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# Slope, Scarp and Sea Cliff Instability Susceptibility Mapping for Planning Regulations in Almada County, Portugal

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**Abstract.** In Portugal, the modifications introduced in 2008 and 2012 in the National Ecological Reserve law (REN) included the mandatory study of slope instability, including slopes, natural scarps, and sea cliffs, at municipal or regional scale, with the purpose of avoiding the use of hazardous zones with buildings and other structures. The law also indicates specific methods to perform these studies, with different approaches for slope instability, natural scarps and sea cliffs. The methods used to produce the maps required by REN law, with modifications and improvements to the law specified methods, were applied to the 71 km<sup>2</sup> territory of Almada County, and included: 1) Slope instability mapping using the statistically based Information Value method validated with the landslide inventory using ROC curves, which provided an AAC=0.964, with the higher susceptibility zones which cover at least 80% of the landslides of the inventory to be included in REN map. The map was object of a generalization process to overcome the inconveniences of the use of a pixel based approach. 2) Natural scarp mapping including setback areas near the top, defined according to the law and setback areas near the toe defined by the application of the shadow angle calibrated with the major rockfalls which occurred in the study area; 3) Sea cliffs mapping including two levels of setback zones near the top, and one setback zone at the cliffs toe, which were based on systematic inventories of cliff failures occurred between 1947 and 2010 in a large scale regional littoral monitoring project. In the paper are described the methods used and the results obtained in this study, which correspond to the final maps of areas to include in REN. The results obtained in this study may be considered as an example of good practice of the municipal authorities in terms of solid, technical and scientifically supported regulation definitions, hazard prevention and safe and sustainable land use management.

## 1. Introduction

There is a widespread consensus in the scientific community that slope, scarp and sea cliff instability are sources of major natural hazards, and a serious constraint for the human activities in areas prone to the occurrence of these phenomena. The present day knowledge on the topic enables the application of efficient tools for susceptibility and hazard mapping, which are solid contributions for a more efficient



land use, in the prevention perspective of the effects of natural hazards, and in consequence, a contribution to sustainable planning policies definition.

In this context, the Portuguese Nacional Ecological Reserve law (REN) was created in 1983 [1] with the aim of protecting the natural resources soil and water, and also to prevent risks, namely coastal and slope instability. In spite of the ecological label, the law did not include any direct ecological (biological) components, and in spite of its various shortcomings and conceptual limitations, has proved to be a powerful instrument in land use management, preventing the indiscriminate and often inadequate use of the territory. Following a minor revision in 1990 [2], in 1998 the law suffered a major revision [3] which improved and clarified its scope and application, providing a more scientifically and technically based approach to the REN components and their corresponding mapping. In the topic of hazard prevention, the work made to improve radically the law was started with the production of a manual for hazard assessment at county scale [4] which was followed by the publication of the law with the definitions and mapping criteria and methods for the different components of REN [5], which included detailed and separate mapping procedures for slope instability, natural scarps and sea cliffs. The law also enforced municipalities to perform the mapping of the REN components according to the new rules, which is an ongoing process in Portugal, but with many local authorities placing some resistance to the adoption of the new mapping criteria.

