Landslide susceptibility assessment in rocky coast subsystem of Essaouira coastal area – Morocco

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Abstract

During the last few decades, many researchers have produced landslide susceptibility maps using different techniques and models including the information value method, which is a statistical model widely applied to various coastal environments. This study aims to evaluate the susceptibility for the occurrence of landslides in Essaouira coastal area using the bivariate statistical method. In this coastal area, 588 landslides of distinct types were identified, inventoried and mapped. They mostly result from the observation and interpretation of different data sources, namely high-resolution satellite images, aerial photographs, topographic maps, and extensive field surveys. The rocky coastal system of Essaouira is located in the middle part of Morocco Atlantic coastal area. The study area was split into 1534 cliff terrain units of 50 m width. For training and validation purposes the landslide inventory was divided into two independent groups: 70% for training and 30% for validating. Twenty-two layers of landslide-conditioning factors were prepared, including: elevation, slope angle, slope aspect, plan curvature, profile curvature, cliff height, topographic wetness index, topographic position index, slope over area ratio, solar radiation, presence of faulting, lithological units, toe lithology, presence and type of cliff toe protection, layer tilt, rainfall, streams, land-use patterns, the normalized difference vegetation index (NDVI), lithological material grain size, and presence of springs. The statistical relationship between the conditioning factors and the different types of landslides were calculated using the bivariate information value method, in a pixel and in elementary terrain units base model. Validation of the coastal landside susceptibility maps was done using the landslide training group partitions. The receiver operating characteristic curve (ROC curve) and Area under the Curve were used to assess the accuracy and prediction capacity of the different coastal landslide susceptibility models. Two methodologies, considering a pixel-based approach or using coastal terrain units, were adopted to evaluate the coastal landslide susceptibility.. The resulted coastal landslide susceptibility maps allowed classifying 38 % of the rocky coast subsystem with high susceptibility to landslides, mostly located in the southern part of the Essaouira coastal area. These susceptibility maps would be useful for general planned development activities in the future as well as for environmental protection.

Keywords: Coastal landslide susceptibility mapping, coastal landslide inventory, conditioning factors, Information Value, Essaouira coastal area, Morocco

1. Introduction

Landslides are common processes in the rocky coastal system of Essaouira province. Resulted essentially from the interaction of sub-aerial, marine and anthropogenic processes (Trenhaile 1987, Sunamura 1992, Hampton & Griggs 2004, Greenwood & Orford, 2007), that is why this system have been exposed to Anthropic activities pressure and erosional processes more than any other natural systems. In consequence, the fast dynamic evolution imposes restrictions on the way the human occupy coastal areas (Teixeira 2006; Marques 2009; Teixeira 2015; Moore and Davis 2015; Gilham *et al.* 2018)

The processes of building landslide susceptibility maps generally involve several qualitative or quantitative approaches, the last data-driven or physically-based supported and dependent of a landslide inventory for training or validating (e.g., Aleotti & Chowdury 1999, Dai & Lee 2002, Van Westen *et al.* 2008, Corominas *et al.* 2014; Oliveira *et al.*, 2017 and Meena *et al.* 2018). For rocky coastal areas, landslide susceptibility/hazard assessment mainly addresses the evaluation of the cliff retreat (Oliveira *et al.* , 2008; Rocha *et al.* , 2007; Oliveira *et al.* , 2017), landslide inventorying or susceptibility mapping (e.g., Marques *et al. 2011*).

The identification of factors, controling the rocky coast system is a critical step to well understand how this system is evolving and predict its future evolution (Neves & Ramos Pereira 1999). Landslides are responsible for significant erosion in rocky coastal systems (Andriani & Walsh 2007; Violante 2009 and Sunamura 2015). Therefore, by knowing the set of predisposing factors that conditioned the landslide occurrence, it is possible to spatially predict where future landslides will occur (Varnes, 1984). There are many different landslide-conditioning factors, with an important role in the preparation of the landslide susceptibility maps (e.g. Zêzere 2002). These factors, although they depend on the scale of analysis and type of landslides, include generally: elevation, slope, aspect, plan and profile curvature, topographic wetness factor index (TWI), topographic position index (TPI), slope over area ratio (SOAR), solar radiation, faulting, lithology, lithological layers tilt, precipitation, streams, land-use patterns, NDVI or vegetation density factor, grain size, and spring presence. (e.g. Van Westen *et al.* 2008, Reichenbach *et al.* 2018, Pereira *et al.* 2020) and when specifically related with sea cliffs susceptibility assessment include also the cliff edge height, coastal slope toe protection (e.g. Marques *et al.*, 2011, 2013; Marques 2018; Guilham *et al.* 2018; Letortu *et al.* 2019; Queiroz and Marques 2019).). In the present work, we follow the classification of Cruden and Varnes (1996) Varnes (1978); WP/WLI's (1993); and Dikau *et al.* (1996), for differentiate the types of landslides that may occur in coastal cliffs: falls, slides, topples, lateral spreads and flows. The identification of each landslide type is a complex task even with the support of intensive fieldwork because of the lack of clear field evidences due to landslide features degradation and due to the inaccessibility, for some cases, of cliff face (Neves *et al.* 2012). The use of different datasets of aerial photographs has been used to encompass these limitations (Oliveira *et al.* 2017). Many bivariate and multivariate statistical models are used to analyze the landslide susceptibility and the majority of these models require a subdivision of territory in terrain units and the selection of the appropriate type of terrain mapping units (e.g. grid cells, slope units, geo-hydrological units, unique condition units, administrative units (Van Den Eeckhaut *et al.* 2009, Marques *et al.*, 2011, 2013, Epifânio 2014, Corominas *et al.* 2014, Zêzere *et al.* 2017).

Data-driven approaches are the most used for landslide susceptibility and hazard zonation (Kanungo *et al.* 2006, Girma *et al.* 2015, Hamza and Raghuvanshi 2017, Mengistu *et al.* 2019, Shano *et* al. 2020) while there are other suitable approaches such as the bivariate, multivariate, and active learning statistical methods suitable to assess susceptibility (Corominas *et al.* 2014). The bivariate statistical methods are based on an inductive logic, which assumed that the combination of conditions pertaining to various conditioning factors, analyzed separately, may possibly lead to landslide prediction in a given area. The evaluation of the conditioning factors and their relationship with the past landslides in the study area, form the basis for the prediction of places where landslides may occur in future (Varnes *et al.*, 1984, Van Westen *et al.* 1997, Dai *et al.* 2002, Lan *et al.* 2004, Girma *et al.* 2015, Chimidi *et al.* 2017, Shano *et al.* 2020).

The information value (IV) method (Yin and Yan 1988), is considered as an appropriate method to evaluate landslide susceptibility (Corominas *et al.* 2014), it has been widely used worldwide in different geomorphological backgrounds (Yin and Yan, 1988; Jade and Sarkar, 1993; Lin and Tung, 2003; Yalcin, 2008; Balasubramani and Kumaraswamy, 2013; Zezere *et al.*, 2017; Mengistu *et al.*, 2019). The IV model is based on the weighted presence or absence of drivers of slope instability. Thus, landslide density for conditioning factor classes can be determined by overlaying the conditioning factors map on the inventoried landslide map (Mengistu *et al.* 2019, Shano *et al.* 2020), if the resulted information value is positive the causative factor class represents strong interdependence with the landslides in the area (Yin and Yan 1988, Shano *et al.* 2020), and the weighted value of a conditioning factor class can be represented as the natural logarithm of density of landslide in a factor class, divided by landslide density in the total map area (Van Westen *et al.* , 1997, Shano *et al.* , 2020).

The validation of the landslide susceptibility map is an essential step for the evaluation of the model predictive capacity. It can be understood as a test on the ability of the model to reflect the real environment, as an evaluation of its accuracy and predictive capacity (Beguería 2006, Frattini *et al.* 2010, Shano *et al.* 2020, Mateus *et al.* 2021).

However, receiver operator characteristic (ROC) is one of the most popular technique used in statistical approaches validations, to check the performance of the prediction ability of the bivariate methods (Shano *et al.* 2020). It represents a plot of the probability with correctly identified landslides, against the probability of incorrectly identified landslides (Gorsevski *et al.* 2006a, Shano *et al.* 2020).

The dynamics of Essaouira coastal area is poorly studied. A beach granulometric technical study was carried out in the Essaouira bay in 1955 by the hydraulic laboratory of Neyrpic (El Mimouni A. and Daoudi L. 2012). Other studies focus on the general morphology of the sandy dunes in the upper part of the beach and on the mainland (Gentile, 1997, Simon, 2000 and Lharti *et al.* 2006)

The main objectives of this work are: i) to define the type and emplacement of each landslide by an inventory validated by field survey; ii) to identify the most important predisposing variables that control the spatial distribution of different landslide types; iii) to set and weight the different conditioning factors applying the information value statistical method; iv) to assess landslide susceptibility in Essaouira coastal cliffs for different types of landslides and to classify susceptible areas to the occurrence of landslides, and, finally, v) to validate the susceptibility map.

2. Study Area

The Essaouira coastal area is located along the middle section of Atlantic coast of Morocco (Fig. 1), which extends over 134 km. It has high coastal systems diversity including estuaries, bays, beaches, sandy spits, cliffs and rock shore platforms (Weisrock, 1980; Simon, 2000; Lharti *et al.*, 2006), where we adopted a classification based on tree subsystems; sandy coast, rocky coast and anthropic coast. The study site (Fig. 1) is characterized by stretches of sandy coast (48%), rocky coast (51%) and anthropic coast (1%, the Essaouira port), delimited on the north by the Tensift estuary, in the south by Timzguida Ouftas village, in the east by Essaouira province municipalities and in the west by the Atlantic Ocean and the island of Mogador in front of Essaouira City (Fig. 1). This coastal area has predominantly a semi-natural landscape which is locally interrupted by heavily anthropized coastal areas especially at the city of Essaouira (Fig. 1).

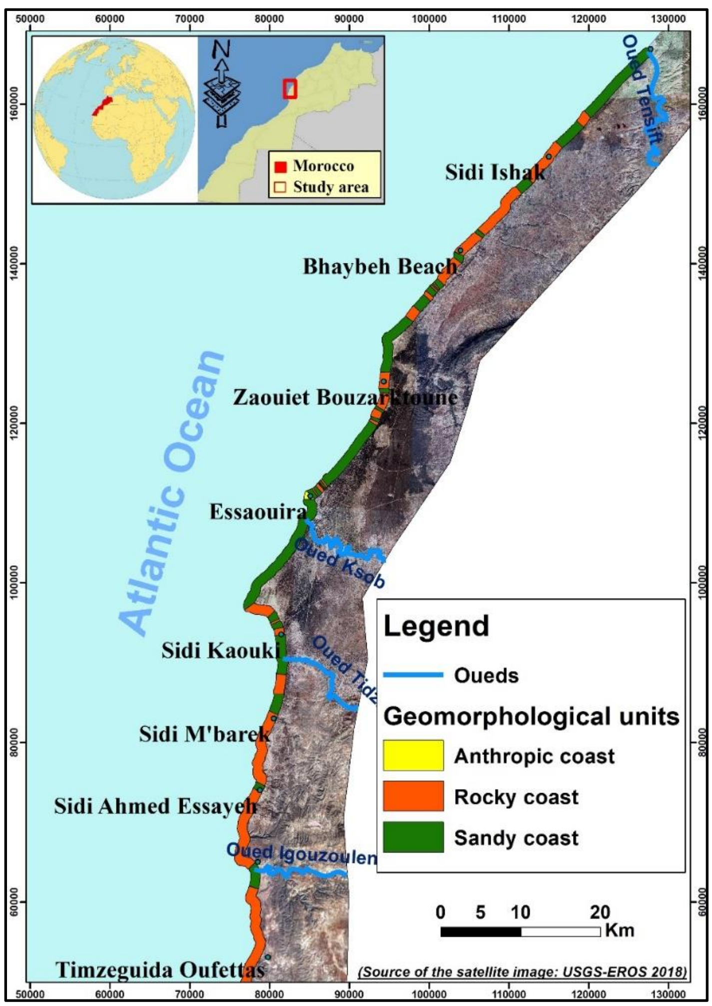

Figure 1: Geographic location of Essaouira coastal area and its sandy and rocky coast subsystems

Geologically, the study area is located in the Atlantic Atlas which is considered the westernmost part of the High Atlas mountains (Weisrock 1980), whose northern part, the largest (Haha and Chiadma) plateau, drop gently from SE to NW, in accordance with the overall structural framework. The landscape is however varied, crossed by cuestas and vigorous crests, turned towards the SE, and related with the frequent alternations of sandstone, dolomitic, limestone, or marl, clay and gypsum layers. The landscape is interrupted by sudden isolated anticlinal folds, as the Jbel Hadid (725 m), quite to the N, or the Jbel Ouamsitten (900 m) to the S. Towards to west, gain relevance the abundance of consolidated dunes and sandstones with oblique stratification and conglomeratic levels (Weisrock 1980).

To the south, a coastal basin with original sedimentary material known as "Haha Basin" (Dufaud *et al.* 1966), is related to the opening of the North Atlantic, which is generally consistent with the end of the Triassic (Choubert *et al*., 1971; Hallam, 1971; Le Pichón, 1971, Weisrock 1980). It consists mainly by sandstones, pelites, conglomerates, and red salt clays, with essentially continental facies. from the Lower Liassic to Upper Cretaceous succeed deep marine sedimentations. During these long periods, the sedimentation of the coastal basin has constantly oscillated between an epicontinental regime, with terrigenous deltaic or alluvial contributions and marine organogenic or evaporitic deposits, and a more openly marine regime with neritic limestones and marls. Towards the north, the coastal platform is largely developed, also called "Moghrebian platform", from the name attributed to the sandy and sandstone deposits that cover it (Choubert and Ambrogi, 1953, Weisrock 1980), and thus tapers off at the southern mountainous part.

