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.~~which qualified as a wide applied statistical model in several coastal environments.~~ This study aims to ~~The aim of this study was to~~ evaluate the susceptibility for the occurrence of landslides in Essaouira coastal area using th~~ie~~s bivariate statistical method. In this coastal area, 588 landslides of distinct types were identified, inventoried and mapped. They mostly result from ~~In this coastal area were identified, inventoried and mapped 588 landslides, of different types, mostly 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. ~~training (70%) and for validating (30%).~~ 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 ~~land-use patterns, 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 ROC curves 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.~~Two methodologies were adopted to evaluate coastal landslide susceptibility, one considering a pixel base approach and~~

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Commenté [a1]: Rev1: b) Regarding the landslide inventory and the training and validation groups. How were selected the two groups? Randomly? Selected according to any specific criteria? Please state in the methods.
c) Why did you use 70% of the inventory and 30% for the validation? Why not 50% for each? You should state in the methods section why did you use these percentages?

Commenté [a2R1]: -The landslide inventory partition in training and validation groups were selected randomly. This partition criteria will be properly described in the methods section.

Commenté [a3]: Rev2: In the modeling, 70% of the inventory were used as training set and the other 30% as validation set – explain why those values were used.

Commenté [a4R3]: •We acknowledge the reviewer doubt. The 70/30 partition was chosen because is in agreement with the commonly used partitions used for landslide susceptibility models training and validation. (as an example please see: https://www.mdpi.com/2220-9964/9/12/696)

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~~another one using coastal terrain units.~~ The resulted coastal landslide susceptibility maps allowed classifying 38 % of the rocky coast subsystem with high susceptibility to landslides, mostly ~~being the majority of these high susceptible areas~~ located in the southern part of the Essaouira coastal area. Th~~e~~ose 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 ~~These processes result~~ essentially from the interaction of sub-aerial, marine and anthropogenic processes (Trenhaile 1987, Sunamura 1992, Hampton & Griggs 2004, Greenwood &~~and~~ 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) ~~Marques, 2009).~~

The processes of building landslide susceptibility maps generally involve~~s~~ 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 ~~Regarding rocky coastal areas landslide susceptibility/hazard assessment, researchers mainly focusing the approach on 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, controlling ~~which control~~ 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, ~~which have~~ 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 angle, slope aspect, slope perpendicular and profile curvature, topographic wetness factor index (TWI), topographic position factor 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).~~These factors, although~~

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Commenté [a5]: Rev2: L 42 – Classical references as Sunamura (1992) and Trenhaile (1987) are much more meaningful in this context. Other suggestion: Hampton & Griggs (2004).

Commenté [a6R5]: •- Done. In the revised version of the manuscript this text section will be rewritten as "These processes result essentially from the interaction of sub-aerial, marine and anthropogenic processes (Trenhaile 1987, Sunamura 1992, Hampton & Griggs 2004, Greenwood & Orford, 2007),"

Commenté [a7]: Rev1: Minor comment: in line 43 you refer to "pressure". What kind of pressure? Urban pressure?

Commenté [a8R7]: •Authors Reply: with "pressure", we intend to refer to the pressure applied by human activities on coastal systems. In the revised version of the manuscript "pressure" will be replaced for "to Anthropic activities pressure"

Commenté [a9]: Rev2: L 44 – In the reference it is suggested to ad "e.g. Marques, 2009" but also other relevant references as Teixeira (2006, 2015), Moore and Davis (2015), Gilham et al., (2018) among others.

Commenté [a10R9]: •Authors Reply: - We agree and thank the reviewer suggestion. In the revised version of the manuscript this text section will be rewritten as "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)"

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they depend on the scale of analysis and type of landslides, include generally; elevation, slope angle, slope aspect, slope perpendicular and profile curvature, cliff edge height, topographic wetness factor index TWI, topographic position factor index TPI, slope over area ratio SOAR, solar radiation, faulting, lithology, coastal slope toe protection, 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).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). while there are other suitable approaches such as the bivariate, multivariate, and active learning statistical methods. 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, Van Den Eeckhaut *et al.* 2009, 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) and a significative large number of bivariate, multivariate, and active learning statistical methods is 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) and 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).