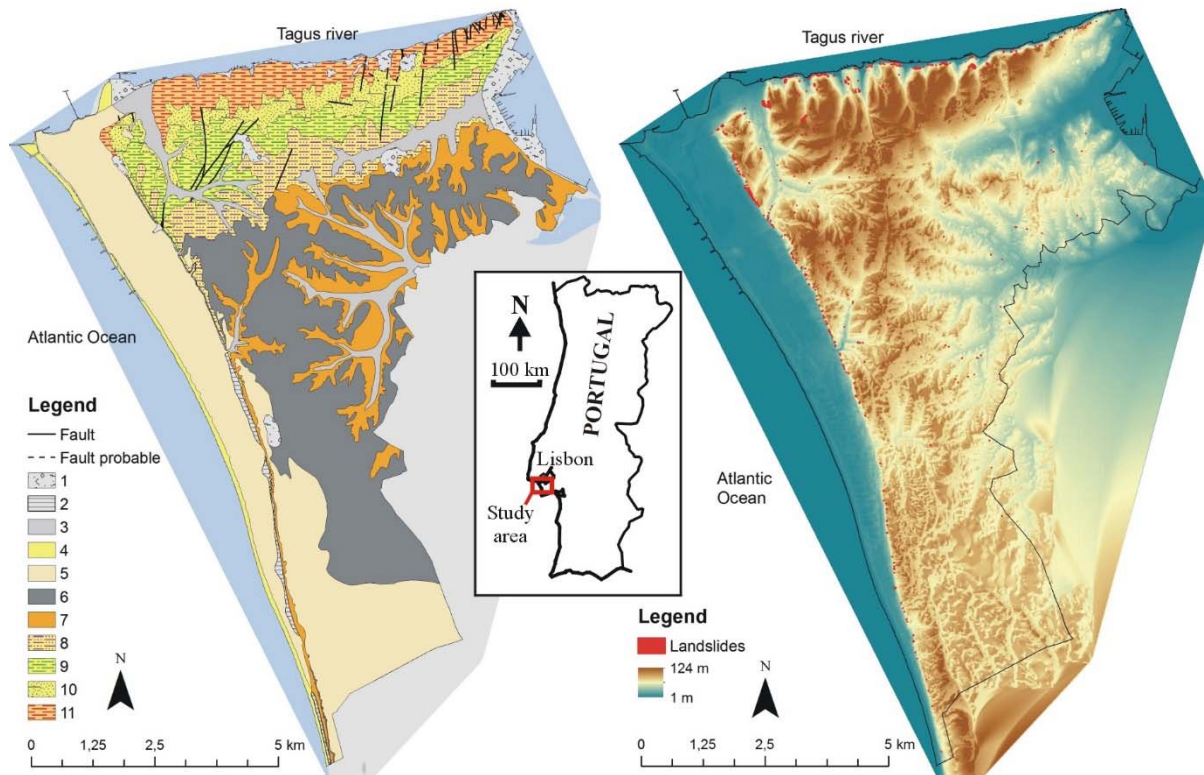
In this paper are presented the methods and results of the REN mapping for slope instability (including slope and scarp susceptibility) and sea cliff instability applied to the Almada municipality, which was carried out using the law criteria with modifications introduced to improve the coherence and usefulness of the maps produced, and also to apply scientifically based procedures to subjects not covered in the legislation.

## 2. Geological and geomorphological setting

The Almada County has a total area of circa 71 km<sup>2</sup>, and is located southwards of Lisbon, being limited at north by the Tagus river estuary, at west by the Atlantic Ocean (Figure 1), and at south and south east by Sesimbra and Seixal counties. The geological structure is dominated by the northern limb of the Albufeira syncline, which affected the Miocene formations that dip 4° to 6° to SSE. The major geological formations in the study area are, from the oldest to the more recent (Figure 1): a) 6 Burdigalian (Miocene) units mainly composed by fine silty sands (local designation, M<sub>II</sub>), weak limestones (M<sub>III</sub>), clays (M<sub>IVa</sub>), sands (M<sub>IVb</sub>), weak limestones (M<sub>Va1</sub>), and sands (M<sub>Va2</sub>); b) 2 Langhian (Miocene) units mainly composed by weak limestones (M<sub>Va3</sub>) and sands and weak limestones (M<sub>Vb+c</sub>); c) 2 Serravallian (Miocene) units mainly composed by clays (M<sub>VIa</sub>), and sands and weak limestones (M<sub>VIb+c</sub>); d) 1 Tortonian (Miocene) unit mainly composed by fine silty sands (M<sub>VIIa+b</sub>); e) Pliocene silty sands; f) Pleistocene gravel, sands and clays; g) Holocene formations including sand dunes, beach sands, slope toe deposits, alluvium, and landfills [6, 7].

The main morphological features are (Figure 1): a) The Tagus left margin steep slopes, with maximum elevation exceeding 120 m, which are composed by successions of scarps cut in the weak limestone units, separated by gentler slopes that correspond mainly to the outcrop of the weaker clayey and sandy units. These slopes are deeply incised by short creeks with steep bed and flanks. b) The old WSW facing sea cliff with maximum height exceeding 80 m, which corresponds to the protected area "Arriba Fóssil da Costa da Caparica". The cliff is separated from the ocean by an accumulation lowland plain mainly composed by dunes and dune sands, with maximum width of circa 1.5 km at the northern end, which suffers progressive reduction southwards, being reduced to a wide beach at the southern end of the county littoral.

