separate components that constitute the risk: on one hand, the physical hazard or threat that can potentially cause damage, and on the other hand, the impact of this threat on human elements and activities located on the area; the latter will, in turn, depend on the vulnerability of the system (i.e. the potential degree of loss or damage) and the elements exposed to the hazard (Villa and McLeod, 2002; UNDP, 2004; Birkmann, 2007).

The analysis and evaluation of coastal risks, hazards and vulnerability is a very complex issue, as there is a huge number of factors and variables, both natural and human-related, that influence coastal behaviour in this sense. This way, various authors have designed methods for the classification and mapping of coastal areas according to risk, hazard and/or vulnerability criteria (e.g. Richmond et al., 2001; De Pippo et al., 2008). A wide review of classification procedures existing in the literature for assessing coastal vulnerability can be found in Cooper and McLaughlin (1998). One of these methods is the development of numerical indices aimed at classifying coastal zones according to their response to a variety of physical phenomena (e.g. Gornitz, 1990; Málvarez et al., 2000; McLaughlin et al., 2002). These include episodic flooding (Dal Cin and Simeoni, 1994), storm- and hurricane-related coastal erosion (Cambers, 1998) or sea-level rise (Gornitz et al., 1994), the latter having received the greatest attention. However, apart from local scale approaches, to date there are no indices specifically aimed at assessing erosion risk on cliffed coasts. As previously mentioned, this type of risk has traditionally been estimated on the basis of its consequences, i.e. from cliff retreat measurements (Priest, 1999; Moore and Griggs, 2002), often without taking into consideration other factors that may influence cliff dynamics or risk distribution (Teixeira, 2006; De Pippo et al., 2008).

This work aims to present a new method for the assessment of sea cliff erosion risk on temperate coastal environments, by integrating data on diverse cliff parameters into a GIS. The procedure is based on the selection, scaling and evaluation of a number of physical, geomorphological and dynamic variables that determine the cliff loss potential (cliff erosion *hazard*), together with additional socioeconomic, human-related variables controlling the damage potential (*impact* of erosion). Hazard variables include cliff lithology, exposure to storms or rainfall regime, while impact variables include land use type or population density. These are combined into two separate indices, the Hazard Index and the Impact Index, which together constitute the Risk Index as a single numerical measure of the risk for a given area.

The method is tested and validated by using real data on cliff erosion and mass movements on the Cádiz coast (SW Spain) (Fig. 1), a 200 km-long coastal area spanning a wide range of physical environments from the geological, geomorphological and dynamic points of view and supporting different levels of human occupation. Unlike previous site-specific risk approaches in the literature, the proposed method is intended to be applicable for the classification of most types of cliffed areas located on temperate coasts according to their erosion risk level. This type of information is of prime importance for implementing adequate land use planning and management strategies, especially on less developed coastal areas.

APPROXIMATE LOCATION OF FIGURE 1

2. Methodological basis

The general framework of the method proposed for the assessment of cliff erosion risk is based on the aforementioned definition of risk as a combination of two components: the erosion hazard and the impact of this hazard, the latter understood as the coupling of exposure and vulnerability (Birkmann, 2007). For each component specific indices are generated (the Hazard Index and the Impact Index) on the basis of certain physical and/or socioeconomical variables which are considered to be determinant.

The selection of the variables for both indices was made according to several important principles. Although a sufficient number of representative variables should be selected, this number should be kept low enough to avoid redundancy (i.e. variables that are closely related and reflect the same processes) and to obtain a simple, feasible index. A key issue in this sense is that, as stated by Cooper and McLaughlin (1998) and McLaughlin et al. (2002), the resulting index should obviate the need for detailed studies in the area where it is to be applied. This way, updated values of the variables chosen should be available and relatively easy to obtain at any given area without requiring exhaustive survey work (Villa and McLeod, 2002). Consequently, the resulting tool will not only be scientifically valid, but also practical and easy to use.

Based on these premises, 11 factors determining both cliff erodibility and the erosivity of dynamic agents were chosen as variables (a_n) for building the Hazard Index. The definition of these variables was made according to the research by numerous authors who have studied the influence of different factors on cliff stability (e.g. Sunamura, 1992; Benumof et al., 2000; Trenhaile, 2002, among others). The variables selected were the following:

- Cliff lithology
- Cliff structure

- Cliff slope
- Presence and characteristics of a protective beach
- Presence and characteristics of a rocky shore platform
- Engineering structures at cliff foot
- Tidal range
- Wave exposure
- Difference between storm and modal wave height
- Relative sea-level trend
- Rainfall

Although the term *hazard* is often linked to phenomena of natural origin, in the present approach the possibility of human contributions to cliff erosion is also considered, so some of the variables in the Hazard Index are or can be influenced by human activities.

Regarding the Impact Index, it is constituted by a combination of exposure-related and vulnerability-related variables, which altogether represent the socioeconomic factors determining the impact of cliff erosion on human activities. These aspects are of prime importance in coastal risk assessment, as highlighted by several authors (Málvarez et al., 2000; McLaughlin et al., 2002; Boruff et al., 2005, among others). A total of 6 variables were selected to build the index, namely:

- Main land use type
- Percentage of developed areas
- Presence of nature reserves
- Presence and type of transportation networks
- Population density
- Population rate of change

Even if impact assessments are often less advanced than hazard evaluations (Birkmann, 2007), this is an essentially geomorphological work and hence is more deeply focused on physical hazard definition than on socioeconomic impact definition. For this reason, monetary costs fall outside the scope of this study and therefore are not included in the Impact Index.

For both the hazard and the impact each variable was divided into four classes, so that all possible cases that can be found at any temperate coastal cliff would fall within one of the classes. The classes were established on a numerical basis where possible, while for the variables that could not be quantified a semi-quantitative approach was adopted by using an ordinal scale, as recommended by Cooper and McLaughlin (1998). Then the classes on each variable were ranked 1-4 from the lowest to the highest hazard for the Hazard Index, and from the lowest to the highest impact for the Impact Index.

Before building the indexes, the variables were weighted with factors (f_n) according to their relative importance in determining overall cliff erosion hazard and impact (Gornitz et al., 1994). The aim was to avoid the underestimation of the most relevant variables at the local level and the overestimation of the less significant ones, as well as to increase the discriminating ability of the method (see section 3). In fact, the weighting of the variables is acknowledged as a need in many coastal classification studies (Cooper and McLaughlin, 1998), but at the same time it is clear that the subjective decisions involved in weighting processes constitute a complex issue (Rygel et al., 2006). Therefore, an important point in this sense is the possibility for the user to adjust the weights when applying the index to a given area, in order to take advantage of local knowledge on each particular case, for instance by making use of expert judgement techniques (Mimura, 1999).

The weighted variables were then combined into the Hazard Index and the Impact Index. Several methods were tested for this purpose, ranging from the sum of the variables to their geometrical average (Gornitz, 1990). In the end the weighted scores of the variables were added up and the absolute values obtained were normalized according to the maximum and minimum values of the corresponding index, as suggested by McLaughlin et al. (2002). Finally, the Hazard Index and the Impact Index were combined into the composite Risk Index in order to obtain a single measure of cliff erosion risk. An important point is that the proposed method is intended to be applied on a relative basis, that is to compare different areas on the basis of cliff erosion hazard, impact and risk.

As will be discussed later, the Hazard Index was tested and validated prior to its inclusion in the Risk Index by using real cliff erosion data recorded in the Cádiz coastal area (SW Spain). Part of these data consisted of cliff recession rates calculated from four sets of vertical aerial photographs of scales between 1:18.000 and 1:33.000, dating from 1956, 1977, 1982/1986 and 1992/1994, and two sets of digital orthophotographs from 2002 and 2005 with a 0.5 m resolution. The contact prints were scanned at a resolution of 600 dpi (Mount et al., 2003) and geometrically corrected by means of GIS tools in order to minimize photograph distortions (Moore, 2000). Around 20 ground control points were selected on each photograph, obtaining an average RMSE (root mean square error) value of 0.48 m. The top of the cliff was digitized on the georectified images and orthophotographs, except on those cliffed sections characterized by a rounded or densely vegetated edge, where the cliff foot was used (Moore and Griggs, 2002; Pierre, 2006). The resulting shorelines were compared in a GIS environment and cliff recession rates were calculated by different statistical methods (Thieler et al., 2005) (Fig. 2).