Commenté [a11]: Rev2: L 60-62 – The landslide predisposing factors which have been used in published studies are listed along specific cliff factors as the cliff toe protections. This requires some separation, due to the specific context of sea cliffs and also because it was found that the factor is relevant in these studies (Marques et al,. 2011, 2013; Marques, 2018, Guilham et al., 2018, Letortu et al., 2019, Queiroz and Marques, 2019).

Commenté [a12R11]: •Authors Reply: - We agree and thank the reviewer suggestion. In the revised version of the manuscript this text section will be rewritten as "These factors, although they depend on the scale of analysis and type of landslides, include generally: elevation, slope angle, slope aspect, slope perpendicular and profile curvature, topographic wetness factor index (TWI), topographic position factor 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)."

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Commenté [a13]: Rev2: L 71 – For sea cliff susceptibility, the terrain unit discussion and one solution were presented in Marques et al. (2011, 2013), which were published before Epifâneo et al. (2014).

Commenté [a14R13]: •Authors Reply: - Done. In the revised version of the manuscript the references will be listed as "(Van Den Eeckhaut *et al.* 2009, Marques *et al*,. 2011, 2013, Epifânio 2014, Corominas *et al.* 2014, Zêzere *et al.* 2017)."

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).

~~The field observations are useful for every type of landslide studies except for small area or single landslide studies (Shano et al 2020)~~. 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 ~~coastal~~ dynamics of Essaouira coastal area is poorly studied~~has been little 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).

Commenté [a15]: Rev2: L 95 – The phrase seems out of context.

Commenté [a16R15]: •Authors Reply: Done. The phrase "The field observations are useful for every type of landslide studies except for small area or single landslide studies (Shano et al 2020)." was removed from the revised version of the manuscript.

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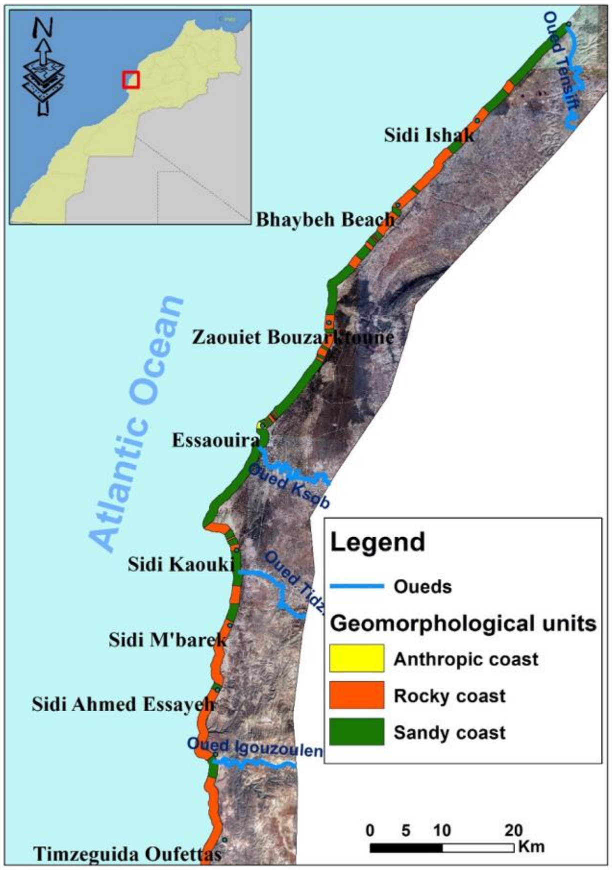
Commenté [a17]: Rev2: There is a lack of clarity on the study area: it is referred in several parts of the paper that study focus on the coastal area, but in Line 107 is stated that the focus is on landslides at the sea cliffs. Later, in lines 113 and 114 and Fig. 1, the coastal subsystems include sandy coast, rocky coast, and anthropic coast. The rocky coast corresponds to sea cliffs or includes sections of low height rocky coast, with no well-defined cliff. It is important to clarify and to use uniform designations along the paper.