The steeper areas of the council are affected by a large number of landslides (Figure 1) of different types, predominantly shallow slides and rockfalls, which have a significant impact on human activities and are a serious land use constrain, mainly because there is old, traditional occupation with buildings, industrial and harbour facilities along the Tagus river margin, mostly at the toe of steep and unstable slopes, scarps and cliffs. Near the toe and also cutting the old sea cliff there are also buildings and other infrastructures in slope instability hazard zones which is also a subject of concern to local authorities.



**Figure 1.** Localization of the Almada County (small inset). **Left:** Simplified geological map of Almada County: 1- Landfills; 2- Slope deposits; 3- Alluvium; 4- Beach sands; 5- Dunes and dune sands; 6- Pleistocene gravel, sands and clays; 7- Pliocene silty sands; 8- Tortonian (Miocene) fine silty sands; 9- Serravallian (Miocene) clays, sands and weak limestones; 10- Langhian (Miocene) weak limestones and sands; 11- Burdigalian (Miocene) fine silty sands, clays and weak limestones [6, 7]. **Right:** Landslide inventory (red dots, with area enlarged for visualization) over DTM with county limits (black line)

### 3. Landslide susceptibility assessment and mapping

According to the Portuguese law [4, 5] the slope instability assessment and mapping should be performed using the bivariate statistically based Information Value (IV) method [8], using a purpose made inventory of past landslides, a set of landslide predisposing factors, and using a 5m pixel terrain unit basis. The IV is a simple yet effective method for landslide susceptibility mapping (e.g. [9, 10]), and also for sea cliff instability susceptibility [11, 12]. In this method each factor is divided in classes, which correspond to variables. The information value  $I_i$  of each variable  $X_i$  is [8]:

$$I_i = \log\left[\frac{(S_i / N_i)}{(S / N)}\right] \quad (1)$$

where  $S_i$  is the number of pixels with landslides in the pixels with the variable  $X_i$ ,  $N_i$  is the number of pixels with the variable  $X_i$ ,  $S$  is the total number of pixels with landslides, and  $N$  is the total number of pixels in the study area. The positives values of  $I_i$  indicate that the variable is correlated with the occurrence of landslides, the negative ones indicate that the variable produces low susceptibility. The near zero values indicate that the variable is not significant in terms of susceptibility ranking. The total information value  $I_j$  for a given pixel  $j$  is:

$$I_j = \sum_{i=1}^m X_{ji} \cdot I_i \quad (2)$$

where  $m$  is the number of variables,  $X_{ji}$  is 0 if the variable (landslide) is absent in the pixel  $j$ , or 1 if the variable is present. This statistical method enables an objective assessment of the susceptibility, based only on the spatial distribution of the predisposing factors classes (variables) and on the presence or absence of landslides in each pixel. The main limitation of the IV method is due to its bi-variate character, i.e., it does not take into account correlations that may exist between variables.

### 3.1. Landslides inventory

Due to the difficult access to a larger part of the more landslide prone areas, which are private properties or have very dangerous terrain conditions, the landslides inventory compiled in this study was acquired using different methods and sources of information, including: a) Comparison of digital photogrammetry processing of aerial photos of 1942 (1:17,000 scale) and 2010 (digital, field size pixel of 0.3 m) for the county northern slopes, scarps and cliffs; b) 2011 aerial photos interpretation covering the whole study area provided by the Almada municipality services; c) Interpretation of internet based aerial imagery (Google Earth, Bing Maps); d) interpretation of terrestrial long range photos e) Field surveys for validation of the photo based data and identification and characterization of other slope instability occurrences not detected in photo interpretation. Bearing in mind the practical impossibility to have access to all the area, were identified and mapped 458 slope mass movements which affected a total area of  $65,6 \times 10^3 \text{ m}^2$ , i.e. circa 0.1% of the county total area (Table 1, Figure 1).