From a structural point of view, the study area is characterized by a double structural division marked by a close adaptation with the hydrographic network (Weisrock 1980); i) the first one is the one linked to the opening of the Atlantic, includes the extensional faults fundamentally oriented NNE-SSW, this for the whole Atlantic Atlas and its northern edge. This second direction may have the same origin as the first; these Hercynian breaks in the basement influenced sedimentation and then reappeared, affecting the cover, during the Atlasic phases (Saadi, 1972). ii) the second direction, WNW-ESE, related to the opening of the Atlantic, is more and more evident (Wadi Ksob, northern fallout anticlines, Wadi Tensift). This direction is attenuated towards the S, while in the central region (Tamanar plateau) a W-E direction appears as a result of the ancient Hercynian direction (Saadi, 1972). In addition to these two fundamental systems, the Essaouira region, and because of the thickness of the saliferous clay layer, is marked by the development of a diapiric style tectonics, well represented especially in the SE of Essaouira (Weisrock 1980).

From a geomorphological point of view, landform distribution in the study area is asymmetrical: all the plateaus dominate to the N and NW sectors, and are almost absent to the S and SE, occupied by the mountain; in accordance with the general layout of the High Atlas, the altitudes rise towards the south and east. The morphogenesis of the Atlantic Atlas thus depends on general physical geography, in addition to the structural morphology of the folded chains, the phenomena of encrustation, coastal eolian constructions and glaciation (Weisrock 1980). The Atlantic Atlas is open to oceanic influence. This area is particularly characterized by its dual character as a mountainous and coastal region, which makes it possible to link continental and marine morphology, the latter offering the advantage of being able to establish a solid chronological base from the Pliocene onwards by comprising a whole series of stepped fossil beaches. The coastal part takes on a uniform appearance from north to south. On average, the Mesozoic bedrock disappears under a sandy cover shaped into innumerable encrusted hills all along the ocean (Weisrock 1980).

From a hydrological point of view, we note the presence of two large watersheds, Oued Tensift and Oued Ksob, to which are added coastal wadis: Oued Tidzi and Oued Igouzoullen. These hydrographic networks present an important source of sediment supply, they are characterized by a flow which is carried out very roughly from E to W, rather faithfully adapted to the topographic framework; however, the courses of the valleys, more often monoclinal or orthoclinal than cataclinal, reveal a long evolution and successive re-adaptations (Weisrock 1980).

The Essaouira cliffed coastal sector is characterized by the presence of many types of landslides, which are being the dominant hazards responsible for the constraint of human activities and a safe land use (e.g., Moore and Griggs, 2002). The seismic context shows that the coast between Safi and Essaouira have landslide activity probably related to the seismic events (Elmrabet *et al.* 1989). The most significant of which, capable of causing disproportionate effects on a highly unstable cliff occurred in 1757, 7th March 1930 (32° N, 11.5° W, M = 5.1, felt in Casablanca, Safi and Essaouira, intensity IV) and 2nd August 1963 (34.7° N, 8.9° W, M = 4.1, felt in Casablanca and Mohammedia, intensity IV). In the 1757 event, the landslide could also have been conditioned by an aftershock of the earthquake on 1st November 1755 affecting the cliff natural instability, which had been enhanced by the effects of the tidal wave (Elmrabet *et al.* 1989).

Climatically, the Atlantic Atlas is located in a relatively low latitude (around 31° parallel), which places it under the predominant influence of subtropical anticyclonic cells, at the limit of the great displacements of polar air masses. It is a position sensitive to the slightest deviations of these centers of action, and thus particularly interesting to reconstitute the possible conditions of the past climatic oscillations, identified by their morphogenetic marks (Weisrock 1980).

The Essaouira province characterized by a steppe climate of type BSh according to the Köppen-Geiger classification, whit low rainfall, the average annual temperature in Essaouira city is 18.7 °C and the average annual rainfall reaches 295 mm (Climate-data.org). The dominant climate in the Essaouira region is semi-arid, with a diversity of both temperature and precipitation values. This is due to the oceanic (Atlantic) setting on one side and to the height of the mountains on the other. The Essaouira region is an area where hot summer winds and humid winter winds change. The "Chergui" (the hot wind from the Sahara) and the northeast wind that blows almost all year round. It characterized by a mild climate all year round. The average temperatures are 16.4 ºC in January and 22.5 ºC in August. As for the annual rainfall, it is around 280 mm. Two main seasons can be distinguished: i) a wet season that includes winter and autumn, with a monthly maximum fluctuating between December and November. Precipitation peaks are clearly marked in autumn and winter, before gradually decreasing from February to May; ii) a dry season from April to September. This season is marked by scarce rainfall. July and August are the driest months throughout the year with almost no rainfall. About the spatial distribution, both the precipitation and the humidity are higher in the coastal zone, for this last it is always higher than 75 %. Summer fog is particularly important at Essaouira, and other sites exposed to maritime influences (Hander, 1988).

Using the rainfall data from stations of Adamna, Chichaoua, Talmest, Abadla and Igrounzar, which were provided to us by the Tensift Water Basin Agency, we analyzed the average monthly variability of rainfall for the period 1965-2015, and main results shows the existence of a rainy season between October and April with a maximum in March for the two stations Abadla and Chichaoua and a maximum in December and November for the stations Talmest, Igrounzar and Adamna. The dry season extends between June and September where the lowest rainfall is recorded in July and August. The monthly variation in rainfall shows an average of 15.3 mm for Chichaoua and 14.4 mm for Abadla. The rainfall is similar over the same period for Chichaoua and Abadla. The values observed in the months of October to April exceed the average rainfall for each of these two stations with a maximum in March (27 mm) and a minimum in July (0.5 mm) and August (1 mm). Thus, the evolution of monthly precipitation is the same for these two stations. It argues in favor of a simple hydrological regime characterized by a regular annual alternation of high and low water. The monthly rainfall of the three stations Adamna, Talmest and Igrounzar show that the maximum rainfall is recorded in the months of November and December, while the average rainfall is about 20 mm for Igrounzar and Talmest and 26 mm for Adamna.

Regarding the annual variations of rainfall at the five stations, the first three concern the stations of Adamna, Igrounzar and Talmest have mean annual rainfall of 322 mm, 229.1 mm and 255.4 mm, respectively. At the station of Adamna, there are several rainy years with values that greatly exceed the interannual average, namely 1987/88, 1988/89, 1994/95 to 1996/97, 2008/09 to 2010/11, with a maximum rainfall of about 718 mm in 1995/96 and a minimum of about 136 mm in 2006/06. For the station of Igrounzar, the highest rainfall was observed during the years 1987/88, 1988/89, 1994/95 to 1996/97, 2008/09 and 2009/10. However, the least rainy years are: 1968/69, 1976/77, 1991/92 and 2014/15. For the Talmest station, the wettest year is 1995/96 which recorded 559.5 mm and the least rainy year is 2014/15. For this station, we do not have data for the years 1971/72 until 1975-76.

From a hydrogeological point of view, the Essaouira basin and its coastal zone constitute a set of independent but very similar hydrogeological systems that correspond to synclinal basins. Within these systems, groundwater exists only in very localized areas. The water generally circulates at depth in different limestone or sandstone levels by karstic pathways, it comes out in the form of springs at low points in contact with an impermeable clay or marl level (Cochet and Combe 1975). The combination of the effects of tectonics and diapirism have caused the compartmentalization of the basin into several aquifer systems.

The piezometry of the Plio-Quaternary aquifer, for example, shows an overall flow direction from E-SE to W-NW, conditioned by the straightening of its bedrock to the east following the uplift of the Tidzi diapir (Mennani, 2001). It presents significant fluctuations between periods of high and low water (Fekri, 1993; Mennani, 2001; Bahir *et al.*, 2002, Bahir *et al.*, 2017), These are related to precipitation which thus controls the regime of the phreatic aquifer. Several problems related to water scarcity and long recurrent periods of drought, have been noticed in the Essaouira region during the last decades (Bahir *et al.*, 2002; Chkir *et al.*, 2008; Chamchati and Bahir, 2013; Bahir *et al.*, 2017). For this reason, the piezometric level in the study area tends to a generalized decline with the inability of some other wells to recover their initial water level, aggravated under the combined effect of the year 1995, the driest year that Morocco has experienced during the 20th century (Bahir *et al.*, 2002), and overexploitation (Chkir *et al.*, 2008, Bahir et *al.*, 2017).

3. Methodology

The current research uses different data sources for landslide susceptibility analysis, and their preparation was supported by field survey and validation. The methodological steps considered for training and validation the coastal landslide susceptibility models are showed in the Fig. 2 and follow this sequence: i) elaborate the landslide inventory, classifying the landslides by type and depth of the rupture surface (shallow and deep); ii) prepare a set of 22 conditioning factors grouped in seven categories (topographical, geomorphological, lithological, geotechnical, hydrological, climatic and tectonic); iii) model coastal landslides susceptibility with the information value method for the Essaouira coastal area, using pixels and elementary terrains units (ETU); iv) and independently validate the predictive susceptibility models using ROC curves and AUC.

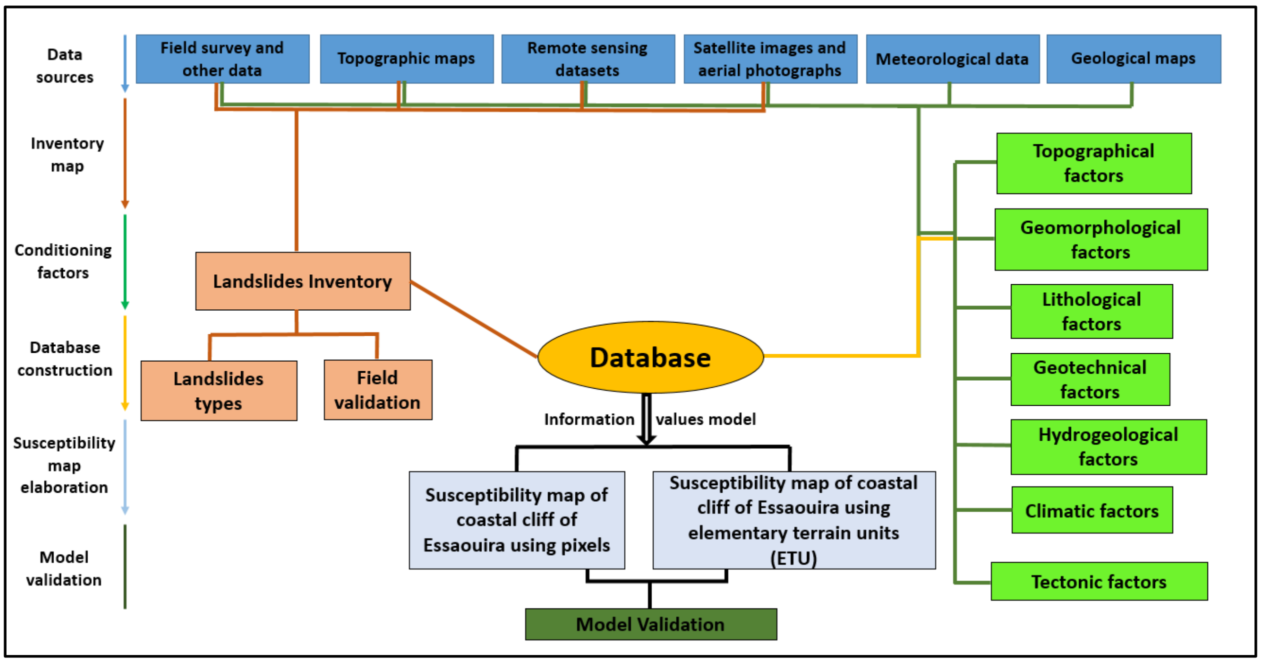

Figure 2: Schematic diagram of the used methodology

A classification of coastal systems into sandy and rocky subsystems was done according to a morphometric and operational criterion, the ETU were defined based on the methodology proposed by (Marques *et al.* 2011), upper and lower limits of the terrain units, are defined by the bottom and the top of the cliff, respectively, while lateral limits were geometrically drawn perpendicular to the contour lines of the topography, and defined by the segmentation of the ridge line into 50 m wide sections. In total, we had 1534 terrain units of rocky coast. Each terrain unit was classified as stable or unstable based on the quantification of the percentage of the unstable area of each slope unit.

3.1. Landslide inventory

The most essential part of landslide susceptibility assessment framework is the landslide inventory including the identification of their location, size and type and depth, to understand the relationship between landslide occurrence and the dataset of predisposing factors (Ercanoglu and Gokceoglu 2004, van Westen *et al.* 2006, Petley 2008, Epifânio *et al.* 2013). Landslide inventory is of the historical type, with no past date of occurrence limits, it was based in the interpretation of different data sources covered all the study area (Tab. 1), such as historical records, 10 m resolution Sentinel satellite imagery, High-resolution Ortho-imagery analysis and an intensive field investigation.