Commenté [a18R17]: •Authors Reply: We acknowledge the reviewer comment. The study area is defined by the sea cliff sectors located along the rocky coast subsystems of the Essaouira coastal area. As recommended, we clarify and use uniform designations along the revised version of the manuscript.


Atlantic Ocean
Oued Tensift
Sidi Ishak
Bhaybeh Beach
Zaouiet Bouzarktoune
Essaouira
Oued Ksob
Sidi Kaouki
Oued Tidzi
Sidi M'barek
Sidi Ahmed Essayeh
Oued Igouzoulen
Timzeguida Oufettas
Legend
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Geomorphological units
Anthropic coast
Rocky coast
Sandy coast
0 5 10 20
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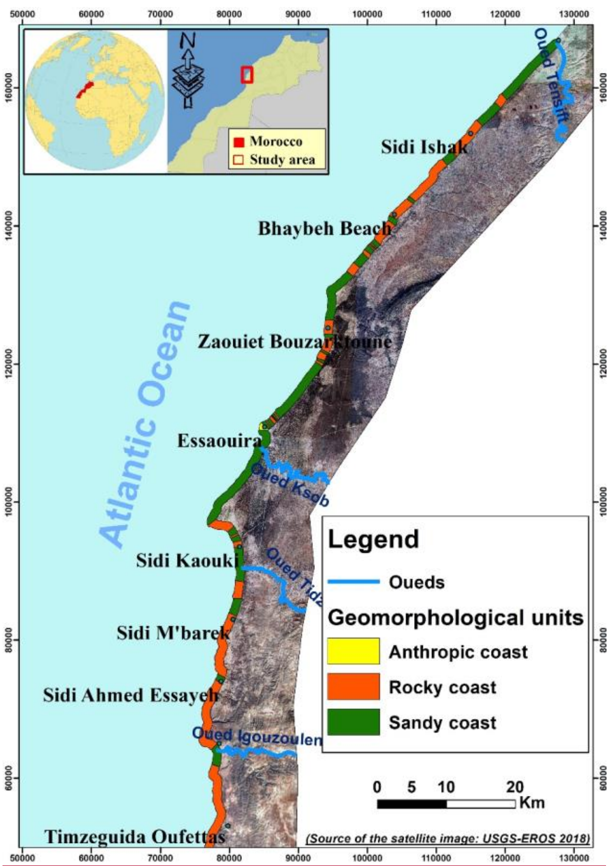

Figure 1: Geographic location of Essaouira coastal area and its sandy and rocky coast subsystems

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~~Geologically, the Atlantic Atlas in general is the westernmost part of the High Atlas, between the Triassic Argana couloir and the Atlantic Ocean (Weisrock 1980). We are therefore in the western High Atlas, whose northern part, the largest (Haha and Chiadma), the plateaus drop gently from SE to NW, in accordance with the overall structural inclination~~. 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)The landscape is however varied, crossed by cuestas and vigorous crests, turned towards the SE and multiplied by the frequent alternations of sandstone, dolomitic, limestone, or marl, clay and gypsum layers; because interrupted by sudden isolated anticlinal folds, as the Jbel Hadid (725 m), quite to the N, or the Jbel Ouamsitten (900 m); while towards the extreme west, we note, in addition to these formations, 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 more or less deep marine sedimentationsTo the south, a coastal basin with original sedimentary material has long been known as the "Haha Basin", which was studied in detail by Dufaud et al. 1966, Its existence 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 of sandstones, pelites, conglomerates, and finally red salt clays that is essentially continental, while from the Lower Liassic succeed more or less deep marine sedimentations, they are divided almost equally between Jurassic, Lower Cretaceous and Upper Cretaceous. 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 distensional 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 the second direction, WNW-ESE, 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 replay 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

Commenté [a19]: Rev1: L. 125-129: Big paragraph, with several sentences separated by semi-colon. Consider rephrasing in shorter and clear sentences.

Commenté [a20R19]: •Done. The paragraph was rephrased as: "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)."