APPROXIMATE LOCATION OF FIGURE 2

In fact, the use of GIS tools is recognized as the most common way of deriving coastal risk or vulnerability indices (Cooper and McLaughlin, 1998; Málvarez et al., 2000). The aforementioned operations of index calculation are ideally performed in a GIS environment, provided the data on the variables are available on GIS-useable formats such as raster and vector layers. This allows one to take advantage of procedures such as spatial analysis operations, interpolations, integration of data from different sources, etc. If this is not possible, GIS can also simply be used as a convenient way of storing and retrieving the information and obtaining graphical outputs (i.e. plotting maps) by organizing the data into independent layers. In any case, the digital format facilitates the use of different weights or mathematical combinations of the variables, as well as an easy updating of the information.

3. Construction of the Hazard Index and the Impact Index

3.1. Hazard index

3.1.1. Index elements

The application of the aforementioned methods led to the development of a cliff erosion Hazard Index composed of 11 variables (a_n) that determine cliff loss potential to a great extent. Table 1 shows the classes and ranking adopted for each variable, where a rank of 1 represents the lowest hazard and a rank of 4 the highest hazard.

It is commonly accepted that seacliff erosion is greatly determined by the relative intensity of two groups of forces: the assailing force of waves and the resisting force of cliff materials (Sunamura, 1983). Consequently, both types of forces are represented across the Hazard Index variables.

POSITION OF TABLE 1

First of all, *cliff lithology* (variable A) and *cliff structure* (variable B) constitute the most important factors controlling cliff stability (Benumof and Griggs, 1999; Benumof et al., 2000), according to a variety of attributes such as grain size, mineral content, presence of bedding planes, density of fractures, etc. The lithological classes in Table 1 include the type of materials that can be found on most coastal cliffs around the temperate coasts of the world, ranked on the basis of their relative erodibility (Sunamura, 1983; Gornitz, 1990). Classes are established in a general way, so “non-resistant metamorphics” include for instance slates and schists, “fine consolidated sediments” include materials such as chalks, and “fine unconsolidated materials” include recent sediments, clays, marls or volcanic ejecta.

Regarding cliff discontinuities, they can be the dominant factor in determining recession in some areas (Sunamura, 1983) by reducing the overall strength of the cliff, especially in low-energy environments (Greenwood and Orford, 2008). The classes proposed in the index cover the general types of discontinuities that can easily be identified on cliffed zones and are commonly recognized as instability indicators. This includes not only internal cliff features such as joints and faults, but also external indicators of active weathering and water erosion features such as rills and gullies (Bush et al., 1999) (Fig. 3A).

A third significant factor regarding the nature of the cliff is *cliff slope* (variable C), which is considered to be directly linked to cliff instability (De Pippo et al., 2008) so that the higher the slope, the higher the hazard (Bush et al., 1999). It is clear that a strong relationship exists between cliff lithology and internal structure and cliff slope, but the complex nature of this relationship allows the use of cliff slope as a variable in the index without implying a redundancy.

A second group of factors influencing cliff erosion is related to the topographic boundary conditions of the cliff. A major feature in this sense is the presence and characteristics of a *protective beach* (variable D) at the cliff foot that can act as a buffer zone by dissipating wave energy and protecting the cliff from wave action. Here the key issue is the width and height of the beach, since a narrow and/or low beach will not only allow waves to reach the cliff base, but will also provide them with sediment that can cause mechanical erosion (Sunamura, 1983, 1992; Benumof and Griggs, 1999). Therefore, the ranking of this variable is performed on the basis of the resulting frequency of waves reaching the cliff foot according to beach characteristics (Fig. 3B), which at the same time renders the variable more widely applicable than if classes were based on absolute beach width or height. Seasonal variations in beach conditions over time can affect the degree of cliff protection in this sense (Lee, 2008), so feasibility of use of the index in a worst-case approach would require this factor to be evaluated according to the situation of minimum beach width and height, that is generally winter conditions. In any case, the temporal variability of the indices proposed is a crucial issue that will be discussed later.

APPROXIMATE LOCATION OF FIGURE 3

In a similar manner, the *rocky shore platforms* (variable E) located at the foreshore or shoreface control the dissipation of wave energy due to their topography and roughness, hence providing protection against the erosion of cliff base. The definition of specific platform width thresholds would not be suitable for an index aimed at general application, so also here the ranking is built in a relative way in order to compare the situation on different cliffed areas. Besides, the protective effect of shore platforms is not only dependent on their width, but also on their continuity and location (Trenhaile, 1987) (Fig. 4A).

As was explained in section 2, most of the factors involved in hazard definition have a natural origin but there can also be an important human component, as is the case of the *engineering structures at cliff foot* (variable F). These structures (e.g. seawalls, rock armours, revetments, gabions, rip-raps) prevent marine erosion at the base of the cliff, hence reducing the hazard even if weathering and other subaerial processes continue acting upon the cliff (Lee et al., 2001). If the structure is not covering the whole length of the cliff foot, then the neighbouring unprotected cliff areas will suffer the effect of flanking erosion (USACE, 1984) (Fig. 4B) and the hazard will be increased (Table 1). The common effect of beach loss in front of the structures is ignored in this ranking, as beach width is already included in variable D. Other types of engineering structures not located at the cliff foot, such as jetties or breakwaters, are not considered in the index, mainly due to the complex and indirect nature of the influence exerted by these structures upon cliff erosion.

The third and last group of factors controlling cliff erosion is that of the dynamic agents that act upon the cliff, including waves, tides, rainfall and sea level. The *tidal range* (variable G) determines to a great extent the elevation of daily water levels and so the limit of cliffward wave propagation (Benumof et al., 2000), which is obviously higher in areas with high tidal range. However, high tidal ranges also allow a better disipation of wave energy, while in cliffs with a low tidal range the erosive efficiency of waves is maximized due to the concentrated wave attack on a narrower zone. As a consequence, while in low coasts higher tidal ranges represent higher hazards (Gornitz, 1990), in this approach for cliffed shores higher tidal ranges are considered to imply a lower erosion hazard (Table 1).

Unlike beaches, cliffs have a limited ability to adapt their form to changing energetic conditions. This way, regarding wave action, it is widely recognized that cliff stability is mainly affected by storm wave fronts and not by modal, fair weather waves (Trenhaile, 1987; Sunamura, 1992; Lee, 2008). In the Hazard Index this fact is represented by the *exposure to storm wave fronts* (variable H) and the *difference between storm and modal wave height* (variable I). The exposure is expressed in terms of the angle between the coastline and prevailing storm wave fronts, considering that shore-parallel storm waves hitting the coast involve higher hazard levels than shore-normal wave fronts (Komar, 1998). The role of refraction processes induced by nearshore morphology is of great importance in this respect, so visual evidence of wave approach directions should be used wherever possible.

Regarding the difference between storm and modal wave height, this constitutes a measure of the relative power of storm waves against that of modal ones, given that wave energy depends directly on the square of wave height (USACE, 1984). The difference is calculated on the basis of significant wave height (H_s), the most commonly used wave parameter in coastal dynamics studies. In this sense, significant wave height during storms can at some places be represented by maximum significant wave height (H_{smax}), already suggested as a risk parameter by Gornitz et al. (1994). The classification and ranking of the difference between storm and modal wave heights shown in Table 1 are the result of the study of different coastal settings in Spain, including both high- and low-energy regimes, despite the difficulties in establishing absolute values to be used in an index aimed at a broad application.

The effect of *relative sea-level trend* (variable J) is obviously less important than wave action in determining cliff erosion hazard (Lee, 2008), but even so it must be taken into account when evaluating cliff loss potential (Naylor et al., 2009). The origin of such sea-level trend is not relevant for the scope of this study, so the total relative changes resulting from the composite of global eustatic sea-level trends plus local land motions are considered (Gornitz et al., 1994). In view of recent estimates about accelerating sea-level rise (IPCC, 2007), it is clear that the magnitude of relative sea-level change on a given area will depend on the time span considered. This way, the data should be obtained from a nearby tide gauge covering at least a 20-year record, for instance by using data supplied by the Permanent Service for Mean Sea Level (POL, 2008), whose reliability should be carefully considered in each particular location.

The last variable included in the Hazard Index is the *rainfall* (variable K), widely acknowledged as playing a significant role in cliff stability (e.g. Sunamura, 1992). Rainfall infiltration and surface runoff constitute two of the so-called “preparatory processes” that reduce the strength of cliff materials (Greenwood and Orford, 2008), thus increasing their erodibility by sub-aerial processes and triggering mass movements (Lee et al., 2001; Dong, 2005). However, rainfall is not generally included into coastal erosion hazard assessments due to the lack of specific indices for estimating erosion risk on cliffed coasts and the limited influence of this parameter on beach erosion. The annual rainfall limits shown in Table 1 are intended to be suitable for most temperate locations around the world.