Table 1: Data sources Table

Data type	Data denomination	Source	Scale / resolution / Duration
Topographic maps	Sidi Ishaq 2008	National Agency of Land Conservation, Cadastre and Cartography (ANCFCC)	1/25000
	Berrakat Erradi 2008		
	Sebt Akermoud 2008		
	Bir Kaouat 2008		
	Moulay Bouzarqtoune 2008		
	Jbel lahdid 2008		
	Essaouira 2008		
	Chicht 2008		
	Ras Sim 2008		
	Essaouira El Jadida 2008		
	Sidi Kaouki 2008		
	Tidzi 2008		
	Sidi Ahmed Essayeh 2009		
	Tafdna 2009		
Geological maps	Tamanar map	Ministry of Energy and Mines, Water and Sustainable Development	1/100000
	Taghazout map		1/100000
	Marrakech map		1/500000
Aerial photographs	Mission TAMANAR 07/2016	National Agency of Land Conservation, Cadastre and Cartography (ANCFCC)	1/7500
Meteorogical data	Adamna station	Hydraulic basin agency of Tensift (ABHT)	1977-2015
	Igrounzar station		1968-2015
	Talmest station		1984-2015
	Chichaoua station		1965-2014
	Abadla station		1969-2014
Satellite images	Sentinel	https://scihub.copernicus.eu/ (Copernicus 2021)	10 m
	High resolution Ortho-imagery	https://earthexplorer.usgs.gov/ (USGS-EROS 2018)	0.3 m
	Digital elevation model	https://search.asf.alaska.edu/ (JAXA/METI 2020)	12.5 m

The identification of the landslides was based on the interpretation of their specific morphological features noticeable in high-resolution imagery, including crown, main scarp, flanks, body and toe (Pawluszek 2019). Other features were detected by the presence of flow materials along gullies, streams with different erosional features, flow tracks, scars along cliff face and block deposits on the cliff base (Epifânio *et al.* 2013, Elkadiri *et al.* 2014). In addition to these, extensive field observations were used to validate the inventory and add new landslides not observed in satellite image or identified in other data sources.

3.2. Conditioning factors

Conditioning factors describe terrain conditions that are directly or indirectly associated with landslide occurrence, they are essential for landslide susceptibility mapping based on data-driven methodologies. Different types of variables (conditioning factors) were compiled and/or generated in a geographical information system (GIS) for susceptibility analysis. According to Marques *et al.* (2011, 2013), all conditioning factors influencing the stability of coastal cliffs and coastal slopes should be considered because they may contribute to predict the spatial occurrence of future instability. It is important to mention that the selection of conditioning factors associated to these processes seems to be a difficult task since those factors usually work in combination, in a multivariate system (e.g. Epifânio *et al.* 2013, Reichenbach *et al.* 2018).

Based on the geomorphological characteristics, bibliography and field surveys, 22 landslide conditioning factors were selected for this study area. From those, 10 conditioning factors were computed from a freely available digital elevation model (ALOS PALSAR RTC DEM) with 12.5 m of resolution (source: https://search.asf.alaska.edu/), namely, elevation, slope angle, slope aspect, slope plan curvature, slope profile curvature, cliff height (calculated by the average of top pixels in each elementary terrains units), topographic wetness index, topographic position index (classed considering the distance of SD to the mean value for both sides of the distribution), slope over area ratio (using a base 10 logarithmic progression of class limits) and solar radiation (Tab. 2).

Solar radiation was used as a proxy variable for slope aspect, because it enables the quantification of the weight of trivial qualitative quadrant (Epifânio, *et al.* 2013) Slope angle is the most important predisposing factor for the occurrence of landslides (Mancini *et al.* , 2010), but in our study area, slope angle does not have the same importance for all type of landslides, plan and profile curvatures can be associated to the acceleration and deceleration of the flow, as well as the convergence or divergence of the flow, and can influence the local drainage systems and the kinematics of landslides (Mancini *et al.* , 2010).

The land use map and the Normalized Difference Vegetation Index (NDVI) were extracted from Sentinel images 2021 (10 m resolution, Tab. 1). The lithology, toe lithology and faulting data were obtained from the compilation of bibliographical review and from three digitalized geological maps; Tamanar and Taghazout 1/100000-scale in the southern section, and Marrakech 1/500000-scale for the northern section, completed with the field survey.

The meteorological data and the historical rainfall records are used for extracting the rainfall factor, using the arithmetic mean method (Smaij, 2011), which consists of calculating the annual arithmetic mean of the values obtained at the weather stations, and projecting them using the Inverse Distance Weighting (IDW) interpolation. While; field survey, topographic maps (1:10,000) and DEM were used for identify and map the stream networks. Presence and type of cliff toe protection, lithology tilting, and presence of springs were extracted from the observation of satellite images and by field survey.

Field work revealed that most landslides occur above the weak or friable layers, therefore, making geotechnical properties a factor to account for. Moreover, grain size was added to the variables list after data extraction from 16 samples using the BetterSize Lazer Particle Size Analyzer 9300S (Tab. 2). Grain size clay, silt and sand (Tab. 2) are spatially identified in the same predisposing factor. The sampling sites are showed in the Fig. 6 (red arrow). The organic matter content analysis is also applied on those samples using the loss on ignition (LOI) method (Heiri *et al.* 2001), as an important factor that has a strong relationship with the presence of vegetal cover (Tab. 2), and who says the presence of vegetation, says the presence of water that promotes the occurrence of landslides.

Table 2: Input conditioning factors

Conditioning Factor	Number of classes	Minimum value	Maximum value	Variable Type
Elevation (m)	13	0	261	numerical
Aspect	10 or 9	Flat (−1)	North 337.5–22.5°	numerical
Slope (°)	11	0	75	numerical
Curvature profile	3	-17.81 (concave)	21.1 (convex)	numerical
Curvature plan	3	-9.82 (convergent)	11.35 (divergent)	numerical
Height (m)	13	0	254	numerical
TPI	6	-88	69.37	numerical
TWI	6	-1.55	29.35	numerical
SOAR	6	0	4.72	numerical
Solar radiation (kWh/m2)	6	400	1000	numerical
Land-use	6	Bare ground, Light vegetation, Breakwater area, Dense vegetation, Cultivated areas, Roads and habitation		categorical
NDVI	5	Water , Bare soil, Sparse vegetation , Moderate vegetation, Dense vegetation		categorical
Layers tilt	2	Towards sea tilting, Sub horizontal tilting		categorical
Grain size Clay (% Clays < 2 µm)	6	3	35	numerical
Grain size Silt (% Silt 2 µm < < 63 µm)	6	6	72	numerical
Grain size Sand (% Sand 63µm < < 2 mm)	6	0	91	numerical
Organic Matter (LOI%)	6	0.94	7.41	numerical
Precipitation (mm)	5	252	306	numerical
Drains network	2	0	1	categorical
Spring	2	0	1	categorical

Faulting	2	0	1	categorical
Lithology	20	See the results section		categorical
Toe lithology	5	Grey_Marls, Marley_limestones, Essaouira_Sandstone, Dolomitic_Sandstone, Dolomitic_limestones		categorical
Toe Protection	4	Rock platform protection, Slope deposit protection, Beach protection, No protection		categorical

3.3 Susceptibility modelling and validation

The method used to evaluate the susceptibility to the occurrence of coastal landslides is the Information Value (Yin & Yan, 1988; Zêzere, 2002), which is a bivariate statistical method particularly suited to study relationships between the dependent variable (landslides) and the set of independent conditioning factors. This method was successfully applied to coastal areas worldwide (Marques *et al.*, 2011, 2013; Epifâneo *et al.*, 2013, 2014).

Using this bivariate statistical method, it is possible to weight each class of each predisposition factor of slope instability in an objective and quantified way.

The Informational Value score (Ii) for any class Xi of an independent variable (X) was determined, for each landslides type Y, by the following equation:

$$\mathbf{Ii=ln}\frac{Si/Ni}{S/N} \qquad \mathbf{(1)}$$

Where:

- › Si = nº of cells with landslides and variable Xi, in the Essaouira coastal area;
- › Ni = nº of cells with variable Xi in the Essaouira coastal area;
- › S = total nº of cells with landslides in the Essaouira coastal area;
- › N = total nº of cells in the Essaouira coastal area.

When a class of the conditioning factor do not have registers of landslides (Si=0), the Ii score is not calculated due to impossibility of logarithmic normalization, than it was assumed that that class has an Ii score lower than the minimum registered. For example, the minimum IV index was -5.7014031 for Slope Aspect Class 1 (Flat areas) for deep translational slides, so we took -5.702 for variable classes without any landslide.

The final value of susceptibility to landslides calculated for each cell j corresponds to the sum of Ii scores present in that unit, given by the following equation:

$$\mathbf{Ij=}\sum_{i=1}^{m} XijIi \qquad \mathbf{(2)}$$

Where:

- › m = number of variables;

› Xij is equal to 1 or 0, depending on whether variable Xi is present or not in cell j, respectively.

To assess coastal landslide susceptibility 15 predictive models are individually developed for each inventoried landslide type in this coastal area, considering the landslide partitions defined on Tab. 3, and the standard model procedures defined previously on section 3. Tab. 3 shows the 15 different landslide partitions according the landslide type used for assess landslide susceptibility: total landslides, deep landslides, shallow landslides, deep rotational slides, shallow rotational slides, deep translational slides, shallow translational slides, rock topple, rock fall, rock slide, debris fall, debris flow and debris slide. With those landslide dataset partitions, we expect to understand better the different drivers responsible for the occurrence of the different types of landslides in this coastal area. Each landslide type inventory dataset was then sub-divided into a training and a validation group (Remondo *et al.* 2003). Training group containing 70% of the inventory was used in the model building and validation group containing 30 % of the inventory was used to carry out an independent cross validation process over the model first results, The 70/30 partition was selected randomly, because is in agreement with the commonly used partitions used for landslide susceptibility models training and validation (e.g., Chen et al. 2020). We adopted also a sensitive approach of eliminating some landslide conditioning factors, that have no or less contribution in landslides occurrence basing on IV score results.

Additionally, to assess the importance of the representativeness of the inventory the susceptibility modelling was considered also, for some landslide types splitting them in 2 subgroups considering the depth of the rupture surface: shallow and deep-seated, for rotational and translational slide types.

Table 3: Predictive susceptibility models strategy and landslide inventory dataset partitions

Model ID	Description of the landslide partition dataset used for assess susceptibility	Training – 70%			Validating – 30%		
		Area	Slides number	ETU number	Area	Slides number	ETU number
Model 1	All landslides (no landslide type or depth of the rupture surface differentiation)	3149643	412	682	1349847	176	292
Model 2	Deep-seated landslides (no landslide type differentiation)	2570471	92	371	1101630	40	159
Model 3	Shallow landslides (no landslide type differentiation)	208086	75	180	89180	32	77
Model 4	Rotational slides (no depth of the rupture surface differentiation)	553238	100	281	237102	43	120
Model 5	Deep-seated rotational slides	490737	67	207	210316	29	89
Model 6	Shallow rotational slides	64840	34	74	27789	14	32
Model 7	Translational slides (no depth of the rupture surface differentiation)	2222341	67	270	952432	29	116

Model 8	Deep-seated translational slides	2082644	26	165	892562	11	71
Model 9	Shallow translational slides	143551	41	106	61522	18	45
Model 10	Rock topple (source areas)	41086	85	136	17608	36	58
Model 11	Rock fall (source areas)	175529	104	219	75227	45	94
Model 12	Rock slides	21920	11	26	9394	5	11
Model 13	Debris fall (source areas)	39314	4	21	16849	2	9
Model 14	Debris flow (source areas)	204500	33	67	87643	14	29
Model 15	Debris slide	14206	8	20	6088	3	8

For the pixel terrain unit approach, susceptibility was assessed for the different landslide types, all dependent and independent variables were transformed into a spatial grid database by 12.5×12.5 m resolution following DEM pixel size, and all the data are projected in lambert conformal conic Zone 1 coordinate system with Merchich datum.

For the ETU approach, in order to assess landslide susceptibility, the application of any statistical method, requires the partition of the study area into smaller terrain units. In the present work the main modelling is developed on a pixel base-model, the conditioning factors layers were transformed into elementary terrains units (ETU), considering the weight of each factor in each ETU, in order to apply the terrain units method and make a comparison between the two approaches (pixel and ETU).

However, susceptibility results are harmonized in elementary terrains units (ETU). The ETU use is done because: i) they have a strong relationship with the morphology and geometry of the system that we are trying to model; ii) they are fitting to the most used land use planning formats as they are mostly vector approaches and system based, either that is a physical system or a human settlement; iii) and they are also a factor of uniformity and help dealing with heterogeneous data (e.g. Calvello *et al.* 2015). Additionally, for planning purposes ETU are easier to clearly identify in the territory when compared to pixel.

4. Results and discussion

4.1. Landslides in cliffs and coastal slopes of Essaouira

The detected landslides were assigned according to Varnes (1978) classification; WP/WLI's (1993); Cruden and Varnes 1996; and Dikau *et al.* (1996) and 10 landslide types were identified: debris fall, debris flow, debris slide, rock fall, rock slide, rock topple, deep rotational slides, shallow rotational slides, deep translational slides, shallow translational slides.

Expert and fieldwork inventory validation allowed for landslide limit corrections and new landslide identification. Some landslides examples are presented in Fig. 3.

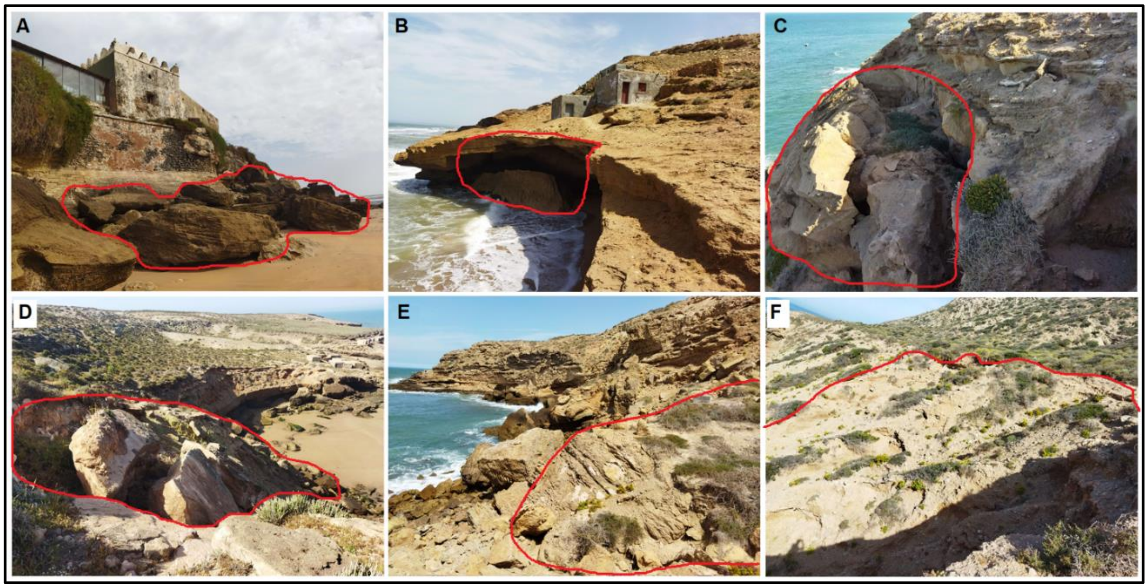

Figure 3: Some landslide types examples from study area; A, B Rock falls, C Rock topple, D Translational slide, E Rotational slide with back tilting, F Debris flow.