Commenté [a21]: Rev2: L 121-129 – Rewrite and clarify the setting of the study area and be more ...

Commenté [a22R21]: •Authors Reply: In the revised version of the manuscript this text section will be rewritten as "Geologically, the study area is located in the Atlantic ...

Commenté [a23]: Rev1: - L. 131: "(...) Dufaud et al. 1966, Its existence..."

Commenté [a24R23]: •Authors Reply: We thank the reviewer observation. We change it to "Dufaud et al. (1966), is related…"

Commenté [a25]: Rev1: - L. 132: "(...) Weisrock 1980), It consists (...)" - substitute "," by "."

Commenté [a26R25]: •Authors Reply: - Done

Commenté [a27]: Rev1: L. 130-135: you have two sentences starting after a comma, instead a full ...

Commenté [a28R27]: •Authors Reply: Done. The text was rephrased as "To the south, a coastal basin with original sedimentary material known as "Haha Basin" ...

Commenté [a29]: Rev2: L 143 – extensional instead of distensional; NNE-SW ??? correct. ...

Commenté [a30R29]: •Authors Reply: - We thank the reviewer observation. We change it to ", includes the extensional faults fundamentally oriented NNE-SSW"

Commenté [a31]: L 144 – What is the second direction – only one was indicated above.

Commenté [a32R31]: •Authors Reply: The other one is linked to the opening of Atlantic. The text was modified to turn clear this question. We change it to "the second ...

Commenté [a33]: Rev1: L. 148: you could delete "of the replay" ...

Commenté [a34R33]: •Authors Reply: Done. We change the phrase to "a W-E direction appears as a result of the ancient Hercynian direction (Saadi, 1972)."

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 fairly 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 readaptations (Weisrock 1980).

Commenté [a35]: Rev2: L 130- 166 – The text chaotic and requires clarification, a deep reformulation, and the use of shorter periods.

Commenté [a36R35]: •Authors Reply: In the revised version of the manuscript this text section will be rewritten as "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 more or less deep marine sedimentations."

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 16.4ºC in January and 22.5ºC 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~~According to the rainfall data, which were made available to us by the Tensift Water Basin Agency. They concern the stations of Adamna, Chichaoua, Talmest, Abadla and Igrounzar, The analysis of the average monthly variability of rainfall for the period 1965-2015 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.

Commenté [a37]: Rev1: L. 195-199: "According to the rainfall data, which were made available…". You stopped this sentence without finishing your idea. Then in L. 196 you end a sentence with a comma and then start a new sentence.

Be very careful with this. You have many examples like this.

This becomes confusing.

Commenté [a38R37]: •Authors Reply: Thanks for the observation. We rewrite the text as "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."

Commenté [a39]: Rev1: L. 202-203: Please, show the maximum and minimum values (mm) of precipitation

Commenté [a40R39]: •Authors Reply: - Done. The description in the revised version of the manuscript will be "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."

Commenté [a41]: Rev2: The rainfall data would be better expressed with the inclusion of graphs instead of descriptive and incomplete data.

Commenté [a42R41]: •Authors Reply: We think there is no need to add graphs. We tried to improve the description and we consider that in this revised version is clear enough taking into consideration the contribution of this factor in this study.

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 and even the inability of some other wells to recover their initial water level, 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).~~These are related to precipitation which thus controls the regime of the phreatic aquifer. A number of 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 and even the inability of some other wells to recover their initial water level, 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.

Commenté [a43]: Rev1: L. 223: In the end of the line "… (Mennani, 2001), It…" – again you end a sentence with a comma.

Commenté [a44R43]: •Authors Reply: Thanks for the observation. We change it to "conditioned by the straightening of its bedrock to the east following the uplift of the Tidzi diapir (Mennani, 2001)."

Commenté [a45]: Rev1: L. 225-231: A big sentence that could be divided in two, starting in line 228 "For this reason…".

Commenté [a46R45]: •Authors Reply: - Done. The text in the revised version of the manuscript will be "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 and even the inability of some other wells to recover their initial water level, 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)."