APPROXIMATE LOCATION OF FIGURE 4

An important issue regarding the evaluation of the Hazard Index variables is the convenience of adopting a worst-case approach when the proper classification is not clear and there are two possibilities of ranking. On the other hand, in places where the numerical value of a given variable is not available, the method could be adapted to compare the characteristics of the variable on different areas in a qualitative way (Bush et al., 1999), for instance by using an ordinal scale.

As explained in section 2, the calculation of the index requires an adequate weighting of the variables (a_n) with factors (f_n) established on the basis of their relative influence on cliff stability (Gornitz et al., 1994). This is a difficult task, as the specific role of each variable in determining cliff erosion is not easy to evaluate. According to the aforementioned considerations, the most relevant aspects are generally those related to cliff materials and beach buffer characteristics, so variables A, C and D can be considered as *determinant variables* and are weighted with a 1 factor. Conversely, the least significant parameters are tidal range, sea-level trend and rainfall, so variables G, J and K are considered as *secondary variables* and weighted with a 0.5 factor. The remaining components of the index, i.e. variables B, E, F, H and I, show an intermediate importance and are considered as *indirect variables* and weighted accordingly with a 0.8 factor.

Several mathematical options were tested to combine the weighted variables into a single expression: arithmetic average, geometric average, square root of average, mean of squares, sum of squares, square of geometric average, etc. The results obtained show that operations involving products, other than expanding the range of values as stated by Gornitz (1990), are quite problematic for subsequent normalization (see section 2), as they yield extremely low hazard values. On the other hand, it is evident that sums are less sensitive than products to possible errors in classification and ranking of the variables (Gornitz et al., 1994). The use of squares is not feasible when weighting factors are used, because it tends to underestimate low hazard values and strongly overemphasize medium and high hazard values so that they become unrealistic. Therefore, the Absolute Hazard Index (HI_{abs}) was built by simply adding up the weighted scores of the variables (Eq. 1):

$$HI_{abs} = \Sigma\, a_n\, f_n \qquad (1)$$

The normalization of the Absolute Hazard Index with respect to its maximum and minimum theoretical values (Eq. 2 and 3) provided an adequate framework to the results.

This led to the final Relative Hazard Index (HI_{rel}), expressed as a percentage of the maximum theoretical hazard.

$$\text{range } HI_{abs} = \max HI_{abs} - \min HI_{abs} \quad (2)$$

$$HI_{rel} = [(HI_{abs} - \min HI_{abs}) / \text{range } HI_{abs}] * 100 \quad (3)$$

3.1.2. Application of the Hazard Index

Finally, the resulting Relative Hazard Index (hereafter referred to as Hazard Index or HI) was applied to the assessment of cliff erosion hazard in the 200 km-long coast of Cádiz province in SW Spain (Fig. 1). Cliffs in this NW-SE-oriented coast are mainly located at the central and southern sector of the province, where they are mostly composed of Miocene conglomerates, sandstones and shales with relatively smooth profiles. The few cliffed areas existing in the northern part of the province are mainly low bluffs on soft Neogene and Quaternary materials. The prevailing coastal dynamics are variable, ranging from meso- to almost microtidal areas affected by different wave energy regimes, which in general can be classified as of low-energy. Most cliffs are located backing sandy beaches of different characteristics, and they support a wide variety of uses, from heavily urbanized areas to well-preserved natural environments (Del Río and Gracia, 2007).

The variables in Table 1 were carefully evaluated for each cliffed sector in Cádiz coast by field inspection and analysis of the information in the literature about the area. Then the Hazard Index was calculated by means of the expressions above, yielding values between 39% and 62% of the maximum theoretical hazard for this area. Results show how the northernmost end of the province is the area with the highest erosion hazard, with Grajuela-Montijo and La Ballena-Peginas low cliffs reaching the maximum HI values. Lithology is the main factor involved in determining the distribution and extent of cliff erosion hazard in this zone, as lateral changes in cliff facies expose soft Plio-Quaternary materials like clays and palaeosols to wave action. Even with the presence of protecting beaches and rocky shore platforms, such erodible materials give rise to a considerably high retreat hazard. Besides, shoreline orientation predisposes storm wave fronts to hit the coast directly with very little dissipation of energy. Such high HI values are also found in the resistant Miocene calcareous sandstones of La Breña cliff, where the most important hazard factors are the nearly vertical cliff slope and the practical absence of a buffering beach or shore platform.

Fairly high hazard values arise for the sandstones and conglomerates located in the central coast between Cape Roche and Fuente del Gallo, mainly due to the general lack of protection by beaches (Fig. 3B), rocky shore platforms or engineering structures, as well as to the relatively low angle between prevailing storm wave fronts and the shoreline. Similarly, narrow beaches, the practical absence of engineering structures and the quite soft cliff lithology consisting of marls and sands are behind the 53-54% values of the HI for the NATO Base and El Retin cliffs (Fig. 4A). On the other hand, moderate erosion hazard values at Torre Bermeja, Torre del Puerco, Punta Camarinal and La Peña are primarily related to fairly resistant cliff-forming materials like sandstones and conglomerates, generally gentle slope and oblique shoreline orientation, although the specific features are different on each coastal trait. For instance, Torre del Puerco shows the widest cliff-fronting beach in the whole study area, thus providing significant protection against wave attack. Cliffs at Santa Catalina, Caños de Meca and Cape Plata-Gracia exhibit a relatively low erosion hazard around 48% mainly because of their resistant lithology and gentle slope. Finally, the lowest HI values can be found at Punta Paloma and especially Vistahermosa areas, where cliff structure, cliff slope and beach characteristics reduce erosion hazard, together with the wide rocky shore platform at Punta Paloma and the seawall located at the foot of Vistahermosa cliff, as both features prevent these cliffs from being directly affected by energetic storm waves.

This way, the overall distribution of the Hazard Index shows that in general the factors determining the highest cliff erosion hazard in the study area are cliff lithology, beach characteristics and engineering structures. Additionally, tidal range and sea-level trends present quite high values along the whole Cádiz coast, hence precluding distinction between higher and lower hazard zones. In this sense, the variables which are most helpful in discriminating hazard levels are cliff slope, beach and rocky shore platform characteristics and engineering structures, due to their wide variety along Cádiz coast.

3.2. Impact index

3.2.1. Index elements

The methods described in section 2 also led to the development of a cliff erosion Impact Index composed of 6 variables influencing socioeconomic damage potential, including exposure and vulnerability aspects. Table 2 shows the classes and ranking adopted for each of these variables, where the ranks 1 and 4 represent the lowest and highest impact, respectively.

This way, *main land use type* (variable A) is deemed as a key factor in determining cliff erosion impact, since it controls to a great extent the economic value of the area. In this sense, the ranking of land use type is established on the basis of a qualitative assessment of such value as suggested by McLaughlin et al. (2002). On the other hand, it was found that the best way to define the area where this variable should be evaluated on any given cliff is the delimitation of a 100 m-wide buffer zone located inland of the cliff foot. The determination of main land use type on this area is easily accomplished by means of recent maps, aerial photographs or satellite images.

The *percentage of developed areas* (variable B) is a more specific concept than land use type, as it includes different types of features which are indicative of development and significant economic value, e.g. buildings, gardens, roads or golf courses. It must be noted that a higher level of development entails a higher erosion impact not only due to the increased exposure, but also because human activities tend to intensify cliff vulnerability by negatively influencing cliff stability. For instance, the building of houses and infrastructure on cliff top increases the load on the cliff, thus decreasing cliff resistance, and the vibrations related to vehicular traffic, works and other activities on cliff top can affect cliff internal structure. Besides, watering of gardens increases groundwater levels, thus increasing the chances of landslide activation (Benumof and Griggs, 1999). As in land use type, this variable is assessed on a 100 m-wide strip located inland of the cliff foot and can be easily evaluated on recent aerial photographs or satellite images. In any case, the percentage ranges defined in the variable (Table 2) are broad enough to allow an easy assessment of this factor.

