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Multi-criteria characterization and mapping of coastal cliff environments: a case study in NW Spain

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Abstract

This paper presents a novel approach to characterize cliff exposure to marine action that combines wave power and biology. This multidisciplinary approach is illustrated through a case study on a coastal stretch in NW Spain – the Catedrales Natural Monument. The engineering perspective is based on quantifying the wave power acting on the cliff. To this end, a statistical characterization of the wave climate in deep water is carried out, and relevant sea states are propagated numerically from deep water to the cliff. Four levels of cliff exposure, from sheltered to exposed, are defined based on wave power and mapped onto the study area. As for the biological perspective, ecological factors, bioindicated variables and biological indicators characterized through field observations are considered and, on this basis, also four levels of cliff exposure are established and mapped. In general, there is good agreement between the exposure patterns obtained through the engineering and biological perspectives; however, there are some differences in certain areas. The upshot is that the engineering and biological points of view should be regarded as complementary. The multi-criteria characterization performed in this paper may be used as a management tool to establish different degrees of exposure to marine action on cliff coasts elsewhere.

Keywords: Coastal management; Erosion; Cliff mapping; Wave power; Marine ecology

1. Introduction

Cliff coasts are the most common coastal environment of the world, covering about 75% of the whole coastline worldwide [1, 2]. Most of these cliffs have great biological and tourist values, representing environmental monuments. Erosion problems induced by wave action are frequent in these coastal areas. Consequently, over the last decades many studies have focused on the characterization and modelling of these coastal systems. A relationship between cliff erosion and

wave force based on laboratory and field data was proposed by [3]. The factors that drive cliff erosion were analysed by means of measurements of annual recession, wave refraction modelling and regression analysis on the Welsh coast by [4]. Later, the cliff erosion along the Oregon coast (US) was examined based on tectonic controls and field measurements by [5] and [6], respectively.

In the last twenty years, the research interest on cliff coasts has increased significantly [7-10]. The collapse of a cliff in France was investigated by means of examinations and measurements of the deposit along with stratigraphical dating by [11]. Cliff processes were monitored in the UK through terrestrial laser scanning [12]. The role of sediments released from cliff erosion to protect low-lying coasts from flooding was analysed by [13]. Other studies dealing with cliff erosion have been based on laser scanning measurements [14-22]; analysis of aerial photographs [15, 23], terrestrial and aerial vehicle photometry [24], multi-view stereo [18] and high-resolution videos [25]; development of models and methods to predict or characterize cliff erosion [20, 26-28]; and integration of local studies into a global database [29].

A few studies have also been focused on the study of marine ecosystems on cliff coasts. Some representative examples are the sampling and characterization of the distribution and prevalence of sponges in relation to the environmental gradients on inclined cliff surfaces [30], the study of distributions of molluscan assemblages on a vertical rocky cliff in the Adriatic Sea based on sampling at three different sites [31], or the analysis of the patterns of benthic colonization and succession on a temperate sublittoral rocky cliff in the Aegean Sea [32], where seasonal patterns of colonization and early succession were later investigated [33]. However, to our best knowledge, a multi-criteria analysis of the exposure based on wave power and biological indicators had not been carried out so far on coastal cliff environments.

The main goal of this work is to characterize the exposure on coastal cliffs based on wave and biological criteria. This assessment allows the classification and mapping of different exposure zones. The work is based on a case study in north-western Spain: the Catedrales beach and cliff (Fig. 1). This coast, which has a length of 1700 m, was declared *Natural Monument* by the Galician Regional Government in 2005.

Figure 1: (a) Location of the study area in north-western Spain. (b) Boundaries of the computational grids used to apply the Delft3D-Wave model, distribution of water depths and location of the ERA5 point. (c) Plan view of the study area.

The wave climate in this region is particularly energetic [34-36], with deep-water significant wave heights greater than 10 m under high-energy conditions. Under these storm conditions, the cliff is eroded due to wave action. A person died at the Catedrales beach due to the impact of a rock detached from the cliff during a storm in March 2018. The prevailing wave direction at the study area is north-west. This is influenced by the location of the cliff in north-western Spain.

The manuscript is structured as follows. The quantification and mapping of wave exposure is detailed in Section 2, including the statistical analysis of extreme values in deep water, the application of a wave propagation model and the computation of wave power along the cliff toe. Section 3 describes the characterization of biological exposure and the mapping of different exposure zones, which are based on ecological factors, bioindicated variables and biological indicators. Finally, the conclusions derived from this work are summarized in Section 4.

2. Wave power perspective

2.1. Extreme value analysis

From the point of view of cliff erosion, it is advisable to statistically analyse the extreme wave regime. For this reason, the Peak Over Threshold (POT) method [37] was applied to the significant wave heights in deep water based on the ERA5 model data of the European Centre for Medium-Range Weather Forecast. The threshold considered was the wave height value with a non-exceedance probability of 0.99 ($H_T = H_{99\%}$). Once the POT method was applied, several cumulative distribution functions (CDFs) were fitted to the extreme values obtained and the best fit was provided by the Generalized Extreme Value (GEV) function [38].

The fit of the GEV cumulative distribution function to the empirical CDF is shown in Fig. 2. Based on this fitted GEV function, the wave height values associated to return periods of 2, 10, 50 and 100 years were obtained. These wave height values, along with the most typical peak period and mean direction values under high-energy conditions, are shown in Table 1. These sea states were propagated toward the cliff toe under high-tide conditions by means of the wave propagation model detailed in Section 2.2.

Figure 2: Empirical and theoretical (Generalised Extreme Value) cumulative distribution functions of the significant wave heights in deep water after the application of the Peak Over Threshold method.

Table 1: Sea states propagated with the wave propagation model [T_r: return period; $H_{s,0}$: deep-water significant wave height; $T_{p,0}$: deep-water spectral peak period; θ_0: deep-water wave direction].

T_r (years)	$H_{s,0}$ (m)	$T_{p,0}$ (s)	θ_0 (°)
2	6.6	15	300
10	8.3	15	300
50	11	15	300
100	12.7	15	300

2.2. Wave propagation

The wave height values associated to return periods of 2, 10, 50 and 100 years, along with the most frequent values of spectral peak period and mean wave direction under storm conditions at the study area (Table 1), were propagated from the ERA5 node location towards the cliff by means of the SWAN (Simulating WAves Nearshore) model [39, 40]. The wave propagations were carried out under high-tide conditions. The SWAN model has been widely applied in the field of coastal engineering [41-60].

The computational domain defined to perform the wave propagation consisted of two grids: (1) a coarse grid covering the region from the ERA5 node location to the shoreline, with grid sizes from 300 m x 300 m to 100 m x 100 m, and (2) a nested grid covering the nearshore region, with grid sizes from 50 m x 50 m to 10 m x 10 m (Fig. 1b). The topographic and bathymetric data required as input by the model were measured during a field survey conducted in the framework of this study. The bathymetric measurements collected were complemented in deep water with the EMODnet (European Marine Observation and Data network) bathymetric data [61].

The significant wave heights at the nested grid obtained with the model are depicted in Fig. 3. The maximum values of significant wave heights at the nested grid are between 3.3 m (for the 2-year return period) and 5.5 m (for the 100-year return period). As can be observed in Fig. 3, the differences in wave height values are located at deep and intermediate depths, but not at the toe of the cliff, since as waves approach the cliff toe, the wave heights are reduced due to depth-induced wave breaking. Thus, the significant wave heights at the cliff toe do not vary between the different return periods, since they are limited by the water depth.

Figure 3: Significant wave heights at the nested grid for return period (T_r) values of 2 years (a), 10 years (b), 50 years (c) and 100 years (d).