Commenté [a47]: Rev2: L 216 – 231 – The hydrogeological information is relevant for the sea cliffs evolution?

Commenté [a48R47]: •Authors Reply: We think it is relevant especially in the southern part, we explained some links between hydrogeological description and the lithological information collected on springs as a possible driver: "… 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 part 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 the subsequent movements of landslide in the post-failure phase, especially where we have marls or clays."

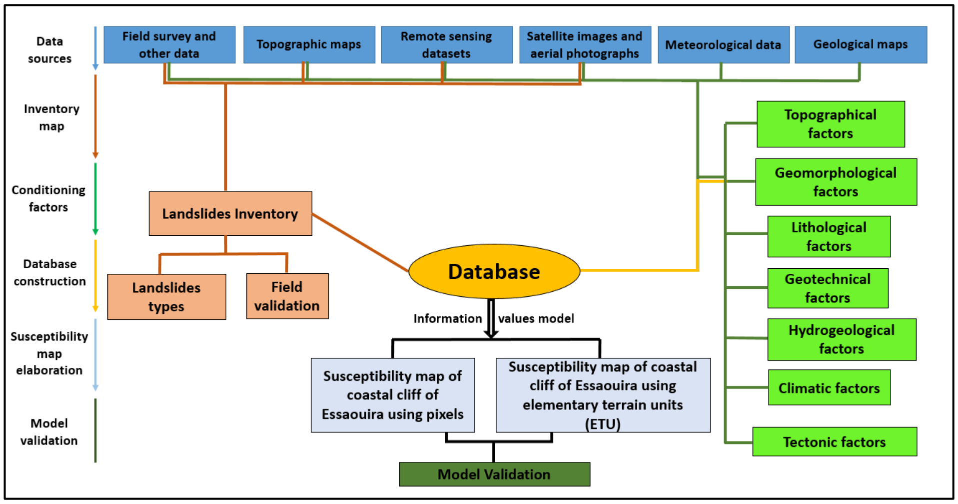

Figure 2: Schematic diagram of the used methodology

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, 10m 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
	Sidi Ishaq 2008		1/25000

Commenté [a49]: Rev2: L 246 - 247 – What was the threshold percentage of unstable area in each terrain unit to be considered unstble.

Commenté [a50R49]: •Authors Reply: We considered the presence or absence of landslides, each terrain unit contain a polygon of a landslide is considered unstable.

Commenté [a51]: Rev2: The aerial photographs and satellite images area coverage for the landslides inventory construction should be included in table 1. This is important because any inventory is incomplete by its own nature and depends heavily on the database available. It is also important to clarify that the inventory is of the historical type, with no past date of occurrence limits, and it is also useful to point out its limitations.

Commenté [a52R51]: • Authors Reply: The aerial photographs and satellite images area cover all the study area and data sources used will be included in Table 1 as suggested. Regarding the question if the inventory is of the historical type, is not. We used mostly recent images to map the landslides. Nevertheless, we consider that for larger deep-seated landslides the inventory is quite complete, since landslide features associated to these landslides tend to remain for long time in the landscape. For shallow and smaller landslides, we assume some uncertainty on the number of landslides mapped, even so, the fact that cliffs are not explored for agriculture and the driest climate could also allow the maintenance of these landslides features on the landscape for a significant time from occurrence, given that way more consistency to the landslide inventory.

Topographic maps	Berrakat Erradi 2008	National Agency of Land Conservation, Cadastre and Cartography (ANCFCC)	
	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

Code de champ modifié
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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, slope 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 (10m 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 ~~part~~section, and Marrakech 1/500000-scale for the nor~~u~~thern ~~part~~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~~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.

Code de champ modifié

Commenté [a53]: Rev1: L. 284: You start again a sentence after a comma. "… (Epifânio, et al. 2013), Slope angle…".