The final inventory of the study area is composed by 588 landslide records (Fig. 4). Rockfalls are the most frequent slope instability phenomena in the study area, with 149 records, followed by rotational slides, while the least frequent landslide type is the debris fall, with only six records. Most of the study area is occupied by translational slides (68 %), followed by rotational slides. These landslide types have usually bigger area per landslide, have deeper rupture surfaces and frequently occur along the whole cliff / coastal slope profile.

Slope instability is present along the whole study area, resulting in the identification of 974 elementary terrain units with landslides (63.5 %), and 28797 unstable pixels (46.5 %).

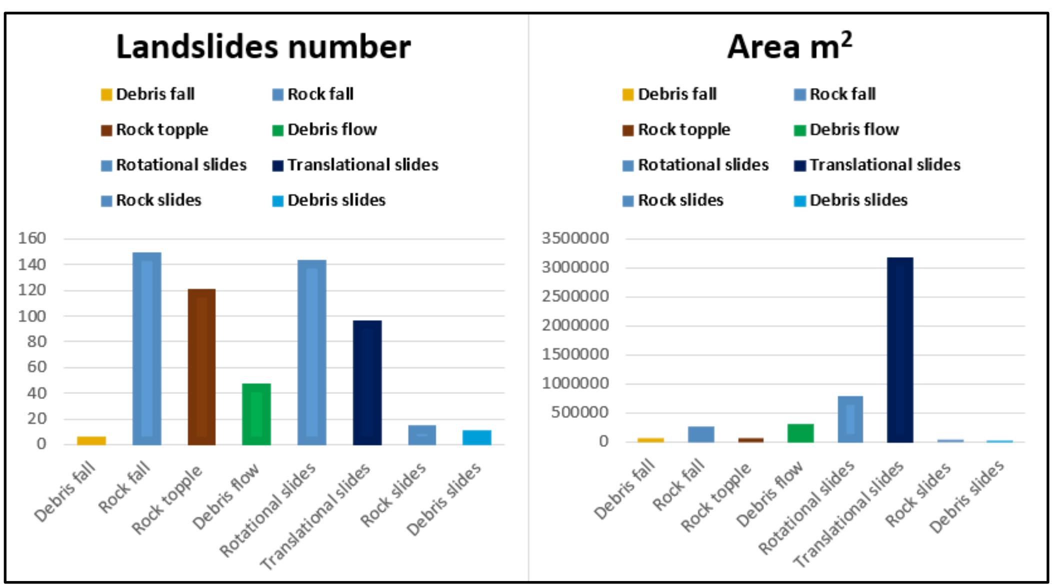

Figure 4: The relative distribution of landslides by type and area in the ETU of the study area

Nevertheless, the heterogeneity of the spatial distribution of landslide types (Fig. 5) over the study area shows higher concentration in the southern section due to the higher concentration of rotational and translational slides.

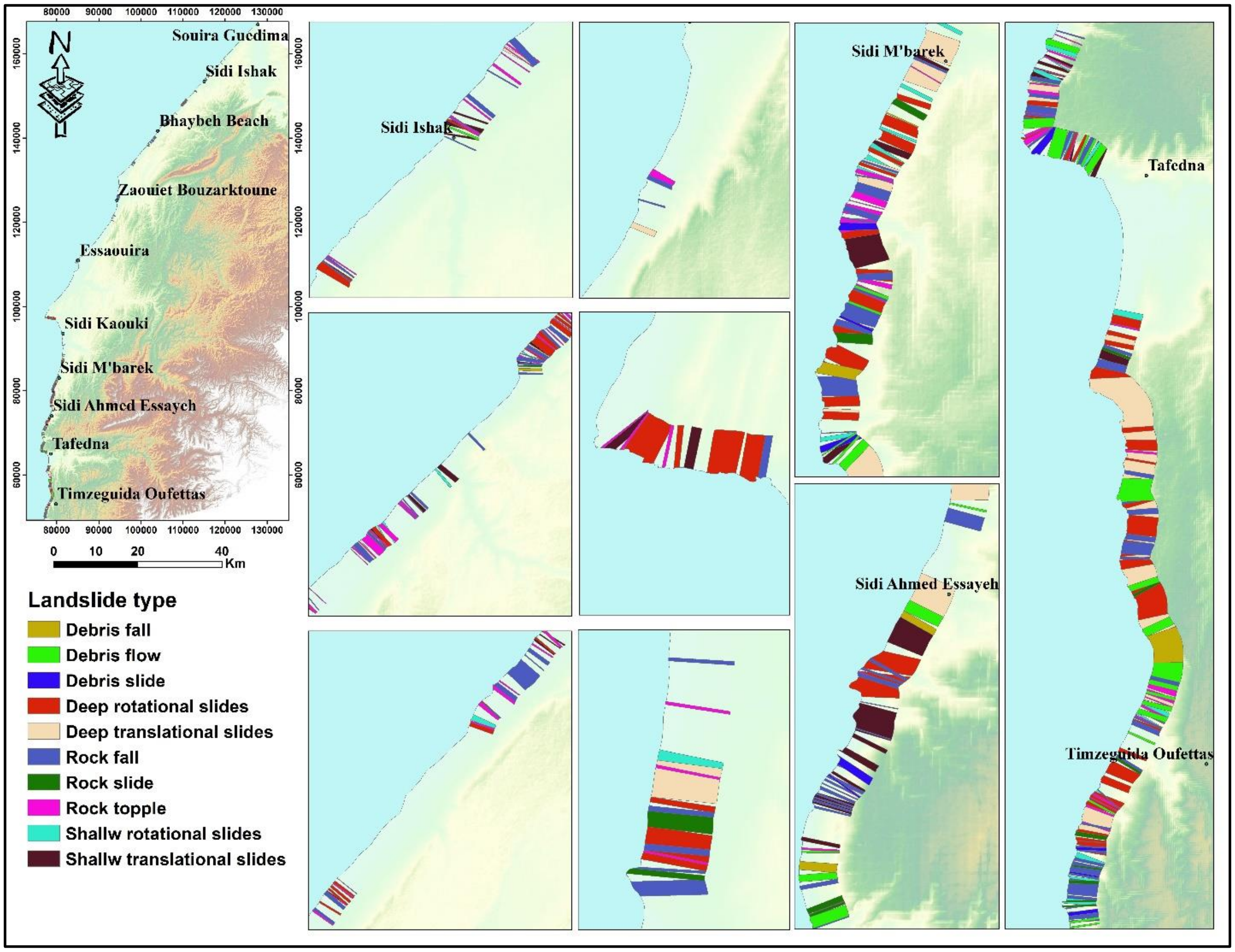

Figure 5: Spatial distribution of landslide types in study area

4.2. Driving forces of instability in Essaouira

Lithology and structure, and landslide deposits are important conditioning factors for susceptibility analysis. These can be proxies of permeability, shear strength and propensity for physical and chemical weathering of rock and soil materials (Varnes, 1984, Epifânio *et al.* 2013). Twenty main lithological units were found in the study area including: (1) calcareous crusting, (2) clay and sandstone, (3) conglomerate and dune sediments, (4) conglomerate with sandy matrix, (5) dolomitic limestones, (6) dolomitic sandstones, (7) dune sandstone with oblique stratification, (8) Essaouira Sandstone/Calcarenite, (9) friable sandstone layer, (10) gray clays, (11) gray marls, (12) heterogeneous conglomerate, (13) limestone bar, (14) lumachelic clayey limestones, (15) marls, (16) marly limestones, (17) pudding conglomerate, (18) sandstone dolomites, (19) sequence of marls and marly limestone and (20) terrigenous red deposit (Tab. 4).

The spatial distribution of lithological units (Tab. 4), shows that in general the limestone units are more frequent in the southern sector often combined with grey marls and clays of the Hauterivian and Aptian (Cretaceous). Calcareous crusting, friable sandstone layers and terrigenous deposits can be found in all coastal area. Conglomerate and sandstone units are more concentrated in the northern sector where consolidate dunes can also be found.

Regarding the number of ETU per lithology type, calcareous crusting and Essaouira Sandstone-calcarenite are the two lithological formations most funded in the majority of ETU, present in 1216 and 1270 ETU, respectively. This can be explained because in the encrustation phenomena, coastal eolian constructions become dominant in the study area as we mentioned in geological settings.

The most lithological formations occupied by the instabilities are: Dune sandstone with oblique stratification, Friable sandstone layers, Gray Marls, Heterogeneous conglomerate, Limestone barre, Marls, Sequence of Marls and Marly limestone.

Table 4: Predominance lithology by area and ETU

Lithology	Predominance area	Number of ETU	Number of unstable ETU	% Of unstable ETU	IV Results
Calcareous crusting	All coastal area	1216	240	19.74	-0.01
Clay and Sandstone	Southern coastal area	33	25	75.76	-1.68
Conglomerate and dune	All coastal area	1340	782	58.36	-0.31
Conglomerate with sandy matrix	Northern coastal area	33	3	9.09	-5.70
Dolomitic limestone	Southern coastal area	320	183	57.19	-1.03
Dolomitic Sandstones	Southern coastal area	13	4	30.77	-5.70
Dune sandstone with oblique stratification	Southern coastal area	284	243	85.56	0.64
Essaouira Sandstone - calcarenite	All coastal area	1270	628	49.45	-1.67
Friable sandstone layers	All coastal area	479	343	71.61	0.39
Gray Clays	Southern coastal area	50	23	46.00	-2.96
Gray Marls	Southern coastal area	229	167	72.93	-1.01
Heterogeneous conglomerate	Southern coastal area	147	119	80.95	1.03
Limestone barre	Southern coastal area	159	154	96.86	0.56
Lumachelic clayey limestone	Southern coastal area	50	32	64.00	0.24

Marls	Southern coastal area	69	60	86.96	0.61
Marly limestone	Southern coastal area	67	63	94.03	0.27
Pudding Conglomerate	Northern coastal area	152	33	21.71	-2.23
Sandstone dolomites	Southern coastal area	50	28	56.00	-0.35
Sequence of Marls and Marly limestone	Southern coastal area	282	275	97.52	0.70
Terrigenous red deposit	All coastal area	48	12	25.00	-1.18

Stratigraphic profiles (Fig. 6 and 7) show detailed lithological change over the study area, and allow for a better understanding of cliff lithology variations, the emplacement of friable layers that have a direct influence on the occurrence of landslides.

In the southern section we noted a big variation in the lithological units regarding the spatial distribution, therefore the majority of stratigraphic logs are concentrated in the southern section (from log 1 to log 13), while there is no much variation in the northern section (from log 14 to log 16). About the lithological materials, we note the presence of friable layers or weak layers (it could be friable sandstone, sand, clays and marls) in all logs except log 3, log 7, log 9, log 13 and log 14.

As tilting layers are more favorable to instabilities because of the gravitational forces, the predominant sub-horizontal layering has also a contribution, while the majority of those layers are deposited on weak or friable layers, which are stimulated the instability in many locations in the study area referring to the field survey. Those friable layers are usually placed between the impermeable or competent layers, they are the result of: either the different diagenesis degrees or compaction; or the high content of clays –according to grain size analysis- that makes them more friable than adjacent layers. According to the field survey, those layers are usually behind the occurrence of many landslides, that is why we consider them important, especially because some of them are in contact with springs, and others are in the bottom part of the cliff, which means more lithostatic pressure thus more susceptibility of landslides occurrence.