POSITION OF TABLE 2

The socioeconomic value of non-developed, ecologically relevant natural areas is represented in the Impact Index by the *presence of nature reserves* (variable C), since the existence of a conservation designation (e.g. Natural Park, National Reserve and so on) increases the impact of erosion affecting these natural zones (McLaughlin et al., 2002). The rationale is that protected natural areas on cliffed coasts have an intrinsic value that might be threatened by cliff erosion even if no human infrastructure is at risk. In this sense, the difficulties in standardizing the types of conservation designation in the index (McLaughlin et al., 2002) to make it widely applicable determine the use of a simple scheme of presence/absence, with a relatively small difference in perceived value and thus in resulting scores between both cases.

The fourth element in the index is the *presence and type of transportation networks* (variable D), considering that the potential loss of railways and roads due to cliff recession entails a serious socioeconomic impact. Pedestrian paths and tracks are not included, as the social impact of their loss in case of cliff erosion and the monetary cost of protecting, restoring or relocating them is relatively low. As with the previous variables, transportation networks are to be evaluated on a 100 m-wide strip inland of the cliff foot.

Undoubtedly, the number of people living on the area is a major issue when analysing any type of risk, and although its use is not common in published indices (McLaughlin et al., 2002), most coastal classifications acknowledge the need for this type of data (Cooper and McLaughlin, 1998). Its importance arises from its direct relationship with both exposure (being affected by the risk) and, in the case of cliff erosion, also to vulnerability (contributing to the phenomenon), as explained in variable B. This way, *population density* (variable E) constitutes a key factor in the Impact Index, and due to its relative nature it is obviously more widely applicable than absolute population figures (Rygel et al., 2006). It must be noted that population is not equivalent to development or urbanization, as population only accounts for residents while variable B includes the infrastructure developed for tourists, such as hotels or holiday homes, which can be quite important in certain coastal areas (Málvarez et al., 2000). On the other hand, the aforementioned procedure of assessing the variable in a 100 m-wide zone located inland of the cliff foot is obviously not feasible in this case, as such detailed population information is seldom available. Consequently, up-to-date data at the most locally available level (e.g. municipality, borough, district or other similar administrative entity) are used, thus implying the assumption of a homogeneous distribution of population across the whole entity. This is not realistic, but it represents the most practical way of approaching population data in the index, and the availability of information is a key issue as explained in section 2 (McLaughlin et al., 2002); moreover, population growth at any given municipality will probably imply more pressure of visitors to cliffed areas in the municipality, even if new inhabitants concentrate on inland areas. The classes proposed in Table 2 are based on information about population density collected for numerous coastal municipalities in different countries across the world.

The last variable included in the Impact Index is the *population rate of change* (variable F), which represents demographic variations over time and therefore provides some kind of approach to temporal changes in erosion impact (Griggs, 1994). The periodic updating of databases from which indices are derived is clearly an important subject (Cooper and McLaughlin, 1998; Bush et al., 1999), and as stated by McLaughlin et al. (2002) socioeconomic impact factors generally show greater variations in a given direction over time than physical hazard elements. For this reason, a measure of socioeconomic changes is included in the index by means of variable F, given that population is the most relevant socioeconomic factor and information about its changes is generally easier to obtain than, for instance, quantitative evolution of developed areas or land use type. As in variable E, the evaluation of population rate of change is performed on the most detailed local administrative entity available, assuming a homogeneous variation in population density. With the purpose of facilitating wide applicability of the index, the variable is expressed as an annual rate, that is percentage of population growth or decrease per year. Ideally this is computed over the last 10-year period in order to take account of recent demographic trends, although the annual rate allows the calculation of the variable over the time span available in each particular case. The classes in Table 2 are established on the basis of data on population rate of change collected from numerous different coastal locations around the world.

Analogously to the calculation of the Hazard Index (see section 3.1), the Impact Index also requires the weighting of the variables with certain factors according to their relative influence on total erosion impact. In this sense, land use and population density (variables A and E) can be considered as determinant elements, and so they are weighted with a 1 factor. Conversely, nature reserves and population rate of change (variables C and F) are deemed as the least significant aspects and weighted with a 0.6 factor. Percentage of development and transportation networks (variables B and D) are considered of intermediate importance and weighted with a 0.8 factor. Once the variables are weighted, the Relative Impact Index is built in the same way as the Relative Hazard Index (see section 3.1), by adding up the weighted scores of the variables and normalizing the results.

3.2.2. Application of the Impact Index

The final Impact Index (ImI) was applied to the assessment of erosion impact in the cliffed sections of the Atlantic Cádiz coast. The evaluation of the variables in Table 2 and the calculation of the index yielded values ranging between 9% and 59% of the maximum theoretical impact for this area. According to the obtained results, the highest erosion impact corresponds to the densely urbanized tourist area of Caños de Meca and the residential zone of Santa Catalina (Fig. 5A), both of them characterized by a high level of human occupation. Moderate values of the Impact Index between 44-47% appear in the northern sector of the study area (cliffs from Grajuela-Montijo to Vistahermosa inclusive) and at Fuente del Gallo, mainly because of the type of land use and the relatively high population density. At Torre del Puerco, La Peña, Torre Bermeja and El Retin cliffs the erosion impact is relatively low due to several reasons, such as the low perceived value of the land use types, mainly croplands and natural zones, or the scarcity of developed surface. The same factors together with the lack of important transportation networks determine the lower levels of impact (between 17-23%) appearing at the cliffs of Cape Roche, Cape Plata-Gracia, Calas de Conil and La Breña. Finally, extremely low values of the ImI are found in the southern sector of the province, namely at Punta Camarinal (Fig. 5B) and Punta Paloma cliffs, which belong to a recently created nature reserve and are characterized by a near total absence of population, buildings, infrastructure, roads or any other human-related features at risk of suffering damage by cliff recession.

APPROXIMATE LOCATION OF FIGURE 5

This way, the general distribution of the Impact Index shows that the factors determining the highest erosion impact for the Cádiz coastal cliffs are those directly related to population, that is population density and population rate of change. The latter, however, is quite uniform along the whole study area, thus hindering an adequate distinction between higher and lower impact sectors. Conversely, the variability of land use type in this area renders it the most effective variable assisting in the discrimination of impact levels.

4. Discussion

4.1. Validation of the Hazard Index

It is generally accepted that new approaches to risk or hazard assessment should be tested and validated before being considered adequate for their specific purposes (Cooper and McLaughlin, 1998). The validity of the cliff erosion Hazard Index proposed in this work was tested by using real cliff erosion data recorded in Cádiz coastal area. In this sense, it is worth noting that many approaches to coastal risk or hazard include in their formulations the very consequence of such risk or hazard, thus constituting partly response-based approaches (e.g. Dal Cin and Simeoni, 1994; Gornitz et al., 1994; De Pippo et al., 2008). Conversely, in the present study cliff erosion itself is not included as a variable, instead being used to ground-truth the results in Cádiz coast and thus to validate the index.

For this purpose two types of information representing real cliff erosion were employed, especifically cliff recession rates for the period 1956-2005 and data on mass movement processes occurring in the area. The latter were included in the validation due to the widely acknowledged fact that using only mean cliff retreat rates is inadequate for defining erosion hazard (Griggs, 1994; Teixeira, 2006; Lim et al., 2009), and also episodic slope failures need to be taken into consideration (Dong, 2005).

Cliff recession rates were calculated according to the method explained in section 2, while mass movements were carefully analysed by field inspection. The main classical types of slope failure processes (Dikau et al., 1996) were identified on different points along the study area: falls, slides, topples and flows. A simple scheme was adopted to translate mass movements on each cliffed sector into a quantitative expression, by assigning a value of 1 to the sparse presence of a given type of slope failure process and a value of 2 to the abundant presence of a given type of slope failure process, without making a distinction between the severity associated with each mass movement type. For instance, if sparse falls and topples were found in a given area, the numerical value of the mass movements was 1+1 = 2; if abundant falls and sparse topples were found, then the numerical value was 2+1 = 3; if abundant falls, sparse slides and sparse topples were found, then the numerical value was 2+1+1 = 4, and so on. In this way a numerical value representing the presence of mass movements was calculated for each cliffed area along Cádiz coast.

Linear multiple regression was used on each cliffed section to test the correlation between the calculated Hazard Index (HI), the cliff recession rate (RR) and the mass movements (MM), by means of an expression of the type: HI = f (RR, MM). Two different recession rates were taken into consideration, namely the average retreat rate for the whole cliffed section (ARR) and the maximum retreat rate (MRR) found at any given point along the section. Results of the analysis (Table 3) show an acceptable goodness of fit of the multiple regression model according to the coefficient of multiple determination R^2, with around 63-65% of the variation in the HI being explained by the model. The goodness of fit expressed by the regression coefficients is similar both for average and maximum cliff retreat rates.