In the western part of the study area, the wave heights are lower along a section normal to the shoreline (represented in yellow in Fig. 3). This is due to the lower depths in that area, which lead to wave breaking farther away from the coastline. The rest of significant wave height variations are due to wave refraction and shoaling during the propagation of waves over the complex and irregular morphology of the study area.

2.3. Wave power at the cliff toe

The results of the wave propagation model were used to assess the wave power values at the cliff toe by means of the following equation [62]:

$$P = \frac{1}{16}\rho g H_{m0}^2 C_g \,, \tag{1}$$

where ρ is the water density, g is the gravity acceleration, H_{m0} is the spectral wave height evaluated from the wave energy spectrum and C_g is the wave group celerity, obtained as [63, 64]:

$$C_g = \frac{c}{2}\left(1+\frac{2kh}{\sinh(2kh)}\right)\sqrt{\frac{g}{h}\tanh(kh)} \,, \tag{2}$$

where c is the wave celerity, k is the wave number and h is the water depth.

Since the wave heights at the toe of the cliff do not vary with the return period (Fig. 3), the

wave power was assessed for a 2-year return period, i.e., for a significant wave height in deep water equal to 6.6 m. The results are shown in Fig. 4. It is clearly observed how the depth-induced wave breaking reduces the wave power. In addition, the lower water depths in the western part of the cliff, which induce lower significant wave heights in this zone (Fig. 3), also reduce the wave power (Fig. 4a).

Figure 4: (a) Plan view distribution of the wave power (T_r = 2 years).(b) Alongshore distribution of the wave power at the cliff toe (T_r = 2 years).

As can be observed in Fig. 4b, the wave power distribution along the cliff toe is highly irregular. This is due to the complex bathymetry and variable orientations of the cliff, which induce varying significant wave heights at the toe and, consequently, a variable wave power distribution along the cliff toe (Fig. 4b). This varying wave power distribution at the cliff toe results in different levels of wave exposure along the cliff, as explained below.

2.4. Wave power classification and mapping

The classification of wave exposure zones was established based on the wave power values at the cliff toe. The wave power thresholds between zones are indicated in Table 2 and the mapping of wave exposure is shown in Fig. 5. The wave exposure levels are influenced by the orientation of the cliff and by the bed morphology at the nearshore region, which govern the values of significant wave height at the toe and the resulting values of wave power along the cliff.

Table 2: Classification of wave exposure zones based on the wave power values at the cliff toe [*P*: wave power].

Wave power characterization	Wave power ranges
Sheltered zone	$P \leq 4.6$ kW/m
Semi-sheltered zone	4.6 kW/m $< P \leq 9.2$ kW/m
Semi-exposed zone	9.2 kW/m $< P \leq 13.8$ kW/m
Exposed zone	$P > 13.8$ kW/m

Figure 5: Mapping of wave power (WP) exposure zones onto the study area.

It may be observed that the inlet in the eastern part of the study area is characterized as a sheltered zone (Fig. 5) due to its lower level of wave power (Fig. 4b, $s \approx 2000$ m). The Xangal Islet, which is located in the central part of the study area (Figs. 1c and 5) and was separated from the cliff by the wave action, has high exposure levels in its windward face (exposed and semi-exposed zones) and a low exposure level in its leeward face (sheltered zone) due to the protection provided by the Islet itself and the higher depths on the windward face. On the west side of the Islet, the wave power and exposure levels are higher than on the east side since the

prevailing wave direction in the study area is north-west (Table 1).

The Pena dos Corvos Islet, which is located in the western part of the study area (Fig. 5), induces a variability in wave exposure similar to that generated by the Xangal Islet, with a greater level of wave power in the windward face of the Islet (exposed and semi-exposed zones) and a low wave power in the leeward face (sheltered zone). In the stretches where there are rocks at the cliff toe, the wave power is also reduced, but the reduction is lower than in the cases of the Xangal and Pena dos Corvos Islets, since the protection provided by the Islets is greater. Under high-tide conditions, these isolated rocks act as submerged maritime structures, mitigating the wave power at the cliff toe.

3. Biological perspective

3.1. Ecological factors

3.1.1. Substrate

The physical properties of the substrate are important for marine benthic organisms. Since water is much denser than air, marine benthic organisms hold to the substrate to avoid being transported by waves and currents. For this reason, the most suitable substrates for marine benthic organisms are hard and rough substrates.

3.1.2. Hydrodynamics

Hydrodynamics is one of the physical factors with more influence on the biology of the cliff. Among the hydrodynamic agents, waves are the main drivers of the horizontal distribution of marine organisms. The most common marine benthic organisms under high-energy wave conditions are variable depending on the biological groups (Fig. 6). In algae, the development of crusted forms attached to the substrate is frequent, often with a stony structure, such as the strongly calcified coralline algae (*Corallina* spp., *Lithophyllum* spp.). In animals, it is common the development of a consistent fixing organ and a body protected by coriaceous epithelia or calcareous plaques, such as goose barnacle (*Pollycipes pollycipes*) or sea acorns (*Chthamalus* spp., *Balanus* spp.).

Figure 6: Marine benthic organisms adapted to high-energy wave conditions: Goose barnacles (*Pollycipes pollycipes*, left image), sea acorns (*Chthamalus stellatus*, in both images) and coralline red algae with a stony structure (*Lithophyllum byssoides*, right image).

Tidal fluctuation is also an important factor which affects the distribution of marine organisms. The tidal range in the study area is about 2.7 m (4.5 m) under neap (spring) tide conditions. The species are arranged on different horizons, according to the most appropriate level for their ecological requirements (Fig. 7). For example, the higher levels of the intertidal zone may be colonized only by organisms specially adapted to strong environmental variations (mainly in the availability of water, salinity and temperature).

Figure 7: Influence of tide conditions on the distribution of organisms.

In the supralittoral zone, living conditions are extreme due to the lack of soil, the significant variations in salinity and temperature, the exposure to the wind, etc. Consequently, very few species are capable of living in this zone. Crustacean lichens are the only organisms that are able to colonize these zones, in particular *Hydropunctaria maura*. This is a black crustacean lichen that serves as the main biological indicator of the extension of this zone (Fig. 8).

Figure 8: Supralittoral zone. The central section is mainly colonized by the crustacean lichen *Hydropunctaria maura* (black colour, left image). In the upper levels, an orange lichen, *Caloplaca marina*, is also usually abundant (right image).

In the intertidal zone, the ecological factors have a wide range of variability. Due to the tidal oscillation, factors such as desiccation, insolation, temperature and salinity, among others, vary in the different levels of this zone. Thus, the communities of organisms that are established at the different levels have a very different specific structure and composition. For this reason, the intertidal zone is usually subdivided into three horizons from the biological point of view: the upper, middle and lower horizons, which are physically delimited by the upper and lower levels of the neap tides. The lower horizon has more homogeneous conditions and a greater biodiversity and productivity. In Fig. 9, the difference is apparent between the supralittoral zone, with a black colour due to its colonization by the lichen *Hydropunctaria maura*, and the intertidal zone, with sea acorns (*Chthamalus* spp.) in the upper horizon and macroalgae (*Ulva* spp.) in the lower level.

Figure 9: Image of the Catedrales coastal cliff under low tide conditions.