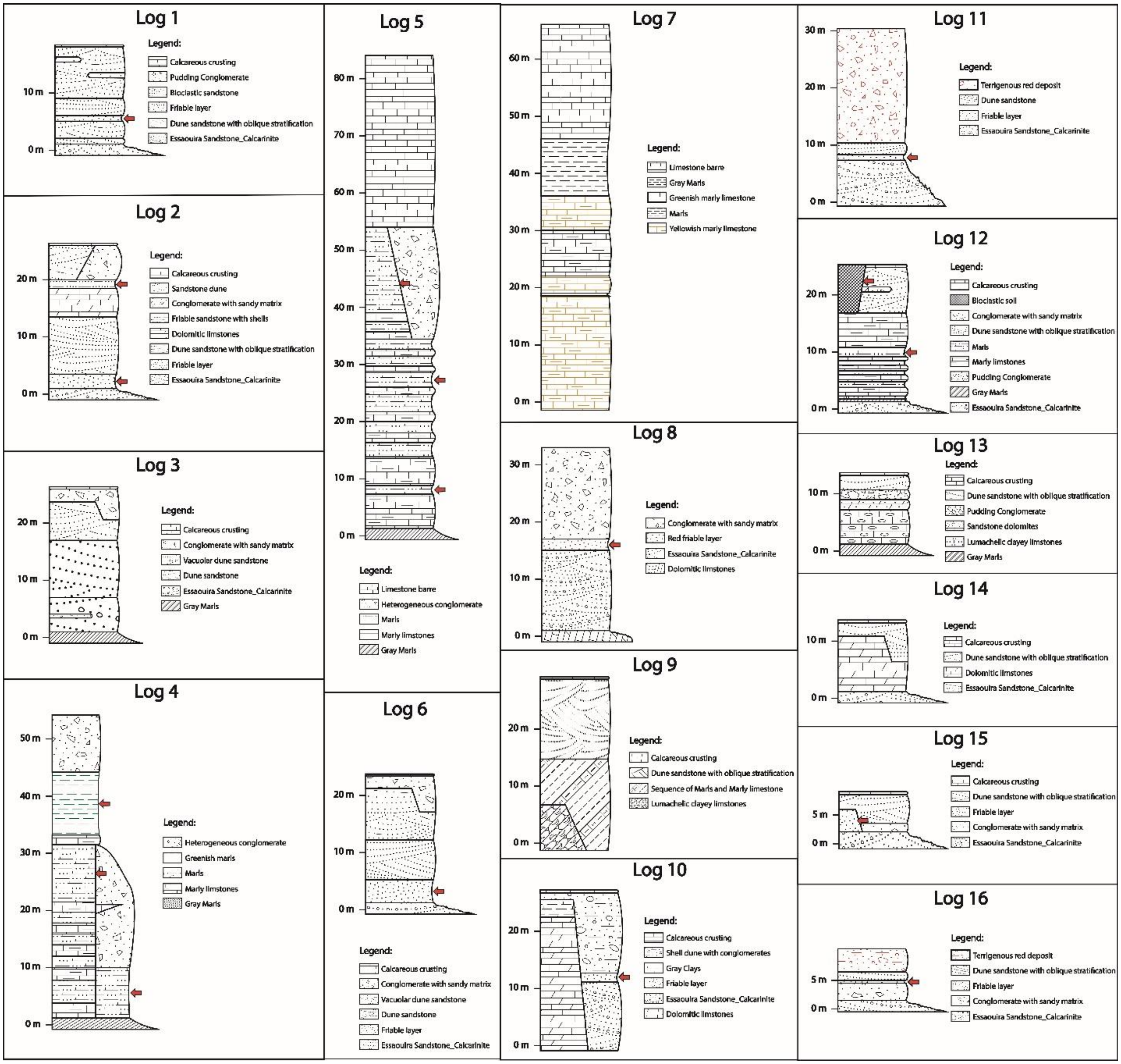

Figure 6: Stratigraphic columns for Essaouira coastal area

Another important factor for landslide susceptibility mapping is elevation factor. The Fig. 7 shows the spatial distribution of these factor, we can remark the southern section cliffs present higher elevation, for the reason that those area are more closed to the High Atlas Mountains feet.

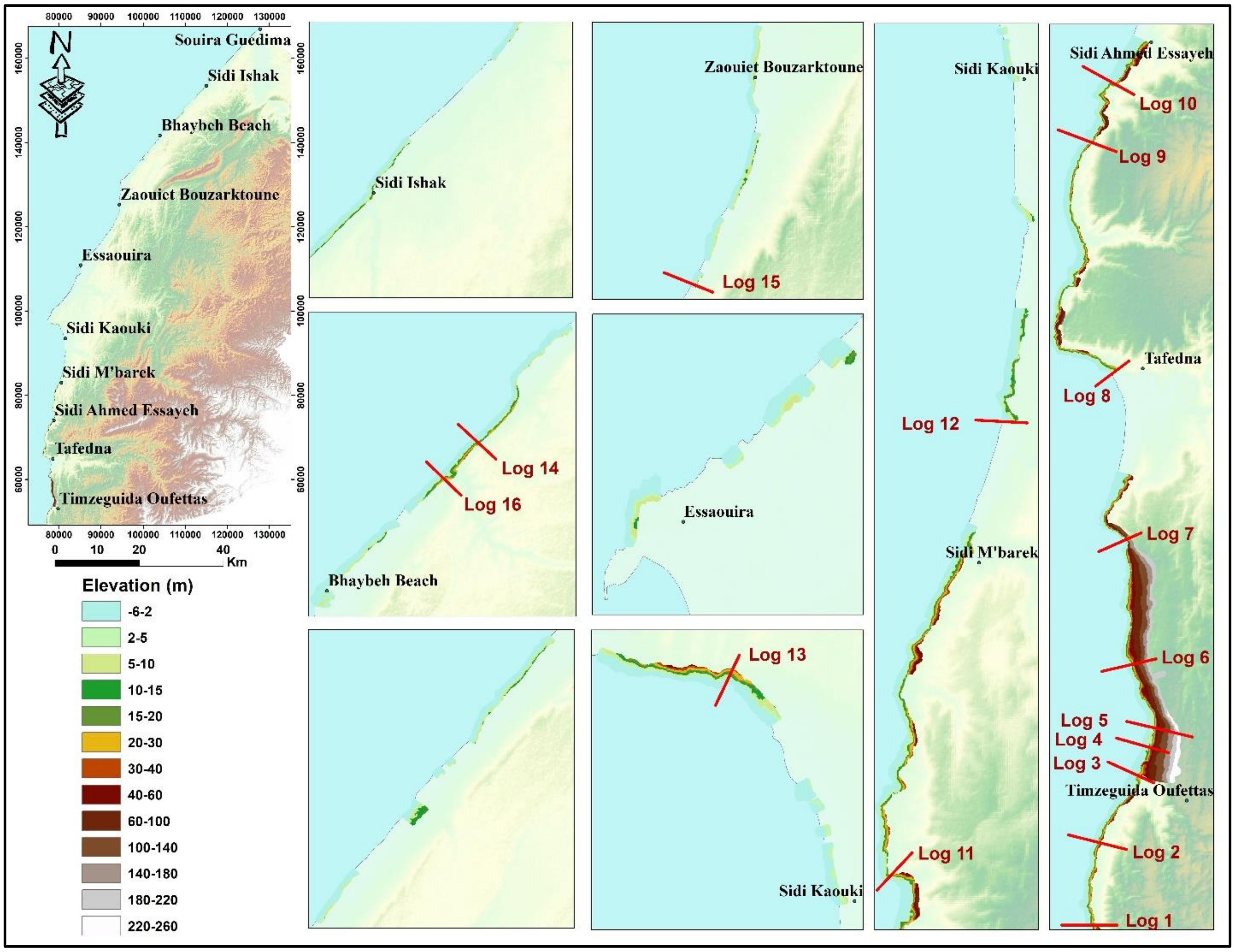

Figure 7: The spatial distribution of elevation factor in the study area with the profiles emplacement.

Others conditioning factors are provided by the fieldwork: i) the presence and type of cliff toe protection as it showed in the Fig. 8 A, B and C, either rock platform, slope deposit or beach protection; ii) lithology tilting that has a big impact on the landslides occurrence as we remark in the Fig. 8 D and E; iii) the presence of stream networks and springs in the cliff face which stimulate the landslides occurrence; iv) the presence of springs, we localized 9 springs, 4 of them concentrated around Timzeguida Oufettas village which has locally a visible impact on landslides occurrence especially considering the presence of marls, which are becoming more sliding in contact with the water. Other springs are located in the southern section except one in the north between Bhaybeh beach and Sidi Ishak village. There are considerably affect the mechanical processes that lead to slope failure and to the subsequent post-failure movements, especially where we have marls or clays.

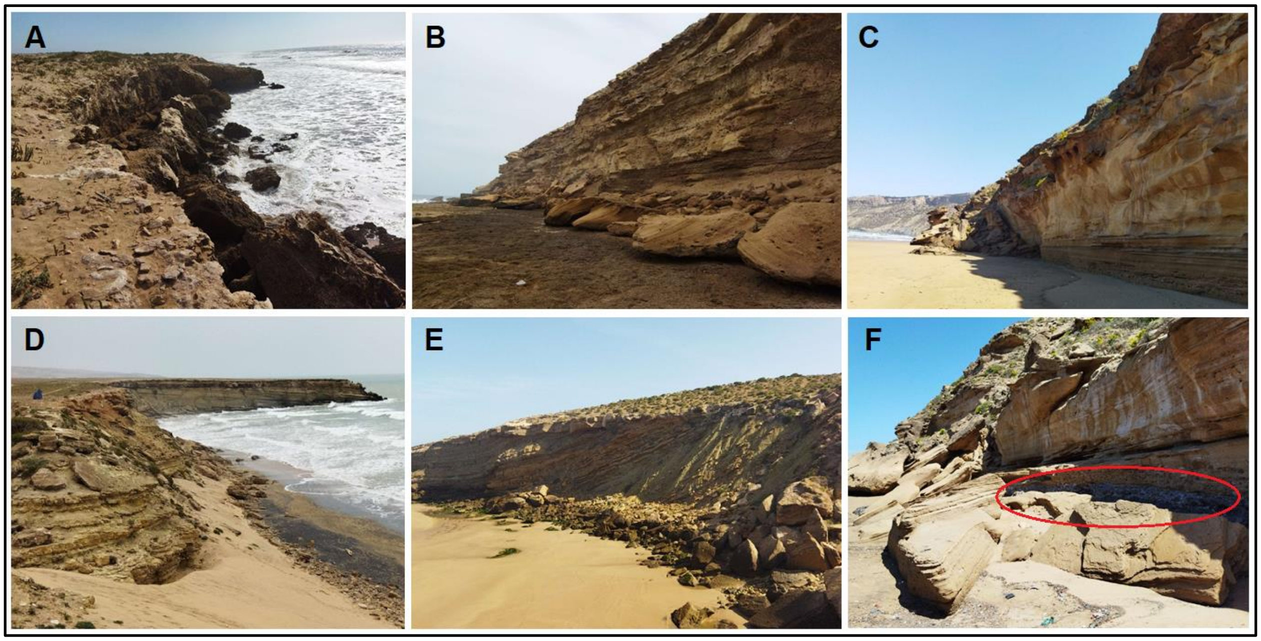

Figure 8: Examples of some conditioning factors; A: Absence of toe protection, B: Rock platform protection, C: Beach protection, D and E: tilted layers towards sea, F: Cliff toe lithology effect.

For the rainfall factor, the interpolation of rainfall records from 4 meteorological stations, from 1968 to 2015, were used to assess the spatial distribution of this conditioning factor, the results shows that the maximum average 306 mm of precipitation falls around Essaouira city, while the precipitation values decrease towards the two extremities of the study area reaching a minimum average precipitation of 252 mm.

Finally, the NDVI and land-use map was prepared from the Sentinel satellite images analysis, six land-use types were extracted, including bare ground, cultivated areas, light vegetation, dense vegetation, roads and habitation, and breakwater area.

4.3. Coastal landslide susceptibility assessment

Coastal landslide susceptibility using the Information Value method, as mentioned in the objectives, was produced considering two different susceptibility zonation approaches, susceptibility assessed at the pixel scale and considering elementary terrains units:

4.3.1 By Pixel:

Table S1 represent the information values scores obtained for each class of each landslide conditioning factor used in the construction of each susceptibility model for 15 landslide inventory partitions defined according their classification into shallow and deep-seated landslides, landslide type or type of affected material (debris or rock).

The information value scores represent a clear contrast between the most favorable areas and the less favorable areas for the different landslide type's occurrence, we will describe the most important conditioning factors for each landslide type:

-For all landslides types (Model 1) - The most relevant conditioning factor to the occurrence of all inventoried landslides are areas with slope angles >45 (IV score =1.377), followed by solar radiation factor between 400 and 600 kWh/m2 (IV score =1.332) and the elevation factor 60-100 m (IV score =1.320). The minimum was obtained for aspect class Flat (IV score =-3.845). Those results pointed out, considering no landslide type or depth of the rupture surface differentiation that slope angle and elevation are the most influent factors for landslide occurrence especially in dry climate areas like Essaouira coastal cliff area, except for model 10 (rock topple), in which the slopes >15º have negative scores.

-Deep-seated landslides (Model 2) - in Essaouira coastal area, occurred more in areas with 400-600 kWh/m2 solar radiation (IV score =1.536), in slope areas >45 ° (IV score = 1.494), and in the high areas between 60 and 100m (IV score = 1.480), where the minimum was in the same class as previous. Although, shallow mass movements occurred more in friable layers with IV score = 3.011, in 600-700 kWh/m2 solar radiation (IV score = 2.072), and in areas with 35 - 45 ° slopes.

-Rotational slides (Model 4, Model 5 and Model 6) - occur in general, in Sandstone dolomites and dune sandstone with oblique stratification lithologies. For deep rotational slides, the grain size factor 38-51 (% Sand) presented the highest value 1.550, followed by slope angle factor class 30-40° with IV score = 1.441. While for shallow rotational slides, the grain size factor presented a strong independence with the occurrence of this landslide type with IV score = 2.323.

-Translational slides (Model 7, Model 8 and Model 9) - deep and shallow ones in the Essaouira coastal area, occurs more in areas with 400-700 kWh/m2 solar radiation and in slope areas >40 °.

-Rock topple (Model 10) - The Grain size factor especially; classes 0-11% Silt (IV score = 2.092) , 66-91% Sand (IV score = 2.037) and 0-7% Clay (IV score = 2.016), are more contributing in the occurrence of Rock topples, as they are usually happened next to friable layers in Essaouira coastal cliff area.

-Rock falls (Model 11) - occurs more in "dune sandstone with oblique stratification" class of lithology factor, while the minimum IV value was -4.978 Heterogeneous conglomerate, which is normal as rock falls does not happen in this lithology type.

-Rock slides (Model 12) - the lumachelic clayey limestones lithology class presented a strong dependence with rock slides, with IV score = 3.253, while the Flat (-1) areas for aspect factor presented the minimum IV score = -3.960.

-Debris fall and flow (Model 13 and Model 14) - the lithological material with grain size Sand 51-66 % and Silt 11-23 % are more favorable to the occurrence of debris falls and debris flow in Essaouira coastal area, and the Slope angle factor class 0-2 ° is less favorable with IV score = -4.822.

- Debris slides (Model 15) - presented a strong dependence with Terrigenous red deposit class, lithology factor, while the minimum was IV score = -3.565 for Flat (-1) class aspect factor, which is normal as this landslide type occurs more in Terrigenous lithologies and in a slope areas.