POSITION OF TABLE 3

Additionally, the weighting scheme chosen was also tested by performing further multiple regression calculations with values of the HI resulting from different combinations of weighting factors. The results showed poorer correlations than in the scheme chosen, with maximum R^2 values of 0.54 against the aforementioned values of 0.63-0.65 obtained for the data of the present work.

If the values of the Hazard Index were not in acceptable accordance with real cliff erosion data, this would mean that other important factors not included in the index are influencing cliff loss potential. As this is not the case, the proposed Hazard Index represents a valid approach to the estimation of cliff erosion hazard.

4.2. General risk assessment

As mentioned above, the evaluation of any type of risk should necessarily include the two separate components that constitute the risk, that is the physical hazard and the socioeconomic impact (Birkmann, 2007). For this purpose the Hazard Index and the Impact Index were combined into the Risk Index (RI), a single numerical value obtained by means of a weighted average of both indexes according to their number of variables. The rationale behind this procedure is that a simple average would actually overestimate the individual weight of the ImI variables (which are 6) against the HI variables (which are 11) in the total Risk Index. On the other hand, the Risk Index obtained by this procedure is expressed as a percentage of its maximum theoretical value in a similar way to HI and ImI. In this sense, it must be noted that although risk is often defined in terms of probabilities (UNDP, 2004), the percentage values of the RI obtained by the proposed method do not bear a direct relationship with probabilities.

The method was applied to the assessment of erosion risk for the Cádiz coastal cliffs, yielding values between 33% and 57% of the maximum theoretical risk (Table 4). The highest risk levels are found at the northernmost end of the study area, due to the high values of both erosion hazard and impact existing at Grajuela-Montijo and La Ballena-Peginas cliffs (Fig. 6). Remarkably high risk levels (RI over 50%) are also present in the NATO Base, Fuente del Gallo, Santa Catalina and Caños de Meca areas, the two former being mainly due to the physical characteristics of the cliffs and the two latter mostly related to human occupation aspects. Moderate values of RI appear in the central sector of the province, at Torre del Puerco, Cape Roche and La Breña cliffs; in all three cases, especially at La Breña, erosion hazard is the main reason behind these risk levels, given the relatively low degree of human occupation and, hence, erosion impact. Slightly lower values of the Risk Index (between 41-43%) are found at several points along the coast, namely at Vistahermosa, Torre Bermeja, Calas de Conil, El Retín and La Peña cliffs. Here cliff loss potential is the main contribution to erosion risk in all cases except Vistahermosa, where socioeconomic damage potential is the key factor. Finally, cliffs located at Cape Plata-Gracia, Punta Camarinal and Punta Paloma show the lowest risk levels in the study area, mostly related to the limited human influence coupled with moderate to low hazard levels.

POSITION OF TABLE 4

The higher number of variables and hence the higher weight allocated to the HI with respect to the ImI obviously leads to a stronger contribution of the hazard component in the total risk. This way, at some sites very low impact values are balanced by high hazard values, thus resulting in moderately high risk levels (Table 4). Nevertheless, from a general point of view cliff erosion risk in Cádiz coast can be considered as moderate to low according to the proposed method, with an absence of high or very high risk zones (Figure 6) and few areas showing a RI value above 50% (Table 4). On the other hand, the inclusion of a wide range of variables into the Risk Index adds a significant discriminating ability to the overall risk assessment procedure, as shown in Cádiz case study. However, a complete differentiation is precluded by the fact that some variables such as tidal range or rainfall regime are quite homogeneous along the study area.

APPROXIMATE LOCATION OF FIGURE 6

4.3. Methodological considerations

The combined Risk Index for the evaluation of cliff erosion risk is aimed at being an easy to use, scientifically sound planning tool that takes into account the major factors behind cliff erosion hazard and impact. Nevertheless, several considerations need to be made on the development and application of the proposed Hazard, Impact and Risk Indices.

A common procedure for assessing cliff erosion risk is the projection of past recession rates into the future; however, this is deemed as a skewed and unreliable method due to the spatially and temporally variable nature of cliff retreat. For this reason a qualitative approach was adopted in this work, by analysing the main physical and socioeconomic factors involved in the causes and consequences of cliff erosion. The proposal is a relatively simple index that is applicable to many different coastal settings worldwide, constituting a general and not site-specific method. In this sense, as mentioned in section 2, the weighting of the variables included in the indices can be used as a tool for adjusting the different elements to local conditions in order to obtain an adequate "contextualisation" of the risk assessment (Birkmann, 2007) without the need for developing site-specific risk approaches as claimed by Rygel et al. (2006). In any case, this weighting obviously entails a component of subjectivity that should be carefully handled, for instance by taking advantage of local knowledge as proposed by Mimura (1999).

Regarding the application of the indices, an important subject is that of zoning, i.e. the method by which individual cliffed sections are defined. The best way to establish a zoning scheme is to apply the indices on homogeneous units or traits of coast, each of them showing fairly uniform lithology, slope, land use, etc. This was easily accomplished for the Cádiz sites due to the previous knowledge of the area, where cliffed sections are clearly separated from each other and well defined in terms of their characteristics. If either previous knowledge is scarce or the cliffs extend uninterruptedly alongshore, then the possibility exists of establishing the units based on one or two cliff features that can be clearly identified as homogeneous in given coastal traits (e.g. coastal orientation), even if the remaining characteristics are not uniform along each of the resultant sections. In most cases this will imply the need for ulterior computations of the non-homogeneous characteristics by different means according to the specific purposes of the work. This way, on one hand, weighted averages could be calculated in order to obtain an objective assessment of the non-uniform variables. For instance, if the chosen cliff section partly covers two adjacent municipalities with different population density, then a weighted average of population density could be calculated for the cliff according to the percentage of cliff included in each municipality. On the other hand, sometimes a worst-case approach may be needed, and in this case the highest possible rank should be taken when ranking a non-homogeneous variable. In any case, it is important to be consistent with the criteria selected to define the units.

Another related issue of great concern is the scale, as the spatial resolution of the zoning will be partly determined by the scale of work. This way, given that risk assessments are often aimed at management purposes, the spatial resolution of the zoning should be in accordance with the level (local, regional, etc.) at which it is intended to support management decision-making, in order to provide useful information. In this sense, any type of index should indicate the approximate range of areas or distances over which it is valid, since the scale of the index greatly influences the feasibility and convenience of inclusion of certain variables (Cooper and McLaughlin, 1998). For instance, factors such as rainfall regime would not be suitable for discriminating erosion risk levels along a small cliffed zone on a local scale, while detailed cliff structure would not be feasible for risk analysis on large regions. For this reason the index proposed in this work can be considered as a medium-scale approach which can be applied over coastal areas at scales between several hundred meters and a few hundred kilometers.

With respect to the relationships between hazard, impact and risk, several authors add to this scheme the response of the system in terms of its resilience or ability to cope with, adapt to and/or recover from the negative consequences of hazardous events (Mimura, 1999; Birkmann, 2007). The resilience would then be the opposite to the vulnerability and hence its evaluation should be included in impact assessments. However, in the present work the features that determine cliff resistance or resilience to erosion from a geomorphological point of view are incorporated as variables in the Hazard Index. This way, vulnerability is only regarded from the point of view of the socioeconomic impact of cliff erosion (not the physical one), so the response or recovery ability would be restricted to policy decisions such as planning strategies, rebuilding of infrastructure and so on, and these issues are not within the scope of this study.

The Hazard Index and the Impact Index were designed in order to be scientifically valid and at the same time as general as possible, for them to be applied in a wide range of cliffed coasts. In this sense, Cooper and McLaughlin (1998) point to the need for considering different variables depending on the study area, but the present proposal is aimed at being useful for management purposes on many different coastal zones worldwide. Nevertheless, it must be noted that this method is only applicable to temperate environments, as erosion factors which are important in tropical cliffs (presence of coral reefs, karst dynamics) or in paraglacial coasts (gelifraction processes, winter ice sheets avoiding wave attack) are not taken into consideration.