3.1.3. Light

Light is an ecological factor that is especially important for algae and lichens, since they are autotrophic beings that require light to live. In the study area, some distribution patterns of marine organisms can be explained mainly by the intensity of the light radiation. The main photophilic organisms are the green algae of the genus *Ulva*; whereas sciophilic organisms that colonize the caves are coralline red algae such as *Phymatholithon lenormandii* or the *Hymeniacidon perlevis* sponge. In the left image of Fig. 10, it is clearly observed the presence of photophilic communities of the algae *Ulva* spp. on flat illuminated substrates (maximum irradiance about 1,500-2,000 $\mu\text{mol}\cdot\text{m}^2\cdot\text{s}^{-1}$); whereas the right image shows communities of sciophilic organisms on a vertical surface in one of the caves of the study area (maximum irradiance about 150-200 $\mu\text{mol}\cdot\text{m}^2\cdot\text{s}^{-1}$). In the latter image, it may be observed the violet-coloured coralline algae *Phymatholithon lenormandii*, the orange sponge *Hymeniacidon perlevis* and the acorn *Elminius modestus*.

Figure 10: Photophilic and sciophilic communities.

3.1.4. Salinity

On coastal cliffs, due to the run-off from rainwater or spring flows, salinity is an important factor for populations of marine organisms. On the cliffs of the study area, salinity ranges from zero (in fresh water infiltrations) to 34 parts per thousands. The fresh water infiltrations are clearly bioindicated by the abundance of the green algae *Ulva intestinalis*. They are capable of living in environments with highly variable salinity, even in fresh water for quite long periods of time, so that these fissures are a suitable environment, where they are protected from the tidal regime. This species can also serve to indicate the areas of the cliff that have infiltrations of continental waters, which may indicate both the degree of fracture of the substrate and the possible erosive effects of the infiltrations. Fig. 11 shows the green algae *Ulva intestinalis*, which is capable of living in a wide range of salinities. It bioindicates inland water infiltrations. In the non-influence zone of these waters, only the lichen *Hydropunctaria maura* is present. The lower horizon is subjected to strong sandy abrasion. In this horizon, a population of the red algae *Porphyra dioica* develops, which is quite discoloured due to the sunlight action.

Figure 11: Photo of the Catedrales coastal cliff with fresh water infiltrations.

3.2. Bioindicated variables

3.2.1. Height

Benthic organisms are indicators to delimit accurately the sea level oscillations. Since the tidal oscillation generates a strong gradient of ecological conditions, different organisms are competitive at each of these different levels (Figs. 6 and 12).

3.2.2. Wave exposure

Wave exposure is one of the ecological factors with a greater influence on the distribution of marine organisms. Water, due to its density, has a very noticeable effect on benthic organisms. The morphology, consistency and fixation system of the different organisms are indicative of their living conditions based on wave exposure (Fig. 6). Fig. 12 shows two cliff zones with different wave exposure levels according to Fig. 5. The left image corresponds to an exposed zone, where it is observed a wide presence of the supralitoral lichen *Hydropunctaria maura* (black colour) as well as the absence of vascular plants. On the contrary, the right image shows a sheltered zone, where the horizon of this lichen is much narrower and there are vascular plants on the cliff.

Figure 12: Images of two zones of the cliff with quite different wave power exposure levels.

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3.2.3. Substrate stability

The life cycle of benthic organisms is highly variable. There are species that complete their life cycle in a few days, while others are very long-lived and require several years. Thus, the presence of one or other species indicates the stability of the substrate that they colonize. In Fig. 13, the colour differences indicate more or less recent rockfalls, which have generated surfaces that have not been colonized yet by the lichen Hydropunctaria maura. This lichen takes about three years to colonize new surfaces again [65].

Figure 13: Images of the supratidal horizon in the study area with recent rockfalls.

3.2.4. Movements of sand and pebbles

The abrasive or occlusive effect of sand suspended in water is another bioindicated variable. In areas with pebble accumulations, the abrasive effect may be more important. There are benthic organisms that, due to their morphology, consistency and/or vital strategies, are very well adapted to these factors and can, therefore, bioindicate them with their presence. Other organisms, of fleeting development, can colonize substrates that have lost their biological component for having spent long periods under the sand.

Fig. 14 shows two photographies of the same zone at different times. The left image shows that the lower levels are covered by sand, whereas in the right photo it is observed that all the sand has been removed and the rocks have been colonized by the pioneer green algae *Ulva prolifera*, which develops rapidly. The abrasive effect of the sand in these areas is considerable. Thus, the organisms observed in the low areas of the cliff are those adapted to this abrasive effect, such as the cirripedal crustacean *Chthamalus stellatus*. On the other hand, Fig. 15 shows the final stretch of a cave, where pebble accumulations are observed. These pebbles are moved under high-energy waves and high-tide conditions. Its strongly abrasive effect is indicated by the organisms that colonize the rocks both at the bottom and on the walls: only crustose algae such as the red algae *Hildenbrandia rubra* and different blue-green microalgae (cyanophyceae).

Figure 14: Images of the same zone of the study area at two different times.

Figure 15: Photo of the final stretch of a cave in the study area.

3.2.5. Seasonality

Some benthic organisms can experience variations in their presence or abundance according to the season of the year. This is important since its presence is indicative of certain environmental conditions. For example, the red algae *Nemalion elminthoides* is an indicator of environments subjected to high-energy conditions; however, due to its presence only in summer,

its value as bioindicator is very useful only in this season (Fig. 16). In the foreground of Fig. 16, two specimens of goose barnacle (*Pollycipes pollycipes*), sea acorns (*Chthamalus spp.*) and several mollucs (*Mytilus galloprovincialis*, *Patella spp.*) are observed, which are also biological indicators of high-energy environments.

Figure 16: Red algae *Nemalion elmintoides* and goose barnacle *Pollycipes pollycipes* at the study area.

3.3. Biological indicators

This section describes the main benthic organisms that can be found in the study area, which were considered as biological indicators. The use of bioindicator species to classify different types of coast depending on wave exposure or to recognize a littoral horizon is based on both quantitative and qualitative criteria. From a quantitative point of view, the coverage by lichens, macroalgae and marine invertebrates was expressed as a percentage of the surface area colonised by them using an ordinal transform scale based on an extended Braun-Blanquet cover abundance scale [66]. The higher the coverage index, the higher the bioindicator value of the species. From a qualitative point of view, the presence of several indicator species of the same variable, although some of them were not dominant, makes the classification of the site more robust.

3.3.1. Marine lichens

Lichens are organisms formed by the mutual symbiosis of an algae and a fungus in which the two members benefit from the association. The algae (phycobiont) feeds the fungus (mycobiont) thanks to photosynthesis and the fungus offers the algae protection against the environment. This symbiosis means that these organisms can colonize extreme environments, where almost no organism can live, such as the rocks of the supralittoral zone.

From a morphological point of view, lichens can be crustose, if they are integrated into the substrate that they colonize forming more or less circular and marginally growing spots; foliose, if they form lobes or laminae attached to the substrate and easily separable; or fruticulose, if they are like small trees more or less branched. Sea lichens are usually black and the phycobiont are commonly blue-green algae (cyanophyceae).

The crustose lichen *Hydropunctaria maura*, which was considered in this study as biological indicator, appears at the supralittoral zone. The extension of the zone occupied by this specie is directly proportional to wave power. The growth rate of the colonies of this species is less than 1 mm per year and the recolonization of a substrate by this lichen after its elimination requires at least 3 years, so its presence indicates a remarkable stability of the substrate. It is a perennial species that does not experience seasonal variations.

3.3.2. Marine benthic algae

Algae are a very heterogeneous group of photosynthetic, unicellular or multicellular organisms with a simple anatomy. Marine benthic algae are traditionally classified into three

groups: green algae (Chlorophyta), red algae (Rhodophyta) and brown algae (Ochrophyta). These groups are very different from a morphological point of view. Their life-cycles and mechanisms of reproduction are also markedly different. Most marine benthic macroalgae do not endure desiccation because they are non-vascular organisms. For this reason, they are only abundant from the middle intertidal horizon.

