IDENTIFYING CLIFFS MORPHODYNAMICS: A 3D GIS APPROACH FOR A BETTER HAZARD MANAGEMENT. EXAMPLES IN CROATIA

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Abstract: In this paper, we present a simple method for elaborating and mapping a multivariate index for coastal cliffs. The final map aims to classify zones of low, medium and high hazards related to morphodynamics. This classification is a synthetic description that must later be explained with geological and other features.

The index is calculated on regularly and closely spaced transects along the coastline. It uses three easily determined parameters: the evolution of the cliff edge, the height and the mean slope.

The sites selected for this study are located in Croatia. The first coastal cliff is located on the island of Vrgada. Massive episodic rockfalls usually occur on this 90° steep cliff. The second is the coastal cliff of Duilovo in the urban area of Split. Erosion processes along this cliff include rockfalls and landslides supported by water, while weathered sediment are moved downslope by gravity during dry periods. At both sites wave action is not the key process in the formation in cliff formation, but it carries away debris and other forms of material that have accumulated downslope. The morphodynamics analysis on both sites was tested and is presented for the first time.

Keywords: Cliffs, hazards, Geographical Information System, Croatia

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Introduction

About 52 % of the world's coastlines consist of cliffs [27]. Surprisingly, these cliffs are less studied and less known in the scientific community than low-lying sedimentary coastlines [18]. However, these coastlines can be highly vulnerable, especially when human infrastructures are built close to eroding areas [4, 21, 24, 26].

Some scientific studies focus on mapping coastal evolution to quantify and predict shoreline retreat, e.g. through a diachronic analysis of the cliffs digitized on historical maps and aerial photographs [9, 13]. Many researches aim to identify the geological, marine and meteorological factors involved in the cliff morphology and slope processes at short time scale [10, 15,16, 21]. Quantitative analysis of cliff morphodynamics is less frequently studied [22], perhaps because it is difficult to conduct field measurements in an environment with a steeper and more restrictive topography than that of a beach or dune.

However, in the last 25 years, airborne LIDAR and more recently digital photogrammetry have seen increasing success in the scientific community of geoscientists [6, 13]. These techniques help in the acquisition of a large amount of precise data as well as in the transition from 2D to 3D mapping and terrain modelling. Such successive topographic surveys are very valuable for assessing the morphodynamics of cliffs, for example, by revealing not only changes in the horizontal displacement of the coastline, but also the profile characteristics and volume of the cliffs and their evolution [11].

In this paper, we present a simple method for developing and mapping a multivariate coastal cliff hazard index. The method uses two data sets that are quite easy to obtain nowadays: (1) 2D data: the shoreline evolution, for example by a diachronic analysis of aerial photographs; (2) 3D topography data extracted from digital models (DM) calculated from digital photogrammetric processing and their derivatives: cliff height and slope. Measurements are then taken at regularly and closely spaced transects along the coast. The multivariate synthesis is calculated using cluster analysis. The final map aims to classify low, medium and high hazard zones in terms of their morphodynamics. This classification is a synthetic description that must later be explained geological and other features.

To test this method, two study sites were selected on the Croatian coast, each characterized by a different lithology. The first coastal cliff is located on the Vrgada Island. Its lithology consists of Pleistocene aeolian-alluvial clastites. The cliff experiences massive episodic rockfalls. The second is the coastal cliff of Duilovo in Split the urban area, which was formed in Eocene flysch. The erosion processes of this soft cliff include rockfalls and rotational landslides.

Study sites

The coastal cliff of Vrgada is located on the island of the same name. It is a ~15 m high cliff consisting of Pleistocene aeolian-alluvial deposits, which alternate from the beach to the top of the cliff [2]. Unlike the north-western gentle slopes, the eastern part of the cliff is a steep vertical slope (90°) more prone to erosional processes. The gravitational processes observed are successive rockfalls [20]. The northern part is an approximately 45° steep slope without obvious gravitational processes, probably due to the dense vegetation [19].

As already mentioned above, Duilovo is part of the Split urban area (Figure 1), where coastal cliffs up to 30 m high have formed. The main rock is Eocene flysch, which in this coastal section is characterized mainly by fine-grained marls with less frequent sandstone layers [21, 26]. Such cliff lithology is susceptible to intense mechanical weathering, especially by water (e.g. rain and surface runoff, ground water leakage, wave abrasion). The entire cliff is steeply sloping (on average about 80°) over its length of ~ 2 km. Such an angle with predominant marl lithology is an ideal place for gravitational processes to occur. The most common gravitational processes are slow wet debris flows and subsequent dry flows of marls previously loosened by surface water. However, rotational landslides occur repeatedly along the western part of the cliff. This section of the cliff was selected for analysis in this work.