To represent landslide susceptibility for each model, we reclassify the final Information Value scores into four classes; Very low susceptibility (IV score < -1), low susceptibility (-1 < IV score < 0), moderate susceptibility (0 < IV score < 1) and high susceptibility (IV score > 1). The Fig. 9 present the spatial distribution of susceptibility classes for pixel-based landslide susceptibility Model 1. It is possible to observe that very low susceptibility class appeared more in the northern section of the study area, while the southern section present higher susceptibility to the occurrence of landslides, especially, due to the weight of the translational and rotational slides in those areas.

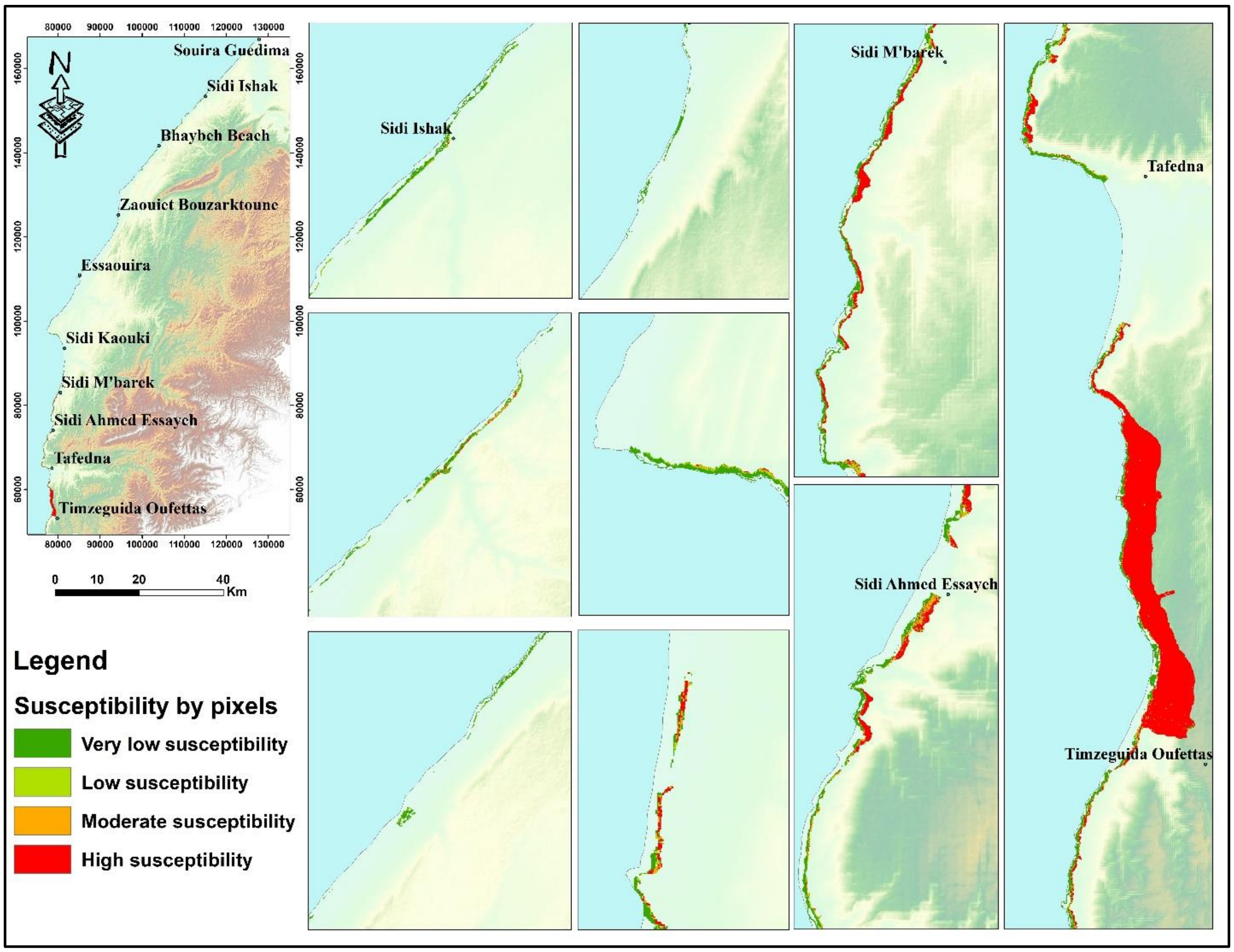

Figure 9: Landslides susceptibility map by pixels method

The information value model allowed classifying 38 % of our study area with high susceptibility to all landslides types occurrence, while very low susceptibility class is present in 56 % of the study area (Tab. 5).

All other landslide types susceptibility models presented high percentages for very low susceptibility class with a maximum of 89.76 % for debris slide. The exception is for debris flow where the highest percentage was for high susceptibility with 53.85 % of the study area.

Table 5: Percentage of landslides susceptibility classes

		Very low susceptibility	**Low susceptibility**	**Moderate susceptibility**	**High susceptibility**
Model 1	All landslides	55.45	2.55	2.66	39.35
Model 2	Deep-seated landslides	60.22	2.32	2.22	35.25
Model 3	Shallow landslides	72.58	4.10	3.80	19.52
Model 4	Rotational slides	52.71	7.02	6.55	33.72
Model 5	Deep rotational slides	55.03	5.84	5.95	33.18
Model 6	Shallow rotational slides	71.29	3.75	4.55	20.40
Model 7	Translational slides	61.08	2.42	2.07	34.43
Model 8	Deep translational slides	63.99	1.42	1.44	33.15
Model 9	Shallow translational slides	74.35	3.41	3.02	19.21
Model 10	Rock topple	67.41	5.52	5.95	21.12
Model 11	Rock fall	71.39	3.21	3.65	21.75
Model 12	Rock slides	80.02	2.72	2.56	14.70
Model 13	Debris fall	59.75	5.82	5.32	29.10
Model 14	Debris flow	39.15	3.04	3.96	53.85
Model 15	Debris slide	89.76	1.67	1.50	7.07

4.3.2 By elementary terrain units (ETU)

In general, the susceptibility assessment is carried out by classifying the elementary terrain units into two classes: stabilized (37% of ETU) and non-stabilized (63% of ETU). The approach was done individually for each type of landslide studied, and shows that, for all type of landslides, the unstable areas (classified as non-stabilized) are located more to the south units of study area.

To represent the ETU landslide susceptibility results, we present a zoomed section of the southern section of the study area next to Timzeguida Oufettas (Fig. 10), for which is possible to observe landslide susceptibility zonation for the elementary terrains units. This map presents the same allure or same variation as the susceptibility map produced by pixels approach, except that, the second approach of ETU, we can use ETU ID to define the susceptible area in situ.

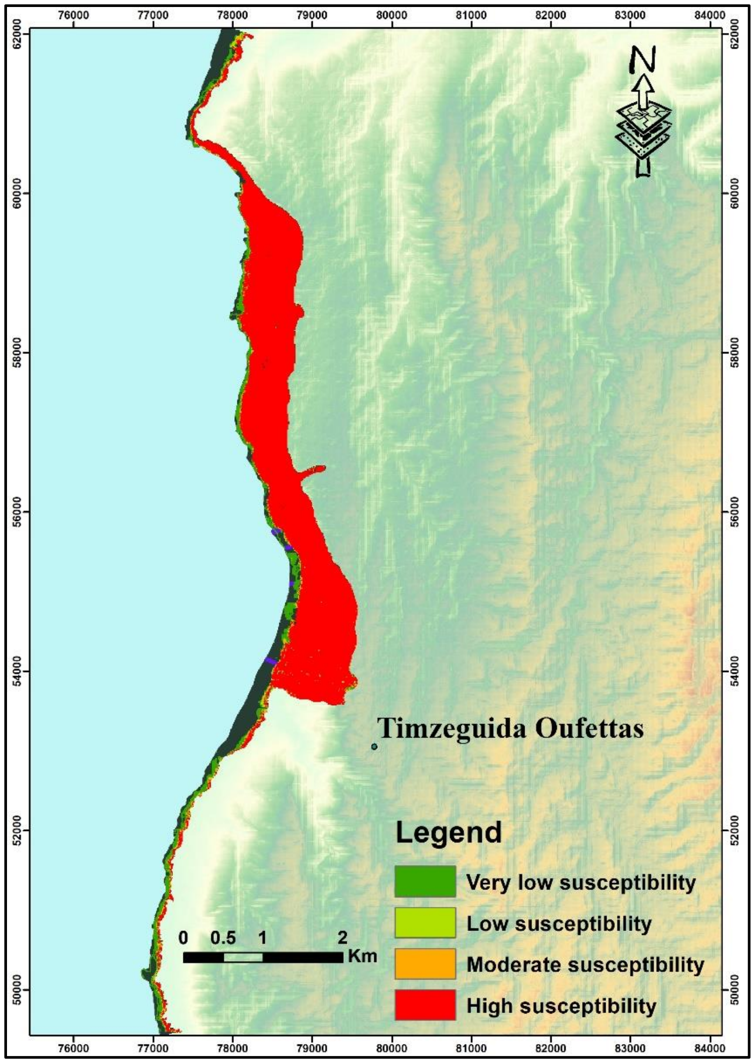

Figure 10: Landslide susceptibility map by ETU method for Model 1

4.4. Coastal landslide susceptibility models validation

All coastal landslide susceptibility models were validated by spatial confrontation with the independent landslide partitions defined as validating subsets. ROC curves (Linden 2006 and Remondo *et al.* 2013) (Tab. 6) of the predictive models were computed, and the respective Area Under Curve (AUC) value were calculated, Tab. 6 shows the AUC values obtained in the validation process for all models, as we can remark all landslide susceptibility models presented values > 0.7 AUC values, Model 1, Model 4, Model 10, Model 13 and Model 14 (0.7 to 0.8) are considered acceptable. , Model 2, Model 5, Model 6, Model 7, Model 8 and Model 9 (0.8 to 0.9) are considered excellent, and Model 3, Model 11, Model 12, Model 15 (more than 0.9) are considered outstanding.

Table 6: AUC values obtained in the validation process for all models.

Models	Landslide type	AUC Low	AUC High	AUC values
Model 1	All landslides	0.751	0.842	0.798
Model 2	Deep-seated landslides	0.767	0.858	0.815
Model 3	Shallow landslides	0.735	1	0.92
Model 4	Rotational slides	0.694	0.872	0.794
Model 5	Deep rotational slides	0.709	0.889	0.813
Model 6	Shallow rotational slides	0.438	1	0.817
Model 7	Translational slides	0.759	0.854	0.809
Model 8	Deep translational slides	0.795	0.893	0.847
Model 9	Shallow translational slides	0.728	0.976	0.895
Model 10	Rock topple	0.25	1	0.75
Model 11	Rock fall	0.755	1	0.961
Model 12	Rock slides	0.827	1	0.948
Model 13	Debris fall	0.44	0.92	0.72
Model 14	Debris flow	0.561	0.878	0.731
Model 15	Debris slide	0.898	0.998	0.972

For total landslides (Model 1) with all factors we obtained 0.710 (Fig. 11), then we eliminated the topographic wetness factor and the rainfall factor as we are in dry climate area and those factors didn't present a strong dependence with the occurrence of landslides, we obtained than 0.798 (Fig. 11), which means that the model 1 performance was improved in term of prediction, adopting this sensitive approach especially when we get low values of AUC.

We presented also the AUC graph for translational slides (Model 7) 0.809 (Fig. 12) and rotational slides (Model 4) 0.794 (Fig. 13), as these two landslide types occupied about 85% of the unstable area in the pixels model approach. These results shows that susceptibility models have a good predictive skill and highlight the higher performance of predictive models when built for each type of landslide in comparison with the model built for the total landslides.

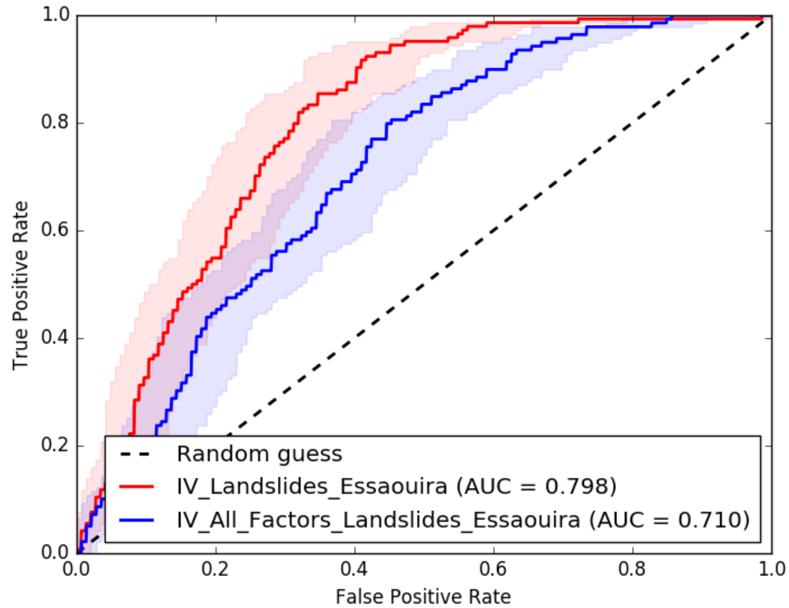

Figure 11: ROC curves of susceptibility model for all landslides with all factors (AUC = 0.710) and without TWI and rainfall factor (AUC = 0.798).