In this work, green algae, such as *Ulva* spp., were considered as biological indicators. This species can appear at any littoral height and under different wave conditions. This is a pioneer species, so that it may indicate substrates recently exposed to possible colonization by marine organisms. Due to its ability to withstand changes in salinity, in the upper parts of the cliffs, it can indicate areas of freshwater infiltration. It is capable of colonizing substrates subjected to sandy abrasion due to its pioneering nature. Populations of this species are present throughout the year, although they are more abundant in spring and autumn.

Red algae were also considered as biological indicators in this work. They have a series of accessory protein-type photosynthetic pigments (phycoerythrins) that give them a peculiar colouration and allow them to live under low light conditions. For this reason, they often abound under other organisms, in the less illuminated areas of the intertidal zone, such as vertical walls facing north, caves, crevices, etc. Some species form evident belts on the coast.

3.3.3. Molluscs

Molluscs are a very heterogeneous group of soft-bodied, non-segmented animals with their dorsal surface generally covered by a shell that protects their internal organs. There are many different groups of molluscs. In the study area, gastropods and bivalves are the most common. The gastropods, such as *Patella* spp., can be found in all coastal horizons due to their ability to move. They are adapted to sandy abrasion and do not experience seasonal variations. *Patella vulgata* occupies the highest and most protected environments, while *Patella intermedia* and *Patella aspera* are present in the lowest levels in sites more exposed to wave action.

On the other hand, the bivalves molluscs, such as *Mytilus galloprovincialis*, are especially abundant in the middle intertidal horizon, where they have less competition for the substrate. They generally abound in areas highly exposed to wave, although they can also be found in more protected areas but with good water renewal by currents. They indicate stable substrates since they are organisms that take at least a year to reach adulthood. They are also adapted to sandy abrasion and do not experience seasonal variations since they are long-lived species.

3.3.4. Cirriped crustaceans

The cirriped crustaceans are sedentary and their shell is made up of calcareous plaques. The different types of cirriped crustaceans are strongly fixed to the rocks by means of a cement that they produce in special glands, either directly or, as in the case of the goose barnacle (*Pollycipes pollycipes*), through a more or less long fleshy foot. When a cirriped is underwater, it opens its plates and projects long appendages that trap plankton organisms. In this work, the *Pollycipes pollycipes* and *Chthamalus* spp. were considered as biological indicators.

Pollycipes pollycipes are characteristic of the middle and lower coastal horizons. They indicate very stable substrates and high levels of wave exposure. They support sandy abrasion and do not experience seasonal variations, since they are long-lived species. On the other hand, *Chthamalus* spp. can be found mainly on rocks of the upper intertidal horizon in moderate to high

levels of wave exposure. They are also long-lived species so that they do not experience seasonal changes. They are adapted to sandy abrasion.

3.4. Biological classification and mapping

The biological characterization of exposure zones was performed on the basis of the ecological factors (Section 3.1), bioindicated variables (Section 3.2) and biological indicators (Section 3.3) analysed. Four biological zones were defined and mapped (Fig. 17).

Figure 17: Mapping of biological (B) exposure onto the study area.

Firstly, the biological sheltered zones are characterized by a high level of sediment silting, narrow horizons of *Hydropuntaria maura* and *Chthamalus* spp., and vascular plants on the cliff very close to the high-tide level (Fig. 18a). These zones are commonly heavily silted by sediment so that, in many cases, only the supralittoral horizon is visible. In Fig. 18a, green algae (*Ulva intestinalis*) are observed due to freshwater infiltrations. The vegetation of vascular plants is also present in the high parts of the cliff.

The biological semi-sheltered zones are characterized by a variable level of sediment silting, broader horizons of *Hydropunctaria maura* and *Chthamalus* spp., and presence of *Mytilus galloprovincialis* (Fig. 18b). These zones are also covered by sediments, so that only the supralittoral horizon, colonized by *Hydropunctaria maura*, and the upper littoral horizon, colonized by *Chthamalus stellatus*, are visible. In these zones, vascular plant vegetation is scarce on the cliff and species indicative of a more notable hydrodynamic action, such as *Lithophyllum bissoides* or *Pollycipes pollycipes*, are not present.

The biological semi-exposed zones are poorly silted, have broader horizons of *Hydropunctaria maura* and *Chthamalus* spp., presence of *Lithophyllum byssoides*, and high abundance of *Mytilus galloprovincialis* (Fig. 18c). Since these areas are less covered by sediments, the middle intertidal horizon is usually visible, with presence of coralline red algae (*Corallina caespitosa*, *Lithophyllum incrustans*). The belt of *Mytilus galloprovincialis*, which is indicative of high-energy conditions, is thick and width.

Finally, the biological exposed zones are poorly covered by sediments, so that the lower horizons are visible. These zones are characterized by wide horizons of *Hydropunctaria maura*, and by the presence of *Chthamalus* spp., *Lithophyllum byssoides*, *Mytilus galloprovincialis* and *Pollycipes pollycipes* in a lower horizon (Fig. 18d). The crustacean *Pollycipes pollycipes* is the species that indicates more clearly the highest level of exposure. In these zones, the middle and lower intertidal horizons are visible. In the lower horizon, different species of algae appear, such as coralline red algae (*Corallina caespitosa*, *Lithophyllum incrustans*) or green algae *Codium tomentosum*.

Figure 18: Examples of biological exposure zones: sheltered (first row), semi-sheltered (second row), semi-exposed (third row) and exposed (fourth row).

4. Conclusions

A multi-disciplinary approach to characterize coastal cliff environments has been presented and illustrated through a case study: the Catedrales Natural Monument, a stretch of coastline and tourism hotspot in NW Spain. The characterization is based on exposure to marine action, determined from two complementary points of view: wave power and biology.

The wave power perspective is focused on the wave power acting on the cliff. To this end, the wave climate in deep water was statistically characterized and a wave propagation model applied to quantify the wave power distribution along the cliff toe. On the other hand, the biological perspective consisted of a joint analysis of ecological factors, bioindicated variables and biological indicators obtained through field observations. In both perspectives, wave power and biology, four levels of exposure to marine action were defined and mapped onto the study area.

The spatial distribution of wave power along the cliff was found to be highly irregular. This is caused by the complex bathymetry of the study area, which induces wave refraction and shoaling, and by the variable orientation of the cliff face, with some parts more exposed than others to the wave direction. The varying wave power along the cliff results in different levels of exposure. For instance, the inlet in the eastern part of the study area is sheltered. On the islets in front of the cliff, the windward faces are exposed or semi-exposed, whereas the leeward faces are sheltered. The rocky outcrops that occur at the cliff toe in some sections act as emerged (submerged) detached breakwaters under low (high) tide conditions, dissipating part of the incident wave power and thereby reducing the exposure level on the cliff face in their lee.

The biological perspective focused on *in situ* analysis of ecological factors, bioindicated variables and biological indicators, and led to similar results to the wave power perspective in most sections. For instance, the inlet in the eastern part of the study area was also found to be sheltered, and the highest exposure level was found to occur immediately east and west of the inlet. Notwithstanding, certain differences arose, e.g., the windward (offshore) face of the Xangal Islet was sheltered from the biological point of view, but exposed from the wave power point of view. The coastal stretch west of Xangal Islet was mostly semi-sheltered from the biological perspective, but included some exposed sections from the wave power perspective.