Commenté [a54R53]: •Authors Reply: Thank you for the observation. We change the text in the revised version of the manuscript to "because it enables the quantification of the weight of trivial qualitative quadrant (Epifânio, et al. 2013). Slope angle…"

Commenté [a55]: Rev1: e) L. 284-286: You state that slope angle does not have the same importance for all types of landslides in your study area. (This would be better stated and discussed in results and discussion section).
- Can you state why? Is it only because different types of landslides require different factors and different weight of each factor? Or is it because in your study area, are there other important factors also contributing for slope instability?

Commenté [a56R55]: •Authors Reply: Thanks for the comment. In fact, slope is an important predisposing factor for landslide occurrence, and different landslide types, as described in literature, could be conditioned by different slope angle classes. Even so, lithology, structure and deposits also play an important role for the occurrence of the different types of landslides. These aspects will better be addressed and discussed in the results and discussion sections as suggested.

Commenté [a57]: Rev1: L. 292: "… noutern part…". Do you mean "northern section", "northern area"?

You often use in the text the terms northern and southern part. Consider using "section" or "area"…instead of "part". It is more correct from a geographical point of view.

Commenté [a58R57]: •Authors Reply: We check the manuscript and we substituted part by section as suggested. In this context we change it to "southern section, and Marrakech 1/500000-scale for the northern section, completed with the field survey."

Commenté [a59]: Rev2: L 295 – 296 – phrase seems incomplete.

Commenté [a60R59]: •Authors Reply: Done; it's only because of comma instead of point. The phrase will be replaced by "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."

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

Commenté [a61]: Rev2: Table 2 – Replace “limstone” by limestone.

Commenté [a62R61]: •Authors Reply: - Done

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 (~~Lee and Pradhan 2007, Epifânio *et al*. 2014, Shahabi *et al*. 2014, Wang 2016~~ 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:

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

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:

Commenté [a63]: Rev2: L 312 – The references deserve improvement: Lee and Pradhan (2007), Shahabi et al. (2014), Wang et al. (2016) studied sea cliffs? Proper references include Marques et al, 2011, 2013; Epifâneo et al., 2013, 2014.

Commenté [a64R63]: •Authors Reply: We thank the reviewer observation. The references list will be like this "This method was successfully applied to coastal areas worldwide (Marques et al, 2011, 2013; Epifâneo et al., 2013, 2014)."

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

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 the~~a~~n 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, as an example please see (Chen et al 2020). ~~adopting~~ 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

Mis en forme : Gauche, Interligne : Multiple 1.08 li

Commenté [a65]: Rev1:L. 342: Consider substituting "than" by "then".

Commenté [a66R65]: •Authors Reply: - Done. The phrase will be "Each landslide type inventory dataset was then sub-divided into a training and a validation group (Remondo et al. 2003)."

Mis en forme : Non Surlignage

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 12.5×12.5m 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.

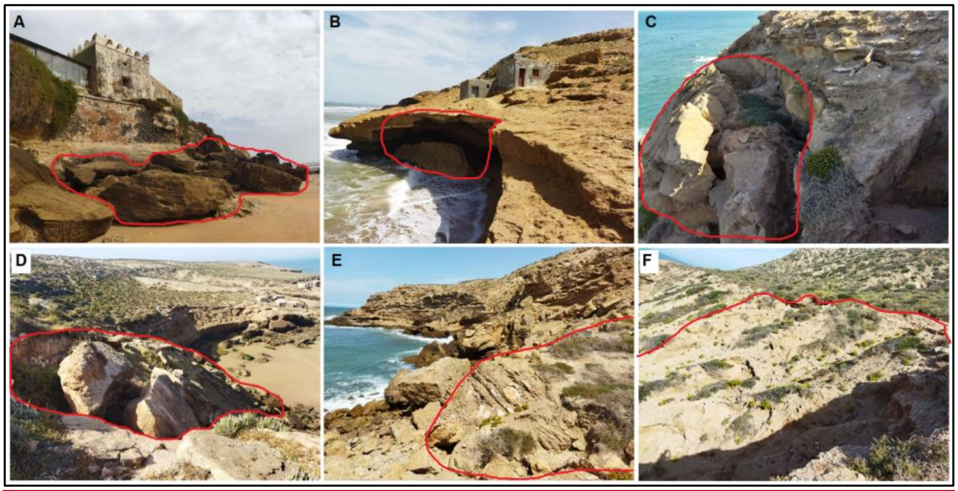


Figure 3: Some landslide types examples from study area; A, B Rock falls, C Rock topple, ~~E~~ D Translational slide, ~~F~~ E Rotational slide with back tilting, ~~G~~ F Debris flow.