**Table 1.** Summary of the landslides inventory of Almada County.

<u>Landslides types</u>	Number	Number (%)	Area (m <sup>2</sup> )	Area (%)
Rockfall or Toppling	33	7.2	1,591	2.4
Deep seated rotational slide (?) <sup>a</sup>	5	1.1	6,999	10.7
Shallow rotational slide (?) <sup>a</sup>	15	3.3	1,610	2.5
Shallow rotational slide	24	5.2	7,841	12.0
Shallow translational slide (?) <sup>a</sup>	85	18.6	21,600	32.9
Shallow translational slide	296	64.6	25,944	39.6
Total	458	100.0	65,585	100.0

<sup>a</sup> Type of landslide not possible to ascertain

Considering that there was a significant number of landslides which could not be classified beyond any reasonable doubt, and also that most of them occurred in the northern slopes of the county and along the old sea cliff, the susceptibility assessment was made considering all movements in the inventory.

### 3.2. Landslides predisposing factors

The predisposing factors used to assess and map the landslide susceptibility, in combination with the landslide inventory, were selected according to law suggestions but also on the availability of information at a scale compatible with the objective of this study. The predisposing factor used were:

a) Geological units. Were considered the geological units present in the geological map of Almada, provided by the municipality [6, 7] and referred in the geological setting, with the exception of the beach sands and dunes which were grouped into one single unit, due to the very close lithology and also because no landslides were recorded in these units.

b) Geomorphological units. Were considered the geomorphological units of the provided by the Almada municipality, with modifications, mainly on the mapping of the hydrographic basin separation lines, being only retained the divides of major basins. In this map were considered the following units: old (Costa da Caparica) sea cliff and related slopes; northern cliffs and related slopes; hill tops; slope deposits; beaches and dunes; slopes; areas along creeks.

c) Land use map. This map was adapted from the map provided by the municipality and includes the following units: agricultural areas; dunes and beaches; tree vegetation areas; roads; compact urban area; disperse urban area.

d) The other maps which contain morphometric based information were derived by processing of a detailed (1:1,000 scale) and recent (2011) digital topographic map with contour lines separated by 0.5m, also provided by the municipality. The derived maps included slope angle, classified in the following classes with slope limits in degrees: 0-2.5; 2.5-5; 5-10; 10-15; 15-20; 20-25; 25-30; 30-90. In the slope exposure map were considered the classes which are current in this type of studies: Plan; N; NE; E; SE; S; SW; W; NW. Were also considered the plan and profile curvatures of the slopes, considering the following quantile based classes for both factors: very concave; moderately concave; slightly concave; rectilinear; slightly convex; moderately convex; very convex. The Topographic Wetness Index was computed according the expression  $TWI = \ln(a/tg\beta)$ , in which  $a$  is the local upslope area draining through a certain point and  $\beta$  is the slope angle [13], and were considered the following quantile based classes: 0-3; 3-5; 5-7; 7-9; 9-11; 11-13; >13.

### 3.3. Landslides susceptibility results and discussion

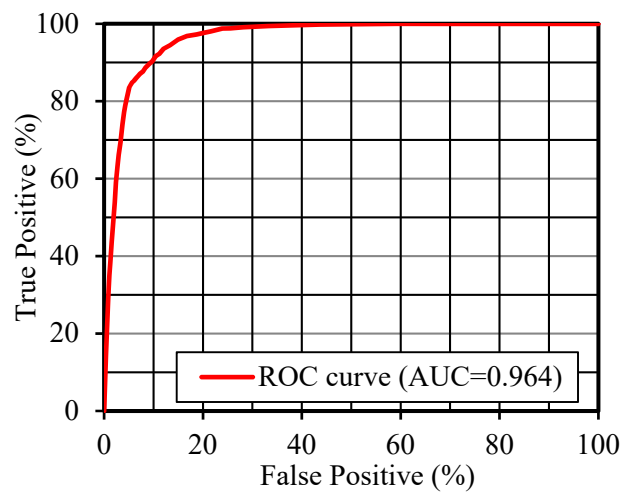
The landslide susceptibility assessment was made using the IV method, which provided the indication that the variables with the higher predisposing scores were slope angles above 25° (25°-30° and >30°), the Miocene (Burdigalian) geological units mainly composed of clays ( $M_{Iva}$ , rotational and translational slides), and of weak limestones ( $M_{Val}$ , rockfalls and topples), the geomorphological units "old (Costa da Caparica) sea cliff and related slopes" and "northern cliffs and related slopes", the very convex and very concave plan curvatures and TWI between 0 and 3.