The fact that the two approaches – one, based on wave power; the other, on a host of biology-related factors – led to generally similar results is a testament to the weight of wave power in controlling the cliff environment. On the other hand, the fact that differences do occur between the two approaches proves that, for all its importance, wave power is not the sole element that shapes the cliff environment and its variability. Other factors play a role, such as: tidal levels, wind exposure, substrate stability, light, insolation, desiccation, temperature, salinity, freshwater from surface runoff or direct precipitation, sediment cover, abrasion by sand and pebbles, etc. Tidal levels are similar in a relatively short coastal stretch like the study area and, therefore, are not a cause of environmental variability within that area, but the other factors mentioned are not constant and do induce environmental variability. For this reason, in studying the cliff environment and its variability, it is important to apply the multidisciplinary approach presented in this work.

This approach can be useful for coastal managers and policy-makers to determine the most exposed zones on cliffs and, on this basis, establish management practices to prevent material and human damages in these zones. The methods presented and applied in this paper to characterize and map cliff environments can be extended to other cliff coasts across the world.

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CREDIT Author Statement

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Javier Cremades: Investigation, Methodology, Writing – Review & Editing.

Luis Medina*:* Conceptualization, Project administration, Funding acquisition, Writing – Review & Editing.

Gregorio Iglesias: Conceptualization, Methodology, Writing – Review & Editing.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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HIGHLIGHTS

- Multidisciplinary approach to cliff environments based on wave power and biology
- Statistical analysis & numerical modelling to determine wave power acting on cliff
- Field observations of ecological factors and bioindicated variables
- Case study proves need for multidisciplinary approach in cliff environments
- Management tool for establishing dangerous zones on cliffs and prevent damages

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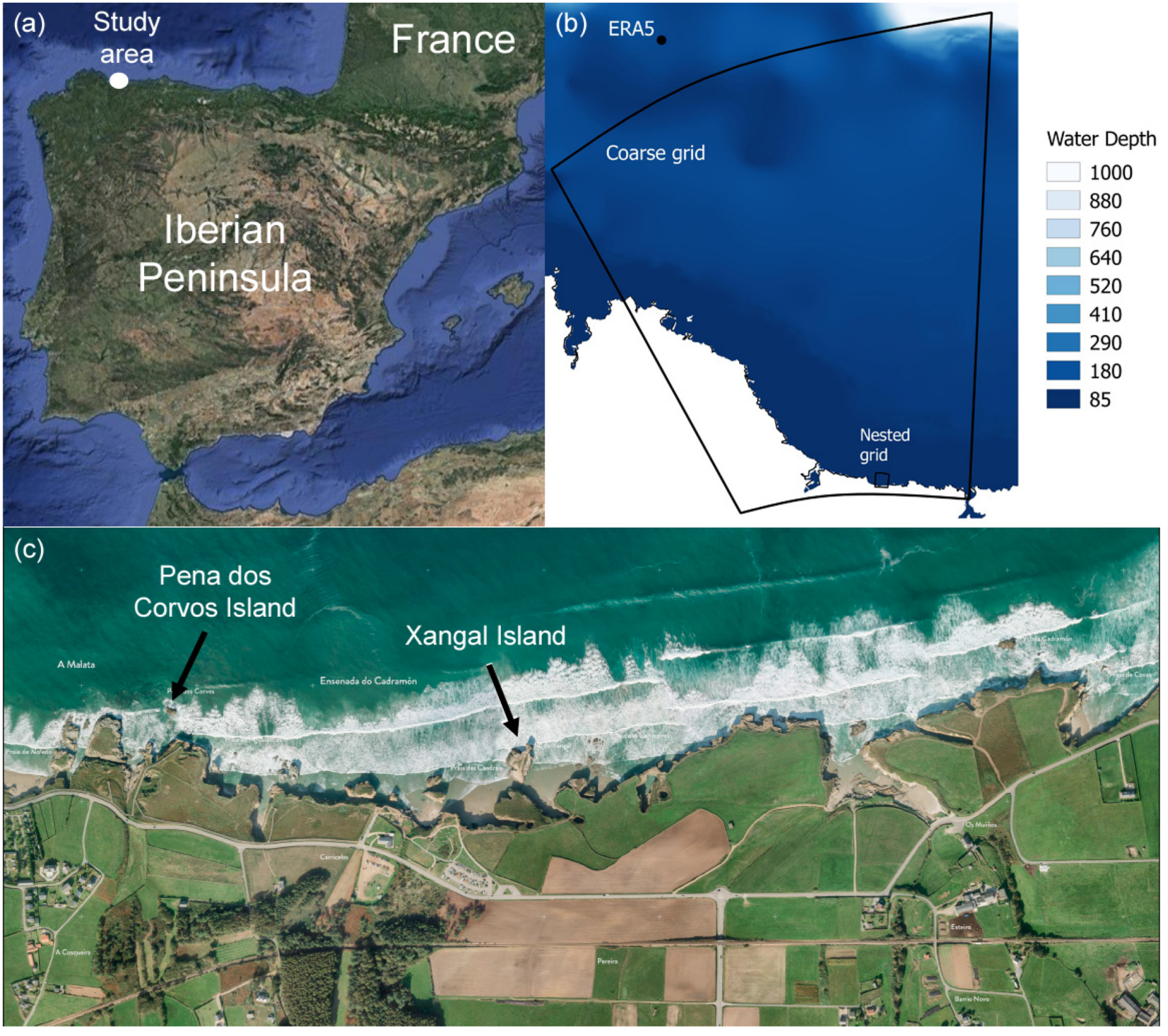

(a)
Study area
France
Iberian Peninsula
(b)
ERA5
Coarse grid
Nested grid
Water Depth
1000
880
760
640
520
410
290
180
85
(c)
Pena dos Corvos Island
Xangal Island
A Malata
Ensenada do Cadramón
Carricelas
A Cosqueira
Pereira
Esteiro
Barrio Novo