Further refinements in the building of the indices can obviously be made, for instance by including more variables that can influence cliff erosion hazard and impact. The Hazard Index could incorporate elements such as joint width and spacing, annual probability of storms, fetch distance, nearshore slope, beach sediment size and so on (Sunamura, 1983; Benumof and Griggs, 1999; De Pippo et al., 2008). The Impact Index could include factors such as cultural heritage elements, importance of coastal tourism activities, per capita income and so on (McLaughlin et al., 2002; Boruff et al., 2005). In any event, redundancy and ambiguity should be avoided when selecting the variables; for instance, a common topic when dealing with cliff stability is vegetation cover, but it was not included in the Hazard Index due to its dependence on rainfall regime, cliff slope and cliff lithology. On the other hand, increasing the number of variables implies increasing the complexity of the index, so in any case a balance should be found between applicability, scientific validity and ease of use.

5. Conclusions

In this work a method is presented to evaluate cliff erosion risk on temperate coasts, understood as the potentially damaging consequences resulting from cliff recession processes. For this purpose a necessary integration of physical variables and socioeconomic factors is proposed in the form of a Hazard Index and an Impact Index, the latter including both exposure- and vulnerability-related parameters. The indices are subsequently combined into a single, easily understood value by means of a Risk Index.

The Hazard Index was validated by using real cliff erosion data from the Cádiz coast (SW Spain). Nonetheless, for the whole process it is important to acknowledge the uncertainty inherent in the determination of the particular influence of each variable in the final hazard, impact or risk. In this sense, there is the possibility of adapting the procedure to specific zones by changing the weighting factors according to the particular features existing in the area. The selection of homogeneous cliff units over which the indices are to be calculated is also a key issue that should be carefully considered in any case.

The proposed method is intended to be used instead of the quantification of cliff recession rates, as it constitutes a holistic approach to risk evaluation that includes both physical and socioeconomic causes and consequences of cliff erosion processes. From a management perspective, analysis performed by this procedure allows the zonation of cliffed coasts according to the risk, hazard and impact levels, and the recognition of critical areas where specific intervention strategies should be adopted. On the other hand, helpful information can also be obtained for assisting in an appropriate land use planning on undeveloped cliffed coasts, so as to prevent infrastructure from being developed on high-risk zones. This way, the method is aimed at being a practical, valuable management tool that is at the same time scientifically sound and easy to use.

Further research is, however, needed in order to ensure adequate assessment of the real importance of each individual variable in the total erosion risk. Additionally, the proposed Hazard Index should be tested against cliff recession and mass movements data in other locations with cliff characteristics different from those in Cádiz area, so as to validate it for more diverse coastal settings. On the other hand, a more detailed approach to the Impact Index could be adopted by including cost-benefit analysis, taking into consideration the specific value placed on different coastal elements and activities, as well as policy-related factors such as management decisions regarding future coastal planning schemes. Finally, although the method described in this work is only valid for temperate environments, a very similar framework could be applied to develop indices for tropical and paraglacial cliffs, by adjusting the variables to incorporate specific processes distinctive of those environments.

7. Acknowledgements

This work is a contribution to the projects MICORE (EU grant 202798), RESISTE (CGL 2008-00458/BTE) and IGCP 495 “Quaternary Land–Ocean Interactions: Driving Mechanisms and Coastal Responses”, and to the research group RNM-328 of the PAI. The useful suggestions of Dr. Andrew Plater and two anonymous referees are greatly acknowledged.

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Figure captions

Figure 1. Location map of main cities (capital letters) and cliffed areas (grey zones, names in italics) along Cádiz coast, in SW Spain.

Figure 2. Example of digitized shorelines corresponding to cliff top position between 1956 and 2005, and shore-normal transects along which shoreline changes are measured.

Figure 3. A: Rills caused by surface runoff on marls, sands and gravels cliff at Torre del Puerco (Conil). B: Waves reaching the base of a sandstone cliff at Fuente del Gallo (Conil).

Figure 4. A. Discontinuous rocky shore platform backed by a sandy cliff on Quaternary materials at El Retín (Barbate). B: Effect of flanking erosion generated by a riprap at Peginas sand cliff (Rota).

Figure 5. A. Residential development at Santa Catalina cliff (Puerto de Santa María). B: Undeveloped cliff located in a military zone at Punta Camarinal (Tarifa).

Figure 6. Distribution of the Hazard (H), Impact (I) and Risk (R) Indices calculated on cliffed areas along Cádiz coast.

Table captions

Table 1. Classification and ranking of the variables included in the Hazard Index (1-minimum hazard, 4-maximum hazard).

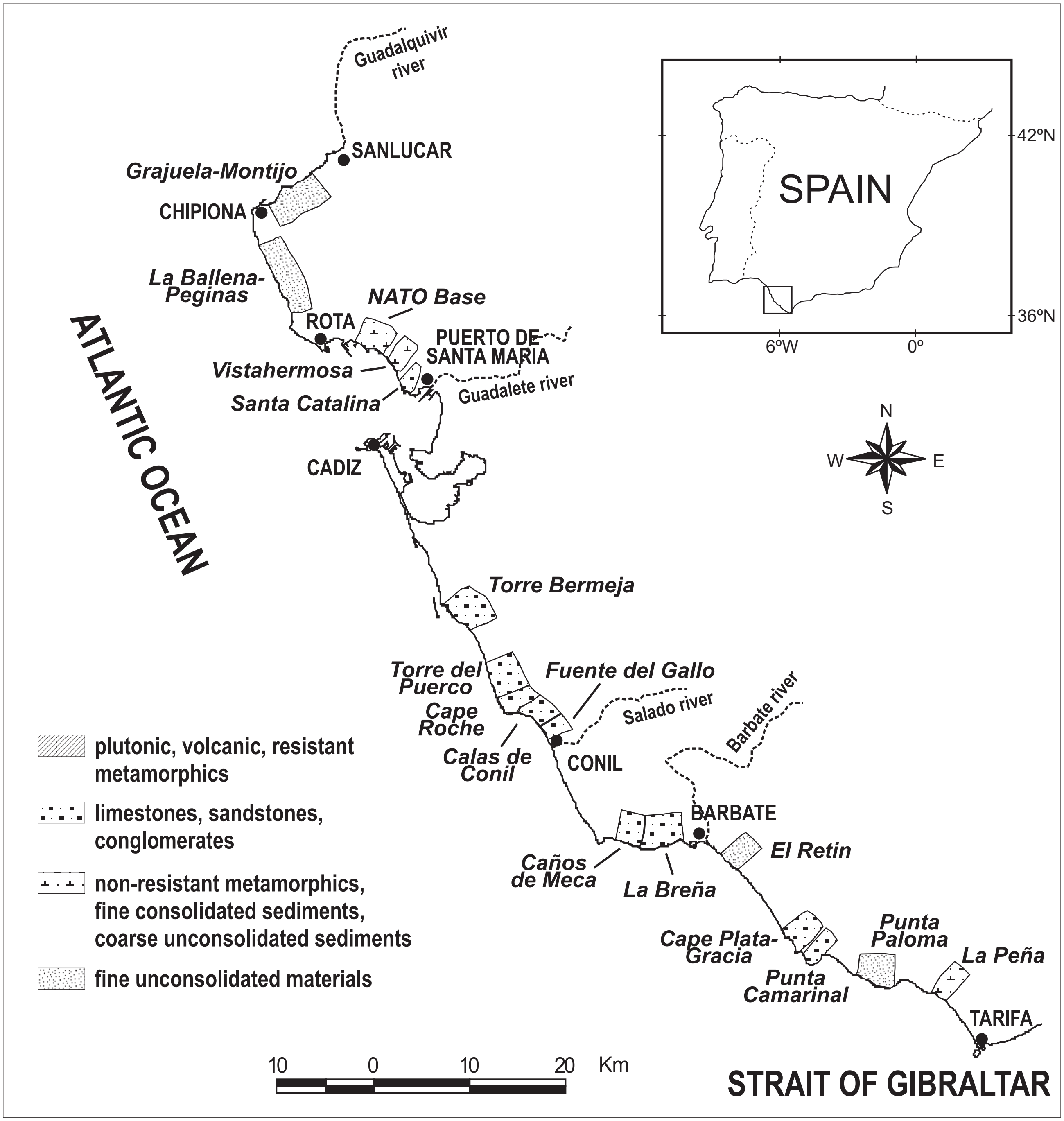
Table 2. Classification and ranking of the variables included in the Impact Index (1-minimum impact, 4-maximum impact).