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%).

Commenté [a67]: Rev1: Figure 3: You jumped from C to E and forgot D.

Commenté [a68R67]: •Authors Reply: We corrected the figures letters. The new version of figure is placed bellow.

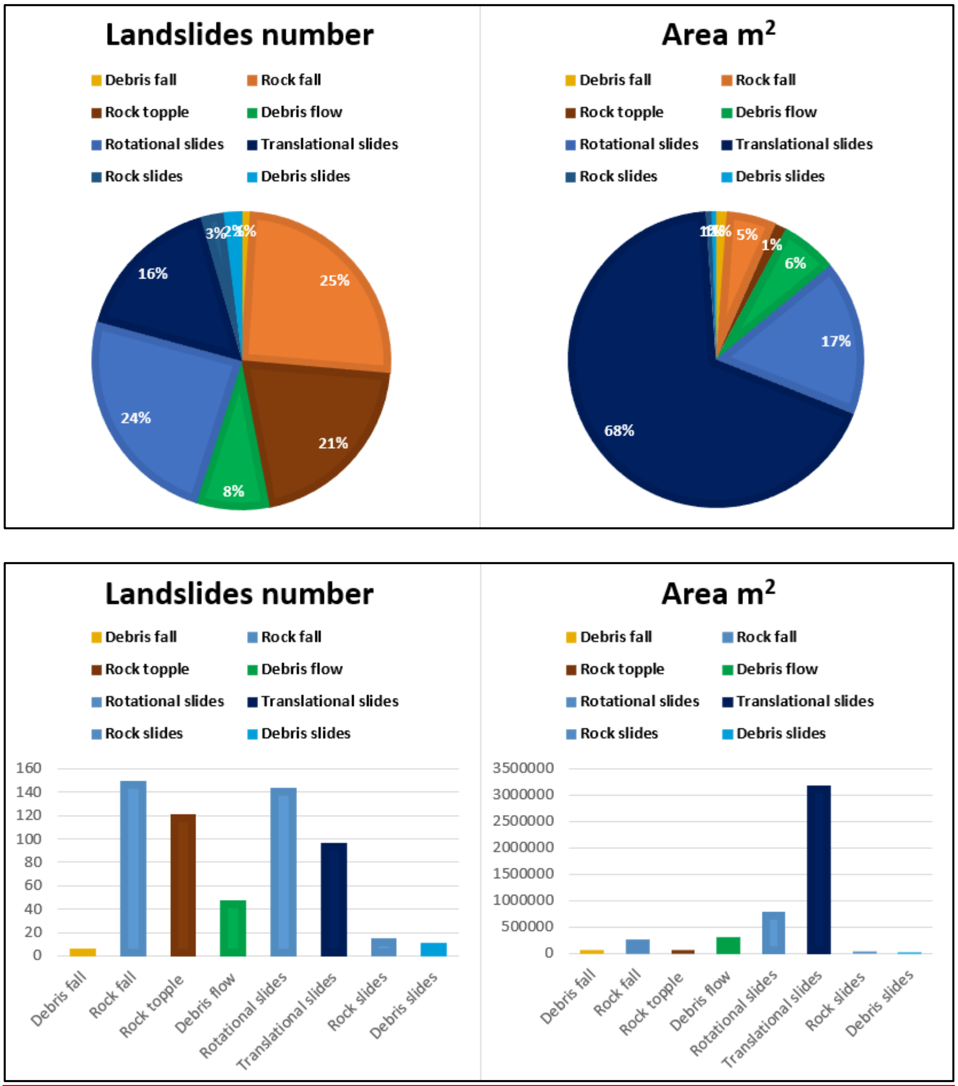