Figure 1

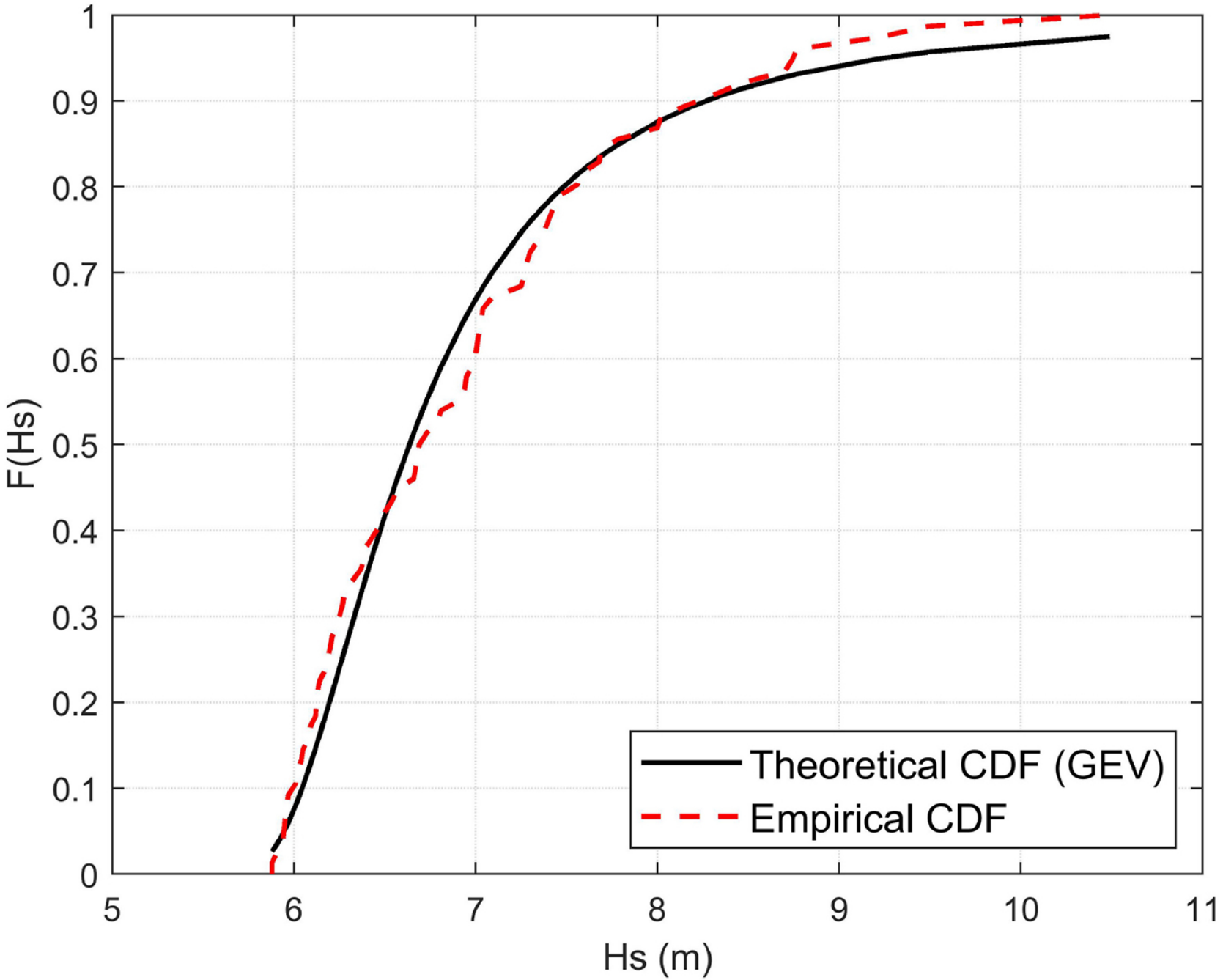

F(Hs)
Hs (m)
Theoretical CDF (GEV)
Empirical CDF
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
5
6
7
8
9
10
11

Figure 2

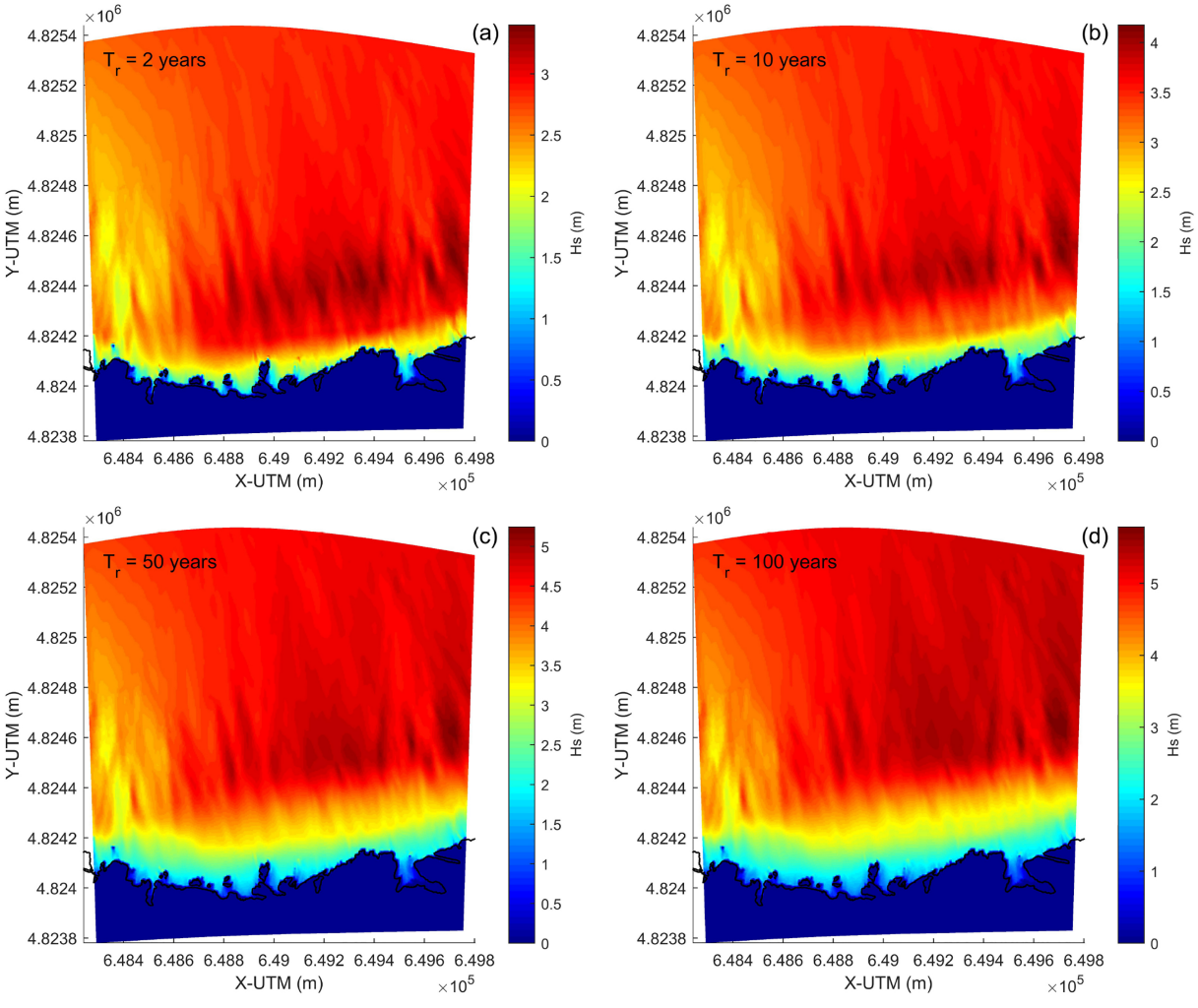

(a)
T_r = 2 years
(b)
T_r = 10 years
(c)
T_r = 50 years
(d)
T_r = 100 years
×10^6
4.8254
4.8252
4.825
4.8248
4.8246
4.8244
4.8242
4.824
4.8238
Y-UTM (m)
6.484 6.486 6.488 6.49 6.492 6.494 6.496 6.498
×10^5
X-UTM (m)
Hs (m)
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

Figure 3

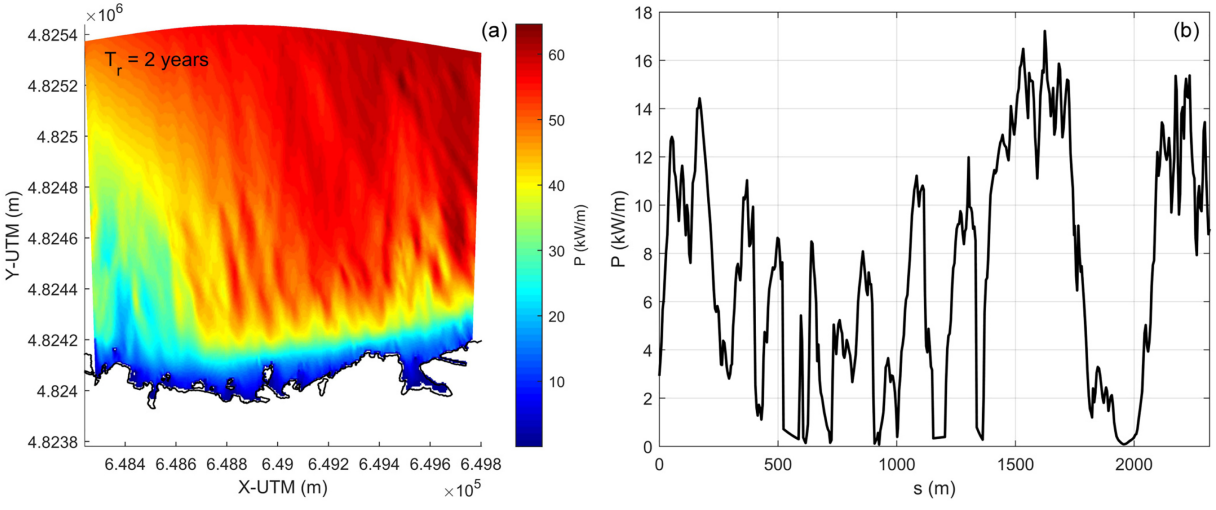

(a)
T_r = 2 years
×10^6
4.8254
4.8252
4.825
4.8248
4.8246
4.8244
4.8242
4.824
4.8238
Y-UTM (m)
6.484 6.486 6.488 6.49 6.492 6.494 6.496 6.498
X-UTM (m)
×10^5
60
50
40
30
20
10
P (kW/m)
(b)
18
16
14
12
10
8
6
4
2
0
P (kW/m)
0 500 1000 1500 2000
s (m)