In terms of rock hardness, it can be said that the rock mass on the Vrgada Island is slightly more resistant than that of the Duilovo cliff.

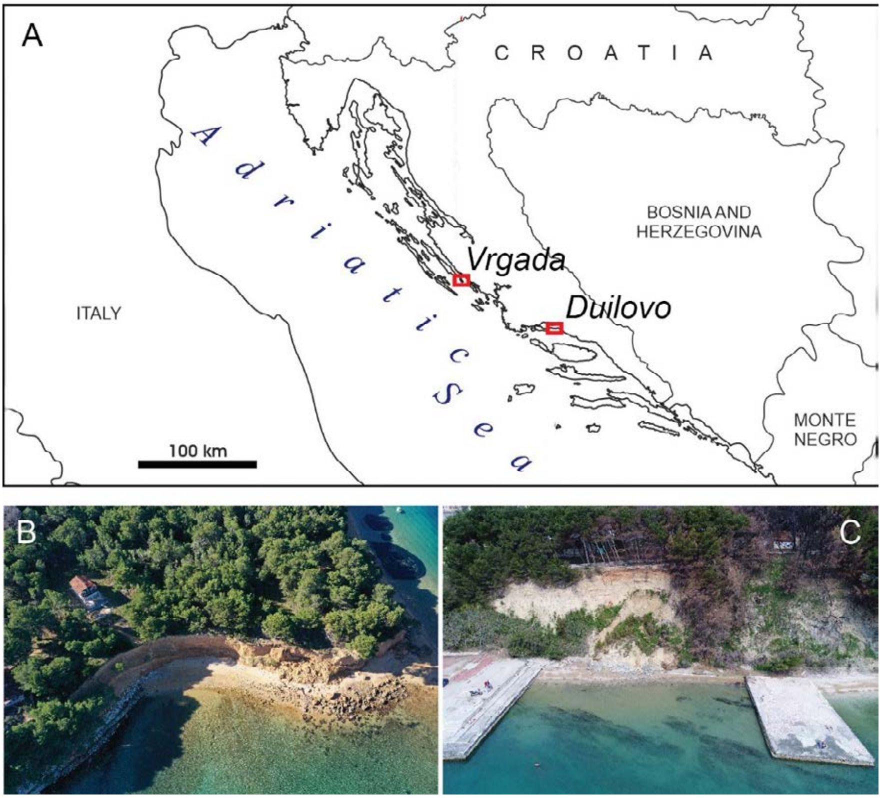

Figure 1 – Location and photographs of the Vrgada and Duilovo cliffs.

Materials and methods

Topographical measurements

The data collection used in this paper for both cliffs was carried out twice: April 2018/May 2018 for the Duilovo cliff and April 2023/June 2023 for the Vrgada cliff. For both study sites, 200 to 400 photos were taken with, both perpendicular to the nadir and at an angle of 45°. The overlap of the photos was 80 % and Structure-from-Motion (SfM) photogrammetry was used with Agisoft Metashape software to post-process the photos (planar orthomosaics) and create digital models (DMs). The DMs were georeferenced using ground control points (GCPs) taken before data collection. The GCPs used were both fixed (painted red dots) and movable (red and white metal plates). Their exact position (3D coordinates) was determined by Virtual Reference Station Real-Time Kinematics (VRS RTK) using a Trimble R8 GNSS receiver and the high-precision positioning service CROPOS (DGU http://www.cropos.hr/). The horizontal and vertical accuracies were within 2 and 4 cm, respectively, while the root mean square error (RMSE) of DMs was within 4 cm. After creation, the orthomosaics and DMs were exported in TIFF format for further processing.

Data processing in GIS

The data set required for the analysis was obtained by processing in a Geographic Information System (QGIS 3.32; Figure 2a).

First, the edges and bottoms of the cliffs were carefully digitised manually on aerial photographs with high spatial resolution (Figure 2b). The edge of the cliff corresponds to the break of the slope. This upper edge is considered as the shoreline as in many other publications on cliffs [4 and references within]. This is a relevant definition for hazard studies as this shoreline is close to potentially endangered infrastructure [3, 7]. The foot of the cliff is another break in slope and it was digitised as a line between debris cones and beach.