The efficiency of the model was assessed using standard success rate ROC curves (Figure 2) which provided a value for the area under the curve,  $AUC=0.964$ . This value is uncommonly high even considering that is a success rate and not a prediction rate, and partially attributed to the quality of model produced, which was based in a robust landslide inventory, but also to fact there are large areas in the county with very low slope angles and in consequence, very low susceptibility to landslides.

### 3.4. Slope instability areas to include in the REN

The observation of the ROC curve shows a slope break around 83% of the total unstable area, which corresponds to 5.2% of the county area. The Portuguese law [4, 5] indicates that the areas to include in the REN maps and thus object of severe land use restrictions, should at least include 70% of the total unstable areas. However, in the study area, the good results of the model and the detailed analysis of the resulting maps indicated that considering a limit of 80% of the total unstable areas, the cartographic results were much more coherent and continuous, implying only an increase from 3.4% to 4.6% of the county area, i.e., an increase of the area to include in REN of 1.2% of the county area, which corresponds to 842,000 m<sup>2</sup>. These considerations lead to proposal of including in the REN the areas containing 80% of the total unstable zones.

However, the map results have pixelated limits which are difficult to manage in the field, that do not adjust properly to the slope limits and that leaves small isolated areas classified as non-susceptible surrounded by landslide susceptible areas. To overcome these problems a generalization procedure was applied which included: creation of a point file with the final IV score; generation of contour lines with the limit IV value of the areas containing 80% of the total unstable zones; smoothing of the curves with a curvature radius of 15m to avoid saw tooth like limits; manual verification of results and elimination of isolated polygons with less than 400 m<sup>2</sup> or with mean width lower than 15 m, which were considered as conservative values for lower limits of usable area for constructions. Also according the law, all unstable areas, surrounded by an outer 10 m buffer area were also included in the final REN map (Figure 3).



**Figure 2.** Success rate ROC curve for the IV landslide susceptibility assessment

#### 4. Scarps and related setback areas mapping

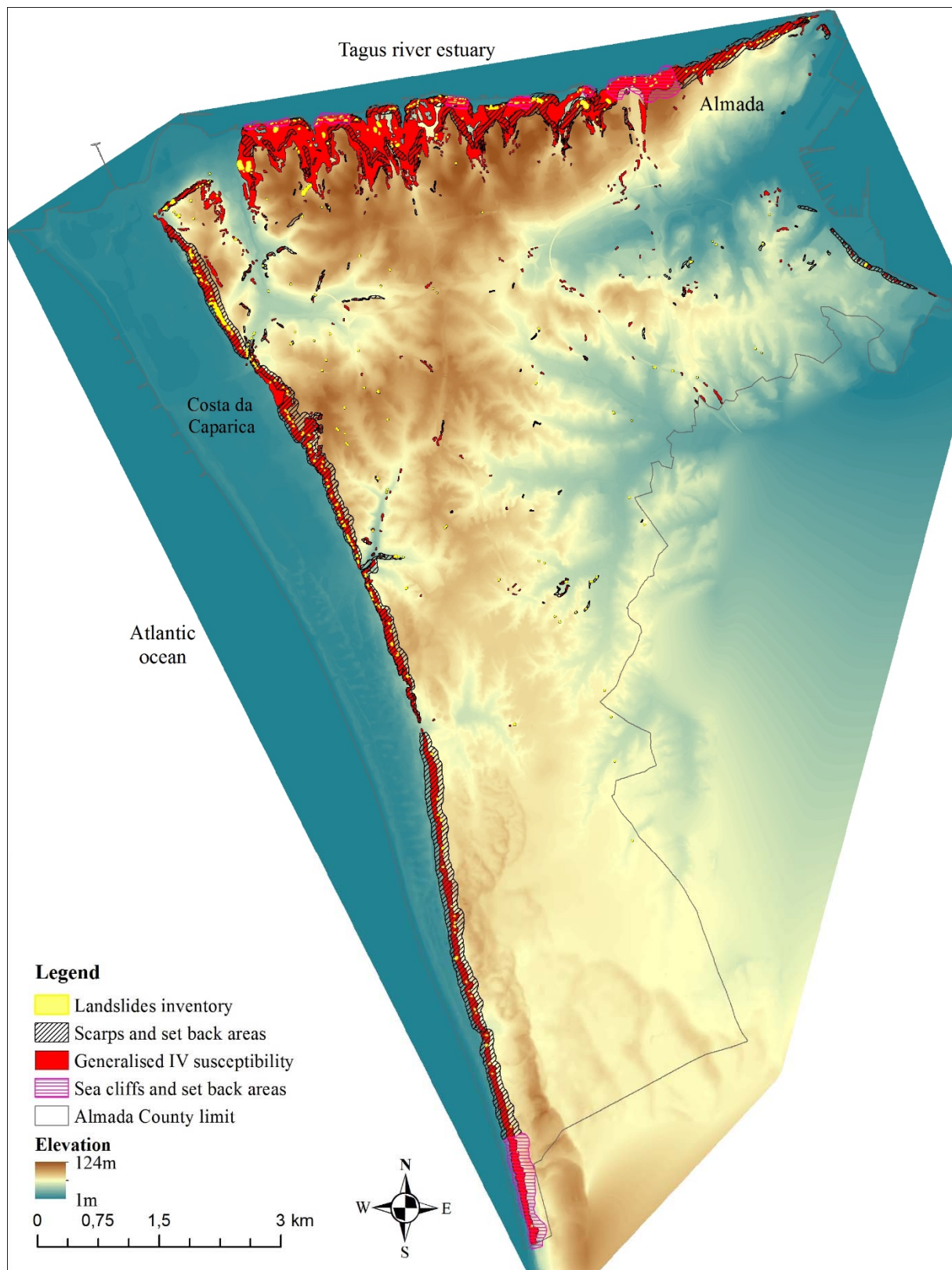
The Portuguese law [4, 5] indicates that slopes with slope angle higher than  $45^\circ$  should be included in the REN, and also setback areas along scarp top and toe, with a minimum width equal to the scarp height. Considering the very detailed 1:1,000 scale topographic map provided for the study, the scarps were mapped using a 2m pixel sized DTM instead of the 5m pixel sized DTM suggested in the law, to enable a more accurate detection and mapping of these morphological features. Considering the lack of information on the effects of the occupation located near the scarps top, for this setback area was adopted the law indications, i.e., a width of the setback area along the top of the scarps equal to the scarp height.