Figure 4

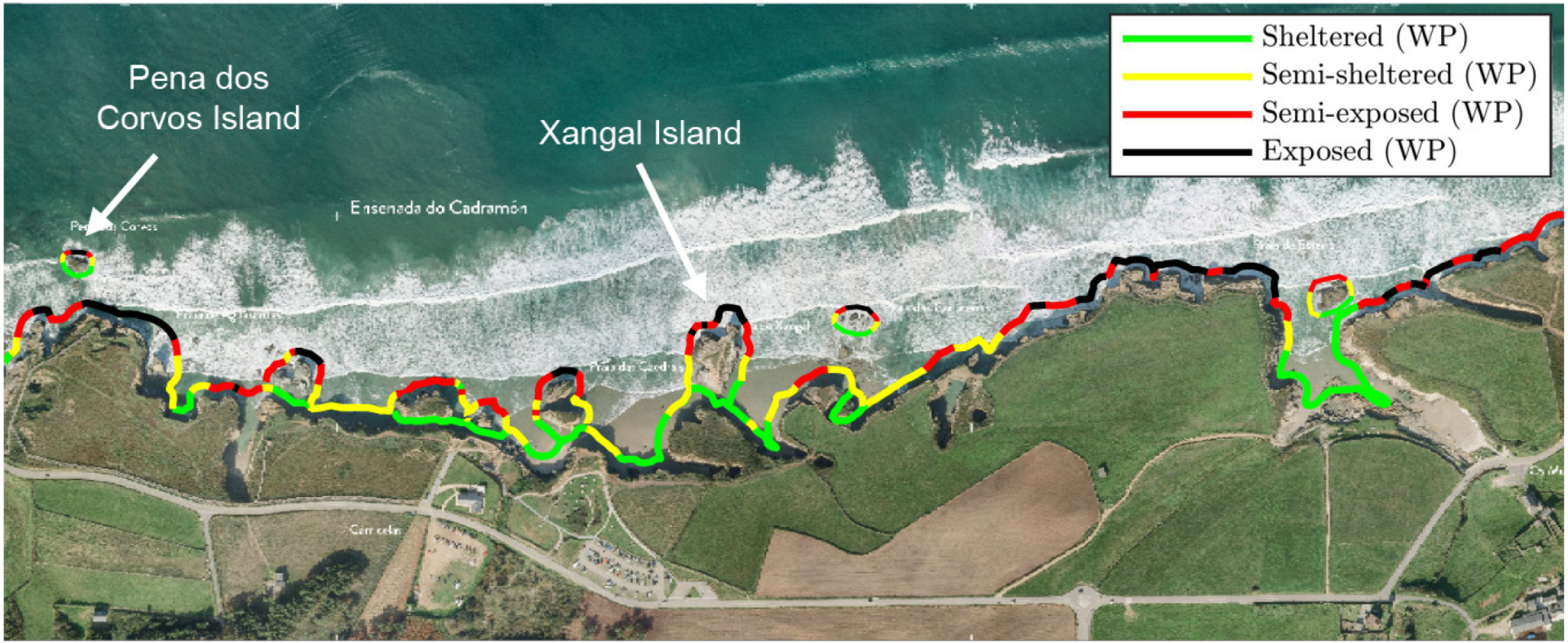

Pena dos Corvos Island
Xangal Island
Ensenada do Cadramón
Sheltered (WP)
Semi-sheltered (WP)
Semi-exposed (WP)
Exposed (WP)