Subsequently, the DMs with the elevation data for each study site were converted into a slope map using the QGIS Slope function (Figure 2d).

Data extraction was performed along 5 m spaced transects perpendicular to the shoreline (Figure 2b). They were calculated using Station Lines, an extension of QGIS for calculating transects along a baseline. This baseline can be drawn by hand and must be approximately parallel to the shoreline. The historic shoreline digitised from an aerial photograph can also be used. 11 transects were drawn in Duilovo and 25 transects in Vrgada, along which the positions of respective historical shoreline (April and May 2018 for Duilovo, April and June 2023 for Vrgada) and the positions of the cliff toe were measured.

The change in shoreline was analysed using a classical and widely used geomatic method [8, 23, 25]: the distances between the intersections of a transect and the shorelines were measured.

The QGIS extension qProf was then used to calculate the height and average slope along each transect (more precisely along a segment delimited between the edge and the foot of the cliff at the first date, April 2018 for Duilovo and April 2023 for Vrgada).

Each of these evolutionary and morphological parameters has a significance for the identification meaning of hazard identification. The more rapid the shoreline retreats, the greater the threat to human infrastructure. The higher the cliff, the greater the kinetic energy of a falling block can be. The steeper the slope, the faster mass movement can occur. So, a low cliff would have a slow evolution rate and *vice versa*.

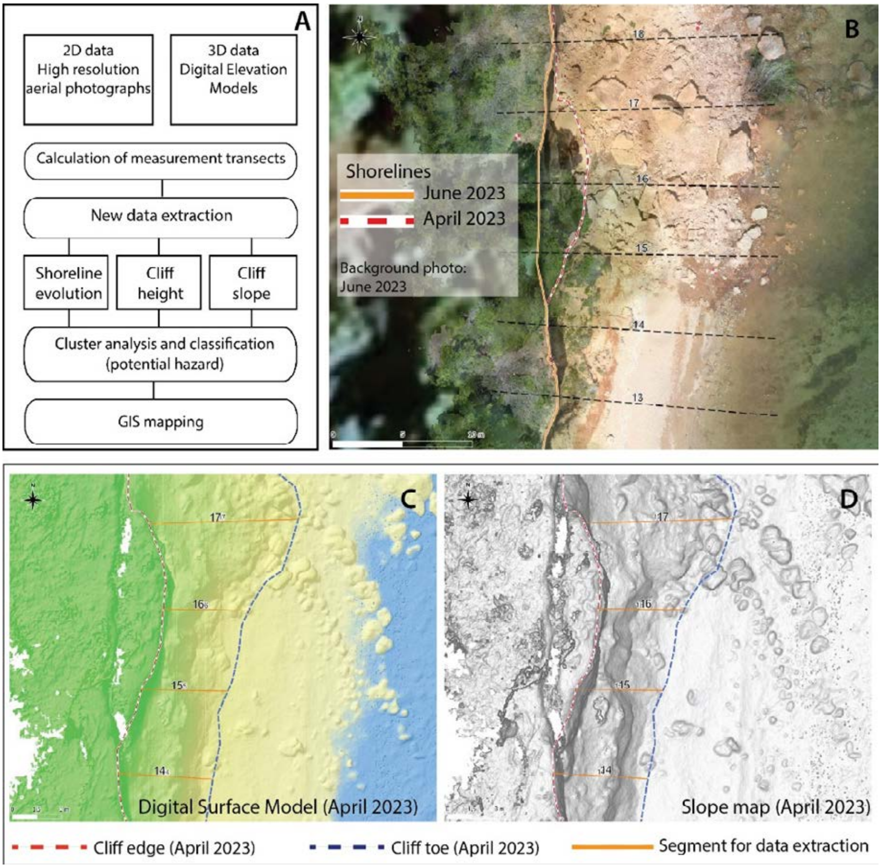

Figure 2 – Methodological chart; examples of shoreline digitization, digital surface model and slope map in Vrgada.