Considering the geological and geomorphological conditions of the Almada County scarps, mainly composed by weak rocks and with their toe frequently limited by steep slopes, the law indications for the setback area definition along the toe of the scarps equal to the scarp height would provide inaccurate results. As an alternative method, were selected the major rockfalls which occurred in the study area and with well-preserved debris deposits, and assessed the scarp height and the horizontal runout distance of the debris measured from the scarp top, to enable the calibration of a rockfall shadow angle adequate for the study area conditions. The analysis of these rockfalls (Figure 4) indicated that a shadow angle of  $34^\circ$  would provide a reasonably safe width for the setback area.

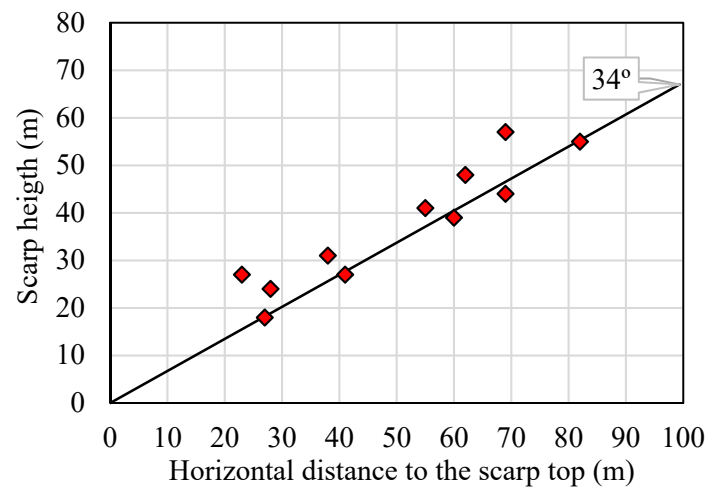
The  $34^\circ$  shadow angle was then applied to all scarps in the study area using the Conefall software [14]. The quality of the results was verified in a rockfall occurred in 6 December 2014, which affected two lanes of a very important highway in the county (national road IC20, near Costa da Caparica, Figure 3). In this case, the defined setback area along the toe made a very accurate prevision of the debris and rock blocks run out over the road pavement, without overestimating it, which is a good indication of its reliability for hazard prevention.