Figure 5



Figure 6

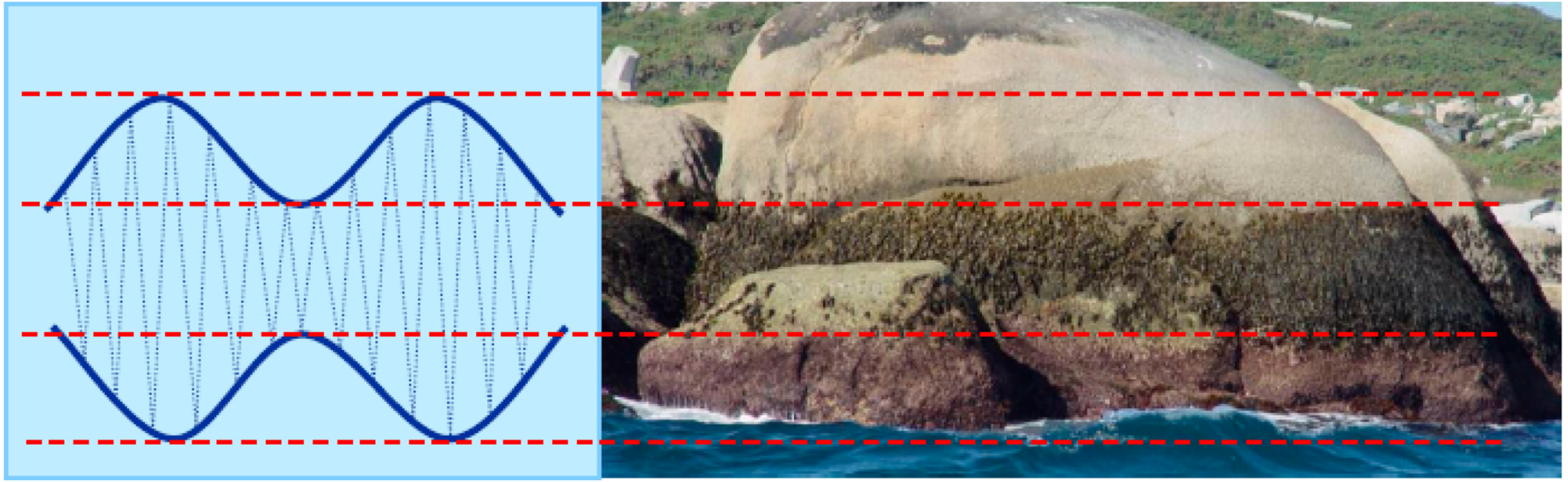


Figure 7



Figure 8



Figure 9



Figure 10



Figure 11



Figure 12



Figure 13



Figure 14

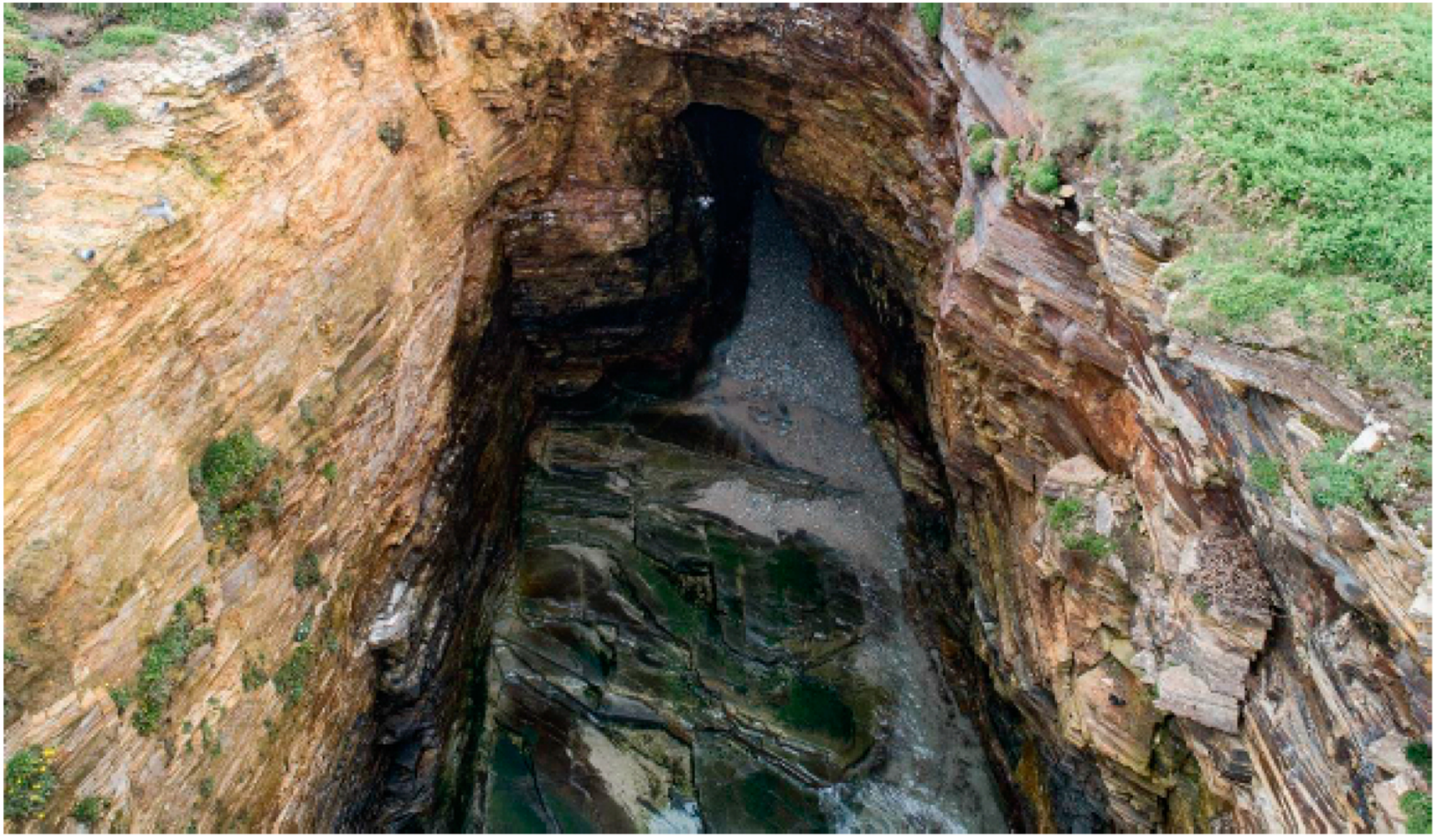


Figure 15



Figure 16

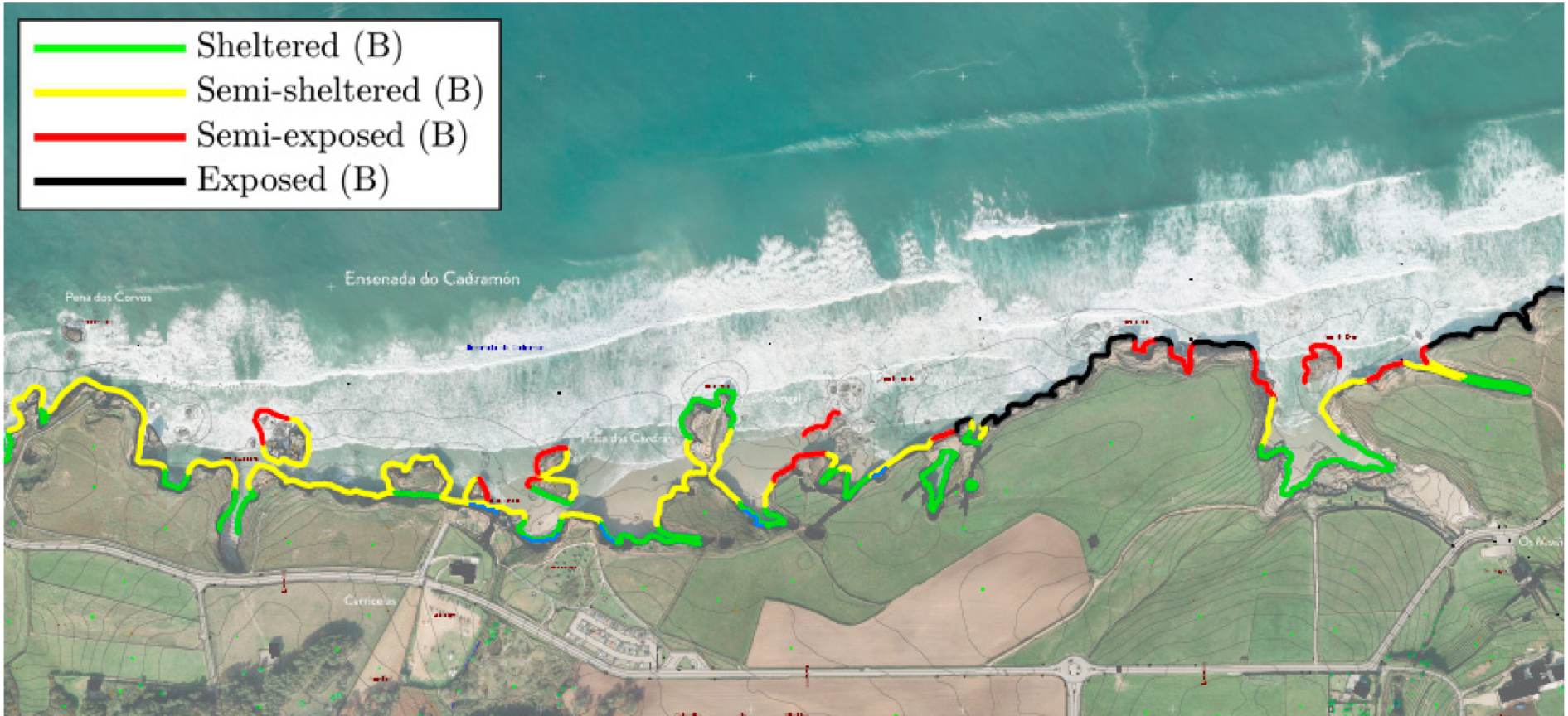

Sheltered (B)
Semi-sheltered (B)
Semi-exposed (B)
Exposed (B)
Ensenada do Cadramón
Pena dos Corvos
Carniceiro

Figure 17



(a)

Hydropuncturaria maura with populations of Ulva intestinalis associated with freshwater infiltrations



(b)

Hydropuncturaria maura

Chthamalus stellatus



(c)

Hydropuncturaria maura

Chthamalus stellatus and Mytilus galloprovincialis

Coral red algae



(d)

Hydropuncturaria maura

Chthamalus stellatus with Litophyllum byssoides, Mytilus galloprovincialis and Pollicipes pollicipes

Coral red algae

Figure 18