Clustering analysis: data and goals

In a multivariate analysis, a first important question is the hierarchy of the parameters under consideration. In this first classification test, we decided to weight all selected parameters equally. However, since these parameters are expressed in very different units and with very different ranges of variation, it was necessary to standardise them first in order to eliminate the units and ranges of variation. The standardisation process is simple and can be summarised by

Equation 1, where x_s is the standardised value, x_i is the original value at a transect, and $\bar{x}$ is the mean and σ the standard deviation of transects for a parameter for a study site. A standardised value is therefore dimensionless and is the ratio between the comparison of the original value at a transect and the mean value ($x_i - \bar{x}$) calculated for all transects, divided by the variability of the values in the statistical series (σ). For example, the slope of a transect is first compared with the mean slope of all the transects in the area and then related to the overall variability.

$$x_s = \frac{(x_i - \bar{x})}{\sigma} \qquad 1$$

The cluster analysis was performed with the latest version of Past 4.17 [12]. This analysis aims to create a typology based on the selected parameters (shoreline evolution, height and slope of the cliff). It can be useful to identify shoreline sections with analogous "behaviours" [1]. At each stage of the calculations, Euclidean distances between each statistical individual (i.e. each transect) were computed. In our case, these are 3D distances (one dimension for each parameter). The shorter the distance, the more similar the entities are. The individuals are gradually grouped into pairs. Sometimes an individual is grouped with a pair that is more similar to it than any other entity. The cluster analysis is presented in a "tree diagram" or dendrogram which showing the stages of progressive aggregation (Figures 3 and 4), with the individuals at the top (the leaves of the tree), the branches below and the trunk at the bottom of the diagram. The discretization threshold is set to a distance chosen so that the main branches of the dendrogram intersect and the desired number of classes is obtained.

Results

Vrgada

The dendrogram shows a fast first step of association of the cliff sectors at a distance of ~ 0.75, which shows their similarity (Figure 3). The very last step of the association takes place at values ~ 5.5, which means that the previously created groups differ significantly. A discretisation threshold can be set at a distance of 2.2. This allows the identification of three classes depending on the increasing distances of association of the groups: a high hazard class in the centre of the area (transects 15 to 17), a medium hazard class comprising the transects in the centre and north; and a low hazard class, comprising the adjacent transects further south of the study area. The small dendrogram on the right side of the colour table above shows that elevation and slope are rapidly linked (Figure 3). This is logical, because in Vrgada cliff is often almost vertical: the higher it is, the steeper the slope can be. Changes in the coastline are less strongly associated with the other two parameters, as the association with the first two parameters occurs later. The colour table helps to perform a more detailed analysis. The colours refer to the small colour scale to the right of the main dendrogram: red indicates a value significantly above the mean

(0 on the standardised scale), blue indicates a value significantly below the mean; green stands for values around the mean (Figure 3). The greater the range of variation, the greater the diversity is. It can be seen that the transects in the low hazard class are characterized by cliff evolution, heights and slopes that are among the lowest (shades of blue), while the transects in the medium hazard class are slightly higher and have steeper slopes (shades of blue, green and light yellow). Transects 15 to 17, which have a higher hazard class, are mainly characterized by strong changes (shades of yellow and red for evolution): the shoreline retreated from 2 to 3.3 m due to a major rockfall during the study period, while the other transects were almost stable. For transects 15 to 17, elevation and slope do seem not appear to be the predominant factors (shades of blue in the colour table).