#### 5. Sea cliffs and related setback areas mapping

In Almada County active sea cliffs occur in two distinct geographical and geological contexts: one in the extreme southwest of the county, exposed to the Atlantic marine actions, and another on the northern limit of the county, acted by the Tagus River estuarine actions. The former are proper marine sea cliffs and their mapping and setback areas was made during a major coastal monitoring project developed for the Portuguese Environment Agency (Agência Portuguesa do Ambiente, I.P.), [15] and were included in the new Coastal Programs (POC) in conclusion, following the previous experience of sea cliff setback areas definition for the first generation coastal plans (POOC) produced between 1998 and 2002 [16]. The sea cliffs were mapped using a 2 m pixel sized DTM and 1:2,000 scale digital topographic maps.



**Figure 3.** Landslides inventory (area enlarged for visualization), scarps and related setback areas, IV landslide susceptibility generalised, sea cliffs and corresponding setback areas over Almada DTM



**Figure 4.** Rockfall run out horizontal distance measured from the scarp top versus scarp height, with the selected shadow angle of  $34^\circ$

Near the cliffs which have continuous or periodical marine action at the toe, were defined two setback areas located landwards of the cliff top with width equal to the cliff height with a minimum value of 20m, with the seawards one with very strict land use restrictions, and a setback area width equal to the cliff height near the cliff toe.

The width of these setback areas was defined by analysis of systematic inventories of cliff failures occurred between 1947 and 2010 [15] and are mandatory criteria to be applied to all involved municipalities. In the cliff sections which are no longer acted by the sea, but are in spatial continuity with active sea cliffs, is only considered one setback area near the top of the cliff, with width also equal to the cliff height with a minimum value of 20 m and a setback area near the toe also equal to the cliff height.

In the cliffs located in the north limit of the county, the situation in terms of legal figures is not clear. These are scarps which toe is acted permanently, periodically or episodically by the Tagus river waters, which are classified in the law as transition waters. In this context, and considering that toe erosion is effective, but should not have the intensity of the direct marine action, and also because the cliffs are in spatial continuity with scarps with similar lithological composition, the criteria for the definition of the setback areas adjacent to the crest and the toe were those adopted for the scarps. The near the cliffs top setback areas were mapped considering its width equal to the height of the adjacent cliff. The analysis of the cliff top retreats recorded in the period between 1947 and 2010 shows that they were always less than half the width of the setback areas, so that the criterion complies simultaneously with the law and ensures spatial continuity of these areas along the adjacent scarps, contributing to the spatial coherence of the cartographic results produced.

For the toe setback areas mapping was also used the shadow angle of  $34^\circ$  defined for the adjacent scarps, which also ensures a spatial coherence of the cartographic results produced, but also an effective way to prevent hazards from cliff and scarp falls.

## 6. Discussion and conclusions

The results of this study are a very clear advance in relation to the crude previous mapping procedures which were used in municipal planning according the old 1983 and 1990 REN laws. In fact, the methods used in this study are far from being the most sophisticated or up to date in the scientific literature. However, it was obtained a very high ROC curve AUC for the success rate of the IV landslide susceptibility assessment, which is in part due to the large areas with negligible landslide susceptibility, but is also due to the comprehensive landslide inventory produced and also the quality of the base maps used in the study. In the course of the landslide susceptibility work, the more robust multi-variate logistic

regression method was applied to the same landslide inventory and predisposing factors, but the results obtained were only very slightly better in terms of AUC and spatial distribution coherence, not providing enough justification for its use instead of the methods indicated by the law. These results suggest also that the improvement of landslide susceptibility assessment and mapping relies more on the quality of the database used, such as improved geological mapping [17] than on the sophistication of the susceptibility models used.

The shadow angle approach, calibrated with past rockfall events in the study area, used for the definition of the setback areas along the scarps proved to be effective in the forecast of a major rockfall event run out which affected the IC20 highway in 2014, an event which could have produced very serious damages and loss of lives.

In spite of some limitations and some simplified approaches, which are mainly due to lack of appropriate databases or availability of feasible study methods, the maps produced in this study ensure an effective basis for the prevention of the hazards related with slope, scarp and sea cliff instability phenomena, and certainly a fundamental piece of information and a clear example of good practice in municipal planning. The results of this study and the maps of the areas to be included in the REN are in course of approval for inclusion in the new municipal plan, in construction.

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