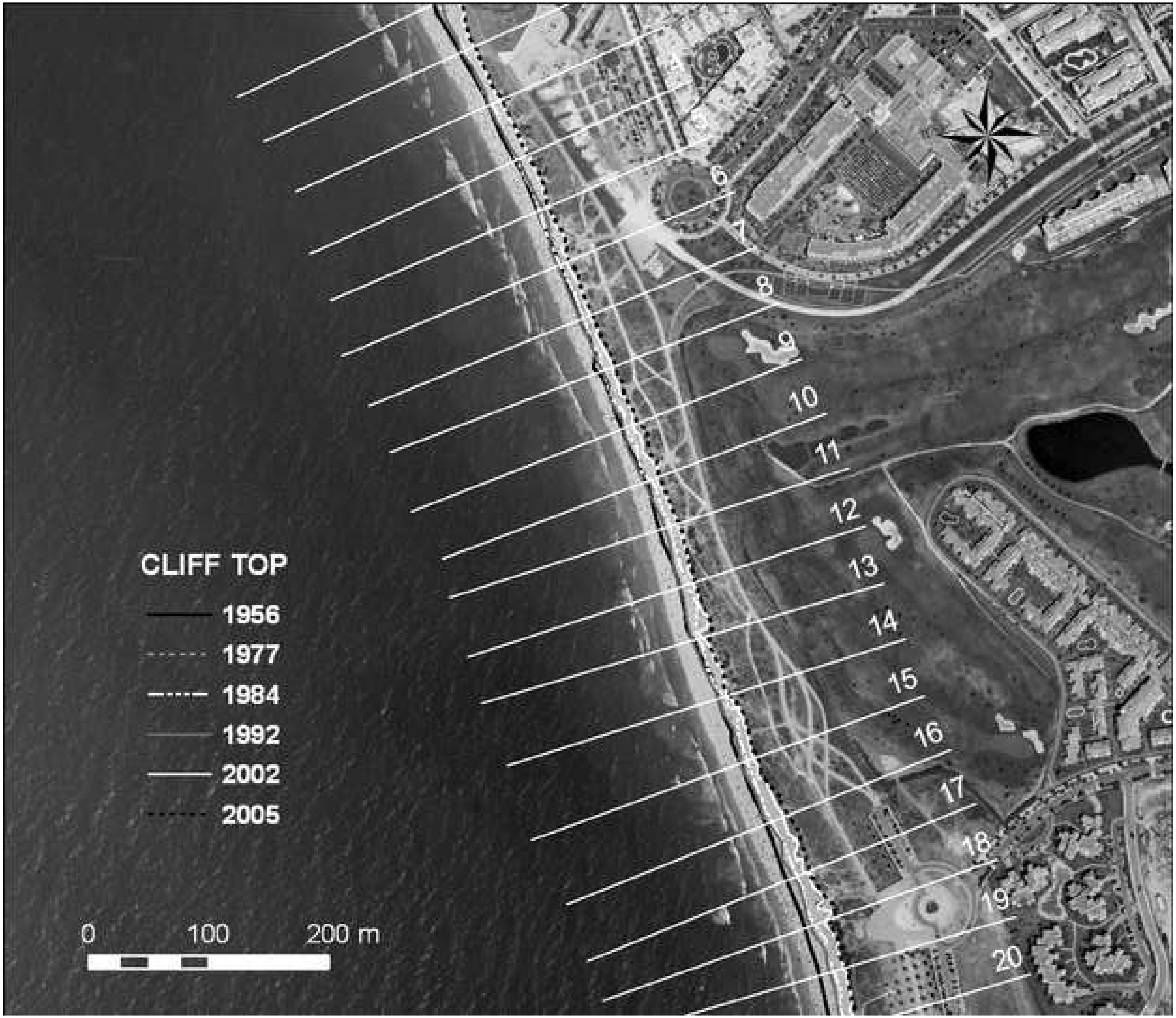
Table 3. Results of the linear multiple regression analysis performed on cliff recession and Hazard Index data. HI: Hazard Index. ARR: Average recession rate. MRR: Maximum

recession rate. MM: Mass movements. Multiple R: Multiple correlation coefficient. Multiple R^2: Coefficient of multiple determination. Adjusted R^2: Coefficient of determination adjusted by the number of independent variables.

Table 4. Values of the Hazard, Impact and Risk Indices calculated on cliffed areas along Cádiz coast.

Figure 1 in EPS format

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La Ballena-Peginas
NATO Base
Vistahermosa
Santa Catalina
ATLANTIC OCEAN
Torre Bermeja
Torre del Puerco
Cape Roche
Calas de Conil
Fuente del Gallo
Caños de Meca
La Breña
El Retin
Cape Plata-Gracia
Punta Camarinal
Punta Paloma
La Peña
STRAIT OF GIBRALTAR
R
I
H
SPAIN
42°N
36°N
6°W
0°
N
S
W
E
HAZARD / IMPACT / RISK
very high (> 80%)
high (80-60%)
moderate (60-40%)
low (40-20%)
very low (< 20%)
10
0
10
20
Km

Figure 6 in TIFF format (color for electronic version)

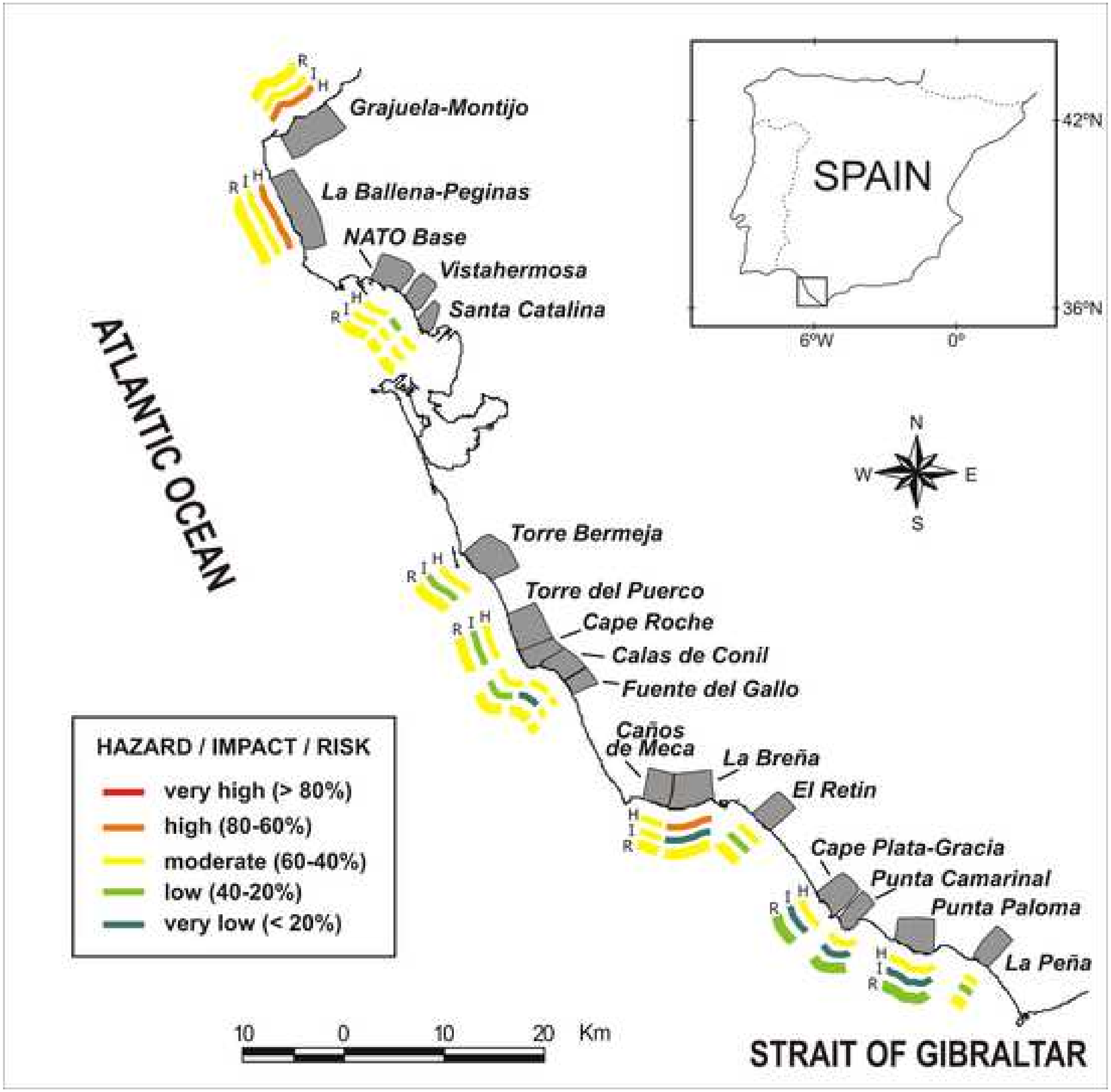
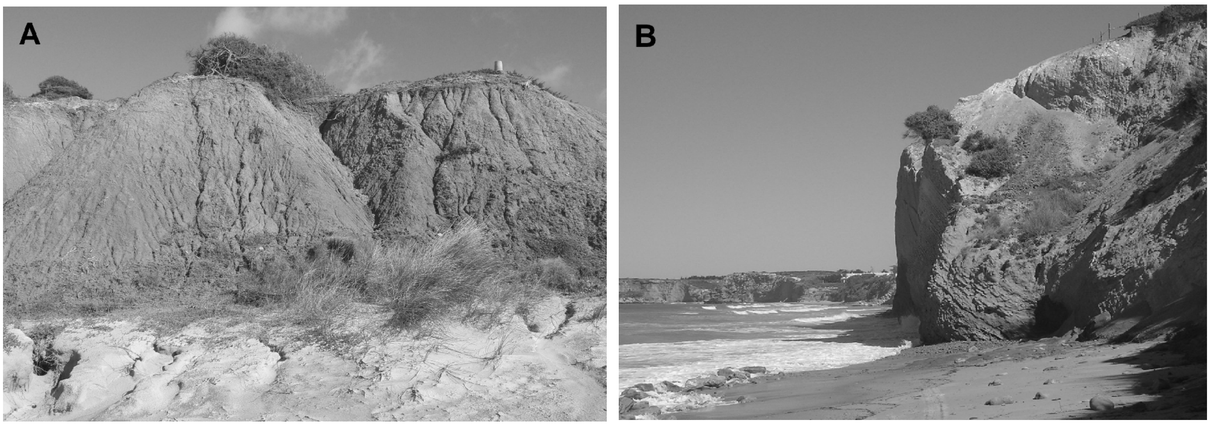