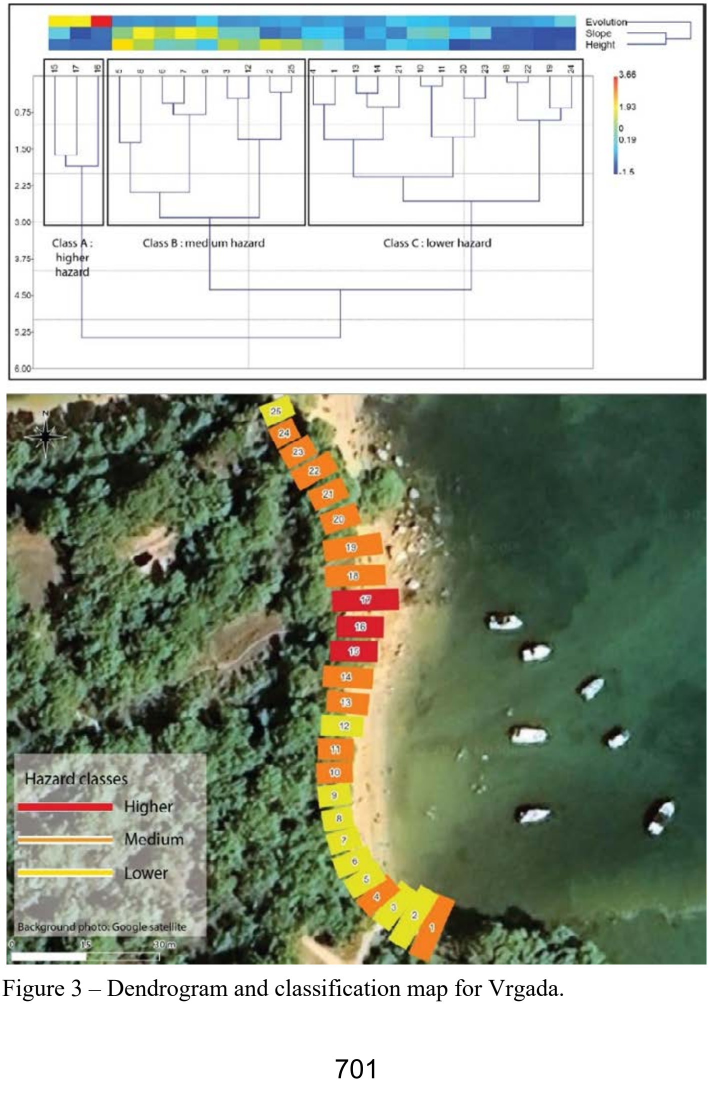

Figure 3 – Dendrogram and classification map for Vrgada.

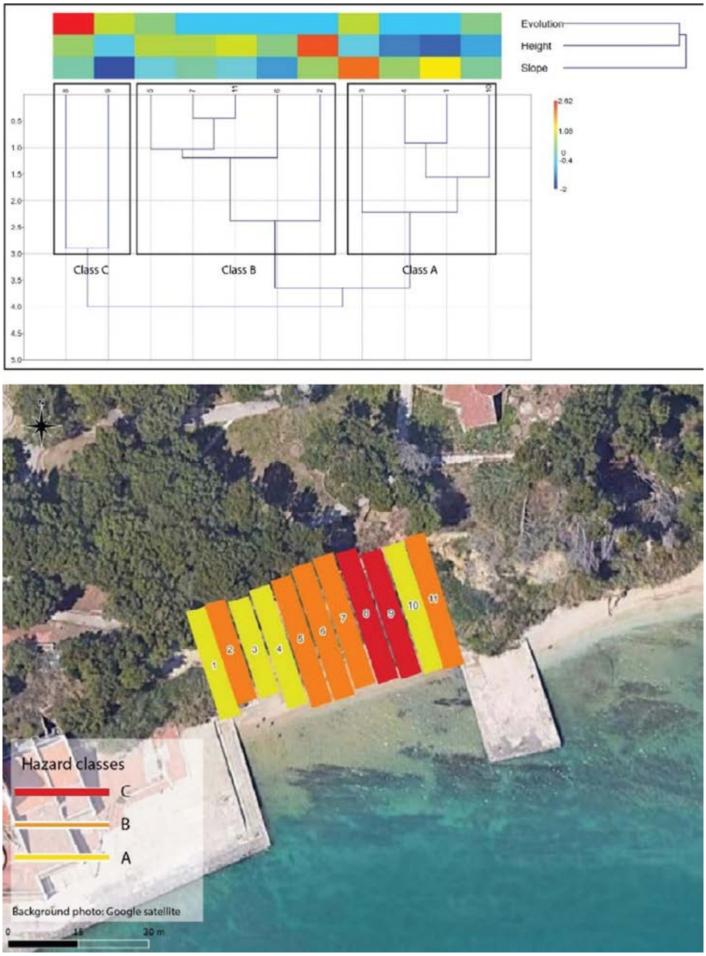

Figure 4 – Dendrogram and classification map for Duilovo.

Duilovo

It is interesting to note that in the Duilovo dendrogram the last level of association occurs at the distance of 3.7 earlier than in the Vrgada dendrogram. This shows that the 11 sectors of Duilovo are relatively more similar than those in the Vrgada dendrogram. This is consistent with the fact that the study area is very small. This is confirmed by the range of variation of the standardised values, which extends from 2.62 to -2 with an amplitude of 4.62 (colours scale in Figure 4), showing that the diversity of cliff conditions is lower than in case of Vrgada (amplitude 5.16). The small dendrogram at the top right shows that in this case, the evolution, elevation, and slope are parameters with a weak relationship: their association occurs late at the end of the dendrogram. In order to create three classes, the discretisation threshold had to be set to a Euclidean distance, i.e. with a larger distance than for Vrgada (2.2). Therefore, there are more relative differences within each class of Duilovo, than within the classes of Vrgada. The colour table helps to interpret the classes that have been created.

We can see that the transects of class A are similar in their evolution and height (green and blue). Only transect 3 (orange) differs slightly in its slope (the steepest in the group). The class B transects are similar in all three parameters. Transect 2 (orange) stands out due to its height (35.8 m, the highest in the class). Transects 8 and 9 of class C are slightly less typical than the others. Transect 9 has a gentler slope (blue), while transect 8 shows a relatively stronger change (red). However, transect 8 shows a very moderate retreat of the shoreline (0.05 m i.e. within the margin of measurement of error), while it is being stable. It is therefore difficult to rank the classes in terms of hazard characterization with this configuration of results.

Discussion and conclusion

The aim of this work was to test the cluster analysis method to describe and classify the level of hazard, using three parameters easy to obtain: cliff evolution, height and slope. This analysis does not require more complex information such as geomechanical parameters [17]. For this purpose, two relatively unknown coastal cliffs on the Croatian coast were investigated. In the case of the Vrgada cliff, the result showed that the highest level of hazard exists along transects 15 to 17, where a rockfall recently occurred. Considering the slopes and heights, which are quite similar along the entire cliff, it seems that other parameters, which were not considered in this analysis, played a more important role for this slope process. For the Vrgada cliff, such parameters could be localised weakness of the rock mass that is the consequence of an existing deep crack, as described in [20]. It was suspected that the intense rainfall in May 2023 was the trigger for the rockfall. After the rockfall, the slope and height of the newly formed cliff face remained mostly unchanged i.e. a steep and vertical slope with an unchanged cliff height. The only exception to the slope is collapsed material, which is eventually washed away. The evolution of the Vrgada cliff is therefore quite simple and involves retreat of the cliff over time without any significant changes in slope and height.

In the case of Duilovo, the cliff evolution shows more complex features, i.e. it was more difficult to explain its evolution based on the index tested in this work. As explained in [21], the vegetation along this cliff plays an important role. It has grown over the slid cliff material. After the rockfall that occurred between April and May 2018, much of the collapsed rock mass was overgrown by vegetation. For this reason, it was very difficult to digitise the position of the two shorelines. As a result, the area with the highest level of hazard (A; Figure 4) was assigned along transects 8 and 9, where the actual vegetation grows and prevents the erosion of the cliff through its roots. On the other hand, a medium-hazard area (B; Figure 4) was designated where landslides and rockfall actually occurred (transects 5, 6, 7). It is assumed that the vegetation cover should be removed from the DM used, and only the digital terrain model (DTM) should be used for the method tested here. Another fact that is not visible and has not been considered in this work is the presence of groundwater breaking out on the surface. Most of this water occurred along transects 5, 6 and 7 where the landslide and the rockfall occurred.

The cluster analysis in the case of Vrgada provided quite understandable results with a higher risk class that stands out from the other two classes and is characterised by an obvious retreat of the shoreline due to a cliff collapse at transects 15 to 17. At the Duilovo cliff, however, the hazard level was much more difficult to determine. The landslide had occurred at transects 3 to 5. It changed the shape and position of the toe of the cliff, but had no impact on the cliff edge. This landslide was not detected by the index used in our method. We suspect that the method is a little too simplistic as the cliff edge was considered as the shoreline, not the cliff toe. Including the cliff toe as a fourth parameter could improve the suitability of the index of the index in the future.

The study periods for our two sites were short. Nevertheless, some remarkable changes in the evolution of the cliffs were detected. In order to examine the applicability of the index in the future, more datasets (new sets of aerial photographs and DEMs) would be useful to rank the hazards and investigate their evolution over time.

The calculated hazard index could also be improved by making it more dynamic by including a temporal dimension for each parameter. Until now, the dynamic dimension was only supported by the shoreline evolution parameter, while the height and slope were calculated for a single date. The evolution of the cliff edge and cliff toe could be calculated using several orthomosaics at different points in time. Changes in cliff heights, slope angles and volume could be considered by comparing multiple DMs.

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