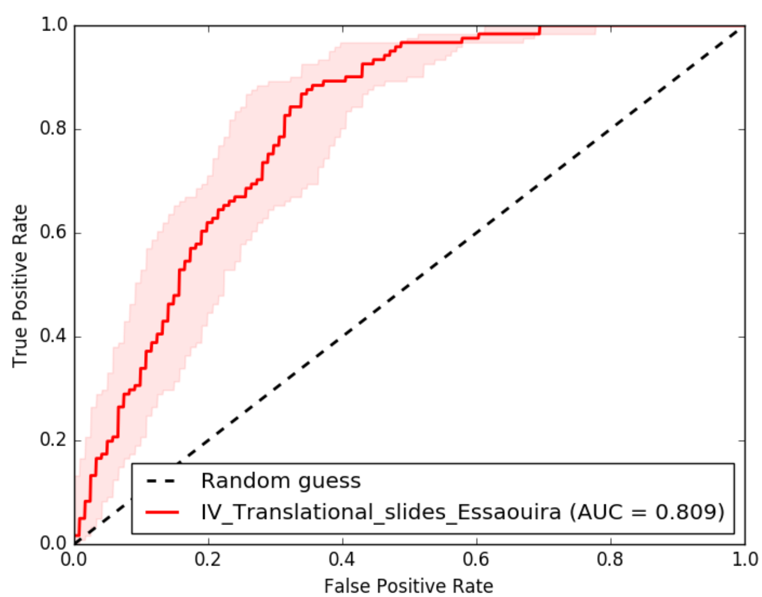

Figure 12: ROC curves of susceptibility model for translational slides (AUC = 0.809)

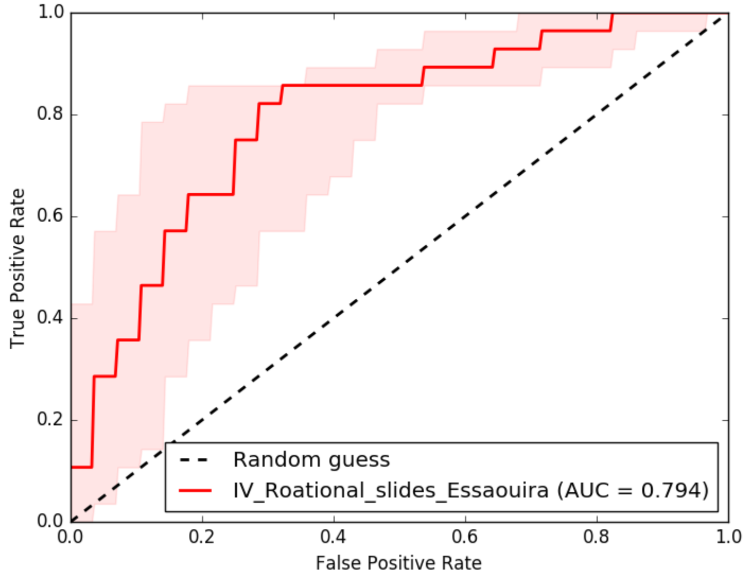

Figure 13: ROC curves of susceptibility model for rotational slides (AUC = 0.794)

5. Conclusion

The information value bivariate statistical approach to assess landslide susceptibility assessment in the 134 km of coastal area of Essaouira, based in geological, morphological analysis (interpretation of aerial photos, satellite images, and field survey), allowed classifying 38 % of our study area with high susceptibility to landslides occurrence (using pixels approach).

The translational slides followed by rotational slides are occupying about 85 % of the landslide area, we can explain that as a matter of fact that; the conditioning factors that are contributing more in the occurrence of those landslides, namely >45 slope angle, 400-700 kWh/m^2 solar radiation and some lithological formations; are occupying all the study area especially the southern section. Another reason is that those landslides type are usually occupied large areas.

Landslides are distributed along the entire study area, with more concentration in the southern section because it's topographic characteristics, mainly next to Sidi M'bark, Sidi Ahmed Essayeh, the northern section Tafedna and Timzguida Oufettas, while the less susceptible areas are more located in the middle and northern section of Essaouira coastal area.

For all landslides types, the most important explaining drivers are; slope factor especially >45 °, solar radiation factor class 400-600 kWh/m2 and elevation class 60-100 m, those factors are already highlighted by many authors as important conditioning factors of many landslides types. Most of the landslide susceptibility models (10 models out of 15) presented a strong interdependence with lithological factor or factors extracted from lithology as grain size and organic matter, which means that the landslides occurrence is highly impacted by lithology variations.

In the study area, precipitation doesn’t present in our study as a decisive conditioning factor, as a consequence of the spatial distribution of rainfall, since the highest values are concentrated around Essaouira city, more related to sandy coast subsystems.

To define in deep detail the spatial distribution of most susceptible areas to the different landslide types along the Essaouira coastal area, especially in the southern section, next to Timzeguida Oufettas village, more deep studies are recommended.

Both pixel and ETU models are holding approximatively the same allure in all the study area. Basing on those models, this study presented an essential material for spatial planning and civil protection emergency actions, in Essaouira coastal area, especially in rocky coast subsystem.

Since ETU are closer to the morphometry of the area, there is a more “guided” analysis in this approach, comparing with pixel-based that is no related with a particular morphology on the cliff area. Both approaches have advantages and inconvenient. It is true that ETU takes more into account the cliff morphometry and it’s more useful for territorial management interventions, but also leads to loss of susceptibility classification detail comparing with pixel approach, which is more relevant in term of resolution.

6. References

Aleotti, P., Chowdhury, R.: Landslide hazard assessment: summary, review and new perspectives. Bull Eng Geol Environ 58:21–44, 1999.

Ammophiletea, Br.Bl., and Tüxen ex Westhoff, Dijk and Passchier: Coastal, Lagoon, Estuarian and Marine Ecosystems, 1946.

Andriani, G. F. , Walsh, N.: Rocky coast geomorphology and erosional processes: A case study along the Murgia coastline South of Bari, Apulia — SE Italy, https://doi.org/10.1016/j.geomorph.2006.03.033, Geomorphology journal, 2007

Bahir, M., Mennani, A., Jalal, M., Fakir, Y.: Impact de la sécheresse sur les potentialités hydriques de la nappe alimentant en eau potable la ville d'Essaouira (Mogador, Maroc). Sécheresse, 13(1): 13-9, 2002.

Bahir, M., Ouhamdouch, S., Carreira, P. M.: Water resource in Morocco face the climatic changes; study case of the Plio-Quaternary phreatic aquifer at the synclinal basin of Essaouira, Comunicações Geológicas (2016) 103, 1, 35-44, 2017

Balasubramani, K., Kumaraswamy, K.: Application of geospatial technology and information value technique in landslide Hazard zonation mapping: a case study of Giri Valley, Himachal Pradesh. Disaster Adv 6(1):38–47, 2013.

Beguería, S.: Validation and evaluation of predictive models in hazard assessment and risk management. Nat Hazards 37: 315-329, 2006.

Calvello, M., Cascini, L., Mastroianni, S.: Landslide zoning over large areas from a sample inventory by means of scale-dependent terrain units, Geomorphology journal. http://dx.doi.org/10.1016/j.geomorph.2012.10.026, 2015.

Chamchati, H., Bahir, M.: Potential Hydrogeological, Environment and Vulnerability to Pollution of the Plio-Quaternary Aquifers of the Coastal Basin of Essaouira (Morocco). Journal of Environment and Earth Science, 3(10): 170-185, 2013.

Chen, W., Sun, Z., Zhao, X., Lei, X., Shirzadi, A., & Shahabi, H.: Performance evaluation and comparison of bivariate statistical-based artificial intelligence algorithms for spatial prediction of landslides. ISPRS International Journal of Geo-Information, 9(12), 696, 2020.

Chimidi, G., Raghuvanshi, TK., Suryabhagavan, KV.: Landslide hazard evaluation and zonation in and around Gimbi town, western Ethiopia – a GIS-based statistical approach. Appl Geomat (Springer) 9(4):219–236, 2017.

Chkir, N., Trabelsi, R., Bahir, M., Hadj Ammar, F., Zouari, K., Chamchati, H., Monteiro, J. P.: Vulnérabilité des ressources en eaux des aquifères côtiers en zones semi-arides – Etude comparative entre les bassins d'Essaouira (Maroc) et de la Jeffara (Tunisie). Comunicações Geológicas, 95: 107-121, 2008.

Choubert, G., et Ambrogi, R.: Note préliminaire sur la présence de deux cycle sédimentaires dans le Pliocène marin au Maroc. N.M.S.G.M. t 7. n° 17. p. 3-72 Ont., 2, 4. 5), 1953.

Choubert, G., Faure-Muret, A., et Hotin ger, L.: La série stratigraphique de Tarfaya (Maroc sud-occidental) et le problème de la naissance de l'Océan Atlantique. N.M.S.G.M. 31, 237. p. 29-40 (lot.), 1971.

Cochet, A., et Combe, M.: Bassin d'Essaouira-Chichaoua et zone côtière d'Essaouira, Notes et Mémoires du Service Géologique n° 231, t. 2, p. 433-446, 1975.

Copernicus Sentinel data [14/05/2021]. Retrieved from ASF DAAC [11/11/2021], processed by ESA.

Corominas, J., Westen, C. Van, Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., Catani, F., Eeckhaut, M. Van Den, Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M. G., Pastor, M., Ferlisi, S., Tofani, V., Herva, J., and Smith, J. T.: Recommendations for the quantitative analysis of landslide risk, B. Eng. Geol. Environ., 73, 209–263, https://doi.org/10.1007/s10064-013-0538-8, 2014.

Dai, A. , and Lee, B.: Landslide characteristics and slope instability modeling using GIS, Lantau Island, Hong Kong, Geomorphology 42 (2002) 213 – 228, 2002.

Dikau, R., Brunsden, D., Schrott, L., Ibson, M.L.: Landslide Recognition: Identification, Movement and Causes. John Wiley & Sons, Chichester, UK, 1996.

Dufaud, F., Brun, L., et Planchut, B.: Le Basin du Sud-Ouest marocain, in Basin sédimentaires du Litoral africain. 1ère Partie, Littoral atlantique, Symposium de New-Delhi, 1964. de l'Asoc, des Services Géol. africains, p. 5-12 (Int., 1), 1966.

Earth Resources Observation and Science (EROS) Center, USGS EROS Archive - Aerial Photography - High Resolution Orthoimagery (HRO), 2018.

El mimouni, A., Daoudi, L.: Evolution à moyen terme du contexte hydrodynamique et morpho-sédimentaire la baie d'Essaouira (Maroc atlantique), XIIèmes Journées Nationales Génie Côtier – Génie Civil, 2012.

Elkadiri, R., Sultan, M., Youssef, A., Elbayoumi, T., Chase, R., Bulkhi, A., Al-Katheeri, M.: A remote sensing-based approach for debris-flow susceptibility assessment using artificial neural networks and logistic regression modeling. Selected topics in applied earth observations and remote sensing, IEEE J Sel Top Appl Earth Obs Remote Sens. doi:10.1109/JSTARS.2014.2337273, 2014.

Elmrabet, T., Levret, A., Ramdani, M., Tadili, B.: Historical seismicity in Morocco: Methodological aspects and cases of multidisciplinary evaluation, Commissariat à l'Energie Atomique, Institut de protection et de sureté nucléaire, Département d'Analyse de sureté, 1989.

Epifânio, B., Zêzere, J. L.,. Neves, M.: Susceptibility assessment to different types of landslides in the coastal cliffs of Lourinhã (Central Portugal), J. Sea Res. (2014), http://dx.doi.org/10.1016/j.seares.2014.04.006, 2014.

Epifânio, B., Zêzere, J.L., Neves, N.: Identification of hazardous zones combining cliff retreat with landslide susceptibility assessment. In: Conley, D.C., Masselink, G., Russel, P.E., O'Hare, T.J. (Eds.), Proceedings 12th International Coastal Symposium (Plymouth, England). Journal of Coastal Research, SI, 65, pp. 1681–1686, 2013.

Ercanoglu, M., Gokceoglu, C.: Use of fuzzy relations to produce landslide susceptibility map of a landslide prone area (West Black Sea Region, Turkey). Eng Geol 75:229–250. doi: 10.1016/j.enggeo.2004.06.001, 2004.

Fekri, A.: Contribution à l'étude hydrogéologique et hydrogéochimique de la zone synclinale d'Essaouira (bassin synclinal d'Essaouira). Thèse de doctorat, Université Cadi Ayyad, Maroc, 161, 1993.

Frattini, P., Crosta, G. & Carrara, A.: Techniques for evaluating the performance of landslide susceptibility models. Eng Geol 111: 62-72, 2010.

Gentile, W.: Caractérisation et suivi d'un champ dunaire par analyses sédimentologiques et télédétection (Essaouira-Cap Sim, Maroc Atlantique). Thèse Université de Province – Aix-Marseille I, 307 p, 1997.

Gilham, J. M.: Developing A Probabilistic Recession Model Through Characterisation and Quantification of the Erosion of Chalk Sea Cliffs in Brighton (Doctoral dissertation, University of Sussex), 2018.

Girma, F., Raghuvanshi, TK., Ayenew, T., Hailemariam, T.: Landslide hazard zonation in Ada Berga district, Central Ethiopia – a GIS based statistical approach. J Geom 9(i):25–38, 2015.

Gorsevski, PV., Gessler, PE., Foltz, RB., Elliot, WJ.: Spatial prediction of landslide hazard using logistic regression and ROC analysis. Trans GIS 10(3):395–415, 2006a.

Greenwood, R.O., Orford, J.D.: Factors controlling the retreat of Drumlin coastal cliffs in a low energy marine environment — Strangford Lough, Northern Ireland. J. Coast. Res. 23, 285–297, 2007.

Halam, A.: Mesozoic geology and the opening of the North-Atlantic. J. geol. 79, p. 129-157 (Int.), 1971.

Hampton, M. A., Griggs, G. B., Edil, T. B., Guy, D. E., Kelley, J. T., Komar, P. D., ... & Shipman, H. M.: Processes that govern the formation and evolution of coastal cliffs. US Geological Survey professional paper, 1693, 7-38, 2004.

Hamza, T. and Raghuvanshi, TK.: GIS based Landslide Hazard Evaluation and Zonation - A case from Jeldu District, Central Ethiopia. J King Saud Univ Sci 29(2):151–65, 2017.