Figure 3 (A and B) in Word file

Figure 3




A

Figure 3B in TIFF format
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Figure 4 (A and B) in Word file

Figure 4

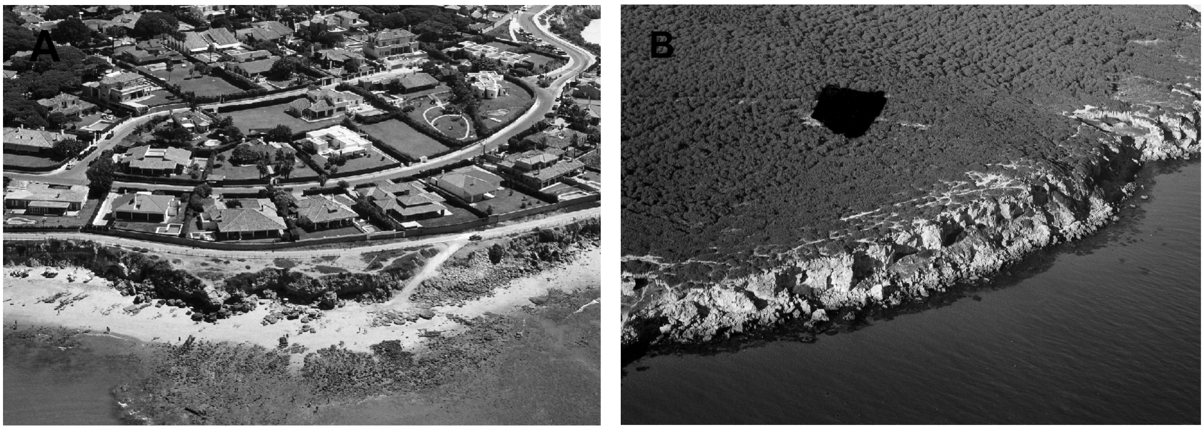
Figure 4A in TIFF format

Figure 4B in TIFF format

Click here to download high resolution image

Figure 5 (A and B) in Word file

Figure 5




A


B

Table 1

VARIABLE	HAZARD RANKING
A- Cliff lithology	1- plutonic, volcanic, resistant metamorphics 2- limestones, sandstones, conglomerates 3- non-resistant metamorphics, fine consolidated sediments, coarse unconsolidated sediments 4- fine unconsolidated materials
B- Cliff structure	1- no significant discontinuities 2- alternate sequences of soft and hard materials 3- isolated gullies and/or evident groundwater flow and/or moderate cracks/joints/faults 4- coastal badlands and/or dense cracks/joints/faults
C- Cliff slope	1- slope < 25º 2- slope 26º-50º 3- slope 51º-75º 4- slope > 75º
D- Protective beach	1- wide/high beach (waves reach the cliff at spring tides coinciding with storm surges) 2- intermediate beach (waves reach the cliff at spring tides or during storm surges) 3- narrow/low beach (waves reach the cliff during daily high tide) 4- no beach
E- Rocky shore platform	1- wide, continuous intertidal rocky shore platform 2- narrow, discontinuous intertidal rocky shore platform 3- submerged rocky shore platform 4- no rocky shore platform
F- Engineering structures at cliff foot	1- seawall or revetment at the cliff foot (whole) 2- not considered 3- seawall or revetment at the cliff foot (partial) 4- no structure at cliff foot
G- Tidal range	1- hypertidal (MSTR > 6 m) 2- macrotidal (MSTR 4-6 m) 3- mesotidal (MSTR 2-4 m) 4- microtidal (MSTR < 2 m)
H- Exposure to storm wave fronts	1- roughly shore-normal storm wave fronts (angle 81º - 90º) 2- angle 46º - 80º 3- angle 11º - 45º 4- shoreline subparallel to main storm wave fronts (angle < 10º)
I- Difference between storm and modal wave height	1- difference < 0.5 m 2- difference 0.5 m - 2 m 3- difference 2 m - 3.5 m 4- difference > 3.5 m
J- Relative sea level trend	1- change < -1 mm/yr (RSL fall) 2- change -1 mm/yr to +1 mm/yr (RSL stable) 3- change +1 mm/yr to +2.5 mm/yr (RSL moderately rising) 4- change > +2.5 mm/yr (RSL strongly rising)
K- Rainfall	1- mean annual precipitation < 500 mm 2- mean annual precipitation 500-1000 mm 3- mean annual precipitation 1000-1500 mm 4- mean annual precipitation > 1500 mm

Table 2

VARIABLE	IMPACT RANKING
A- Main land use type	1- natural areas 2- cropland 3- sparse buildings and/or parking lots 4- densely urbanized areas and/or industrial areas
B- Percentage of developed areas	1- development 0-25% 2- development 26-50% 3- development 51-75% 4- development 76-100%
C- Presence of nature reserves	1- not considered 2- absent 3- present 4- not considered
D- Presence and type of transportation networks	1- no structures for vehicular traffic 2- minor roads 3- major roads 4- motorways and/or railways
E- Population density	1- density $\leq$ 50 persons/km^2 2- 51 persons/km^2 $\leq$ density $\leq$ 300 persons/km^2 3- 301 persons/km^2 $\leq$ density $\leq$ 1000 persons/km^2 4- density > 1000 persons/km^2
F- Population rate of change	1- annual change $\leq$ 0% 2- 0.1% $\leq$ annual change $\leq$ 2% 3- 2.1% $\leq$ annual change $\leq$ 5% 4- annual change > 5%

Table 3

Table 3

HI = f (ARR, MM)		HI = f (MRR, MM)	
Multiple R	0.81	Multiple R	0.79
Multiple R^2	**0.65**	**Multiple R^2**	**0.63**
Adjusted R^2	0.60	Adjusted R^2	0.58

Table 4

	Hazard Index	**Impact Index**	**RISK INDEX**
Grajuela-Montijo	62.0	47.0	56.7
La Ballena-Peginas	60.4	47.0	55.7
NATO Base	54.1	47.0	51.6
Vistahermosa	39.2	47.0	42.0
Santa Catalina	48.6	53.0	50.2
Torre Bermeja	50.2	24.2	41.0
Torre del Puerco	50.2	36.4	45.3
Cape Roche	55.7	22.7	44.1
Calas de Conil	56.5	16.7	42.4
Fuente del Gallo	57.3	43.9	52.6
Caños de Meca	48.6	59.1	52.3
La Breña	60.4	16.7	45.0
El Retín	53.3	24.2	43.1
Cape Plata-Gracia	48.2	18.2	37.6
Punta Camarinal	50.6	9.1	35.9
Punta Paloma	46.3	9.1	33.2
La Peña	49.4	28.8	42.1