Hander, M. : Contribution à l'étude de la bioclimatologie humaine au Maroc : l'exemple d'Essaouira, Thèse de Doctorat, Paris-IV, 356 p, 1993.

Heiri O., Lotter A. F. & Lemcke G.: Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology, 25, 101–110, 2001.

Hungr, O., Leroueil, S., Picarelli, L.: The Varnes classification of landslide types, an update. Landslides 11 (2), 167–194, 2014.

Jade, S., Sarkar, S.: Statistical models for slope instability classification. Eng Geol 36(1–2):91–98, 1993.

Kanungo, DP., Arora, MK., Sarkar, S., Gupta, RP.: A comparative study of conventional, ANN black box, fuzzy and combined neural and fuzzy weighting procedures for landslide susceptibility zonation in Darjeeling Himalayas. Eng Geol 85:347–66, 2006.

Lan, HX., Zhou, CH., Wang, LJ., Zhang, HY., Li, RH.: Landslide hazard spatial analysis and prediction using GIS in the Xiaojiang watershed, Yunnan, China. Eng Geol 76:109–28, 2004.

Le Pichon, X.: La genèse de l'Atlantique Nord. La Recherche, n° 8. p. 21 (Int.), 1971.

Lee, S., Pradhan, B.: Landslide hazard mapping at selangor, malaysia using frequency ratio and logistic regression models. *Landslides*, *4*, 33–41, 2007.

Letortu, P., Costa, S., Maquaire, O., & Davidson, R.: Marine and subaerial controls of coastal chalk cliff erosion in Normandy (France) based on a 7-year laser scanner monitoring. Geomorphology, 335, 76-91, 2019.

Lharti, S., Flor, G., Daoudi, L., Flor, G.B., El mimouni A., Ben Ali, A.: Morfologia y Sedimentologia del complejo playa/dunas costeras de Essaouira (Marruecos atlantico) : modelo de transporte costero. Actas de la IX Reunión Nacional de Geomorfología, Santiago de Compostela (A. Pérez Alberti y J. López Bedoya, ed.), pp 401-417, 2006.

Lin, ML., Tung, CC.: A GIS-based potential analysis of the Landslides induced by the chi-chi earthquake. Eng Geol 71:63–77, 2003.

Linden, A.: Measuring diagnostic and predictive accuracy in disease management: an introduction to receiver operating characteristic (ROC) analysis. J Eval Clin Pract. 12: 132–139, 2006.

Mancini, F., Ceppi, C., Ritrovato, G.: GIS and statistical analysis for landslide susceptibility mapping in the Daunia area, Italy. Nat. Hazards Earth Syst. Sci. 10, 1851–1864, 2010.

Marques, F.: Sea cliff instability hazard prevention and planning: examples of practice in Portugal. J. Coast. Res. SI 56, 856–860, 2009.

Marques, F., Matildes, R., Redweik, P.: Statistically based sea cliff instability hazard assessment of Burgau-Lagos coastal section (Algarve, Portugal). Proceeding of the 11th International Coastal Symposium. Journal of Coastal Research, SI64: 927-931, 2011.

Marques, F.: Regional scale sea cliff hazard assessment at Sintra and Cascais counties, western coast of Portugal. Geosciences, 8(3), 80, 2018.

Marques, R.T.F.: Estudo de movimentos de vertente no concelho da Povoação (ilha de São Miguel, Açores): Inventariação, caracterização e análise da susceptibilidade. Ph.D. Thesis, Geological Risks, University of Azores, Ponta Delgada, Portugal, 2013.

Mateus, L. R., Frederico, G. S., & Cesar, F., Barella: Landslide susceptibility mapping using the statistical method of Information Value: A study case in Ribeirão dos Macacos basin, Minas Gerais, Brazil, Annals of the Brazilian Academy of Sciences, An Acad Bras Cienc (2021) 93(1): e20180897 DOI 10.1590/0001-3765202120180897, 2021.

Meena, S. R., Ghorbanzadeh, O. and Blaschke, T.: A Comparative Study of Statistics-Based Landslide Susceptibility Models: A Case Study of the Region Affected by the Gorkha Earthquake in Nepal, *ISPRS Int. J. Geo-Inf.*, https://doi.org/10.3390/ijgi8020094, 2019.

Mengistu, F., Suryabhagavan, KV., Raghuvanshi, TK., Lewi, E.: Landslide Hazard zonation and slope instability assessment using optical and InSAR data: a case study from Gidole town and its surrounding areas, southern Ethiopia. Remote Sensing of Land 3(1):1–14, 2019.

Mennani, A.: Apports de l'hydrochimie et de l'isotopie à la connaissance du fonctionnement des aquifères de la zone côtière d'Essaouira. Thèse de doctorat, Université Cadi Ayyad, Maroc, 152, 2001.

Michard, A., Westphal, M., Bosert, A., et Hamzeh, R.: Tectonique de blocs dans le socle atlaso-mésétien du Maroc : une nouvelle interprétation des données géologiques et paléomagnétiques. Earth Plan. Sci. Let. 24, p. 363-68 (Int.), I975.

Moore, L.J., Griggs, G.B.: Long-term cliff retreat and erosion hotspots along the central shores of the monterey bay national marine sanctuary. Mar. Geol. 181 (1–3), 265–283, 2002.

Moore, R., & Davis, G.: Cliff instability and erosion management in England and Wales. Journal of Coastal Conservation, 19(6), 771-784, 2015.

Neves, M., Ramos-Pereira, A.: The interaction between marine and sub-aerial processes in the evolution of rocky coasts: the example of Castelejo (southwest Portugal). Bol. Inst. Esp. Oceanogr. 15, 251–258, 1999.

Neves, M., Zêzere, J.L., Henriques, C.: Garcia, R., Oliveira, S., Piedade, A., Modeling the long term evolution of rocky coasts in central Portugal. Avances de la Geomorfología en España. Actas de la XII Reunión Nacional de Geomorfología pp. 73–76, 2012.

Oliveira, S. C., Catalão, J., Ferreira, Ó., Alveirinho D. J.: Evaluation of cliff retreat and beach nourishment in southern Portugal using photogrammetric techniques. Journal of Coastal Research, 24(4A): 184-193. https://doi.org/10.2112/06-0781.1, 2008

Oliveira, S. C., Zêzere, J.L., Lajas, S., Melo, R.: Combination of statistical and physically based methods to assess shallow slide susceptibility at the basin scale. Natural Hazards and Earth System Science, 17, 1091–1109, https://doi.org/10.5194/nhess-17-1091-2017, 2017

Pawluszek, K.: Landslide features identifcation and morphology investigation using high-resolution DEM derivatives, Natural Hazards (2019) 96:311–330 https://doi.org/10.1007/s11069-018-3543-1, 2019

Pereira, S., Santos, P.P., Zêzere, J.L., Tavares, A.O., Garcia, R.A.C., Oliveira, S.C.: A landslide risk index for municipal land use planning in Portugal. *Science of the Total Environment*, 735: 139463. https://doi.org/10.1016/j.scitotenv.2020.139463, 2020

Petley, DN.: The global occurrence of fatal landslides in 2007. Geophysical Research Abstracts, vol. 10, EGU General Assembly 2008, p 3, 2008.

Queiroz, S. M., & Marques, F. M.: Sea cliff instability susceptibility considering nearby human occupation and predictive capacity assessment. Engineering Geology, 253, 75-93, 2019.

Reichenbach, P., Rossi, M., Malamud, B. D., Mihir, M. and Guzzetti, F.: A review of statistically-based landslide susceptibility models, https://doi.org/10.1016/j.earscirev.2018.03.001, *2018.*

Remondo, J., González, A., Díaz De Terán, J. R., Cendrero, A., Fabbri A., and Chung, C. J. F.: Validation of Landslide Susceptibility Maps; Examples and Applications from a Case Study in Northern Spain, Natural Hazards 30: 437–449, 2003.

Rocha, J., Ferreira, J. C., Simões, J., & Tenedório, J. A.: Modelling coastal and land use evolution patterns through neural network and cellular automata integration. Journal of Coastal Research, SPEC. ISSUE 50, 827–831, 2007

Saadi, M.: Relations des alignements structuraux au Maroc avec différents phénomènes géologiques et leur contribution à la compréhension de l'évolution structurale du pays. N.M.S.G.M., 236, p. 13-18 (Int.), 1972.

Shahabi, H., Khezri, S., Ahmad, B.B., Hashim, M.: Landslide susceptibility mapping at Central Zab Basin, Iran: A comparison BETWEEN analytical hierarchy process, frequency ratio and logistic regression models. *Catena*, *115*, 55–70, 2014.

Shano, L., Raghuvanshi, T. K. and Meten, M.: Landslide susceptibility evaluation and hazard zonation techniques – a review, geoenvironmental-disasters, springer open, 2020.

Simon, C.: Le géo-système dunaire anthropisé d'Essaouira – est (Maroc Atlantique) dynamique et paléo-environnements. Thèse de doctorat. Univ. Aix Marseille I, 204 p, 2000.

Smaij, Z.: Typologie de la qualité des ressources en eaux du bassin de Tensift Al-Haouz et cadre juridique de protection et de préservation. Université Cadi Ayyad Faculté des sciences et techniques. Marrakech. 96p, 2011.

Sunamura, T.: Geomorphology of rocky coasts. Wiley, Chichester. 302 pp, 1992.

Sunamura, T.: Rocky coast processes: with special reference to the recession of soft rock cliffs doi: 10.2183/pjab.91.481 ©2015 The Japan Academy, 2015

Taleb, M.S., Fennane, M.: Vascular Plant Communities of Morocco, Geobotany Studies, Springer International Publishing AG, part of Springer Nature, 2019.

Teixeira M.: Movimentos de Vertente: Factores de Ocorrência e Metodologia de Inventariação. Geonovas (20):12 p, 2006.

Teixeira, M., Bateira, C., Marques, F., & Vieira, B.: Physically based shallow translational landslide susceptibility analysis in Tibo catchment, NW of Portugal. Landslides, 12(3), 455-468, 2015.

Trenhaile, AS.: The Geomorphology of Rock Coasts. Oxford: Oxford University Press, 384p, 1987.

Van Den Eeckhaut, M., Reichenbach, P., Guzzetti, F., Rossi, M., Poesen, J.: Combined landslide inventory and susceptibility assessment based on different mapping units: an example from the Flemish Ardennes, Belgium. Nat. Hazards Earth Syst. Sci. 9, 507–521, 2009.

Van Westen, C.J., van Asch, T.W.J., Soeters, R.: Landslide hazard and risk zonation — why is it still so difficult? Bull. Eng. Geol. Environ. 65, 167–184, 2006.

Van Westen, CJ., Castellanos, E., Kuriakose, SL.: Spatial data for landslide susceptibility, hazard, and vulnerability assessment: an overview. Eng Geol 102:112–131, 2008.

Van Westen, CJ., Rengers, N., Terlien, MTJ., Soeters R.: Prediction of the occurrence of slope instability phenomenal through GIS-based hazard zonation. Geol Rundsch 86(2):404–14, 1997.

Varnes, D.J.: International Association of Engineering Geology Commission on Landslides and Other Mass Movements on Slopes. Landslide Hazard Zonation: A Review of Principles and Practice UNESCO, Paris, 1984.

Varnes, D.J.: Slope movement types and processes. In: Schuster, R.L., Krizek, R.J. (Eds.), Special Report 176: Landslides: Analysis and Control. Transportation and Road Research Board, National Academy of Science, Washington D. C., pp. 11–33, 1978.

Varnes, DJ.: Landslide types and processes. In: Turner AK, Schuster RL (eds) Landslides: investigation and mitigation, Transportation Research Board special report 247. National Academy Press, National Research Council, Washington, D.C, 1996.

Violante, C.:Rocky coast: geological constraints for hazard assessment,Geological Society, London, Special Publications, 322, 1-31, 1 January 2009, https://doi.org/10.1144/SP322.1, 2009

Wang, L.-J., Guo, M., Sawada, K., Lin, J., Zhang, J.: A comparative study of landslide susceptibility maps using logistic regression, frequency ratio, decision tree, weights of evidence and artificial neural network. *Geosci. J.*, *20*, 117–136, 2016.

Weisrock, A.: Géomorphologie et paléo-environnements de l'Atlas atlantique (Maroc). Thèse d'état, Paris I, 931 p, 1980.

WP/WLI.: International Geotechnical Societies' UNESCO (Working Party on World Landslide Inventory), Multilingual Landslide Glossary. Bitech Publisher, Richmond, British Columbia, Canada, 1993.

Yalcin, A.: GIS-based landslide susceptibility mapping using analytical hierarchy process and bivariate statistics in Ardesen (Turkey): comparisons of results and confirmations. Catena 72:1–12, 2008.

Yin, K.L., Yan, T.Z.: Statistical prediction models for slope instability of metamorphosed rocks. In: Bonnard, C. (Ed.), Proceedings of the 5th International Symposium on Landslides (Lausanne, Switzerland), 2, pp. 1269–1272, 1988.

Zêzere, J. L., Reis, E., Garcia, R., Oliveira, S., Rodrigues, M. L., Vieira, G., and Ferreira, A. B.: Integration of spatial and temporal data for the definition of different landslide hazard scenarios in the area north of Lisbon (Portugal), Nat. Hazards Earth Syst. Sci., 4, 133–146, https://doi.org/10.5194/nhess-4-133-2004, 2004.

Zêzere, J.L.: Landslide susceptibility assessment considering landslide typology. A case study in the area north of Lisbon (Portugal). Nat. Hazards Earth Syst. Sci. 2, 73–82, 2002.

Zêzere, J.L.: Pereira, S., Melo, R., Oliveira, S.C., Garcia, R.A.C., Mapping landslide susceptibility using data-driven methods. Science of the Total Environment 589, 250–267, 2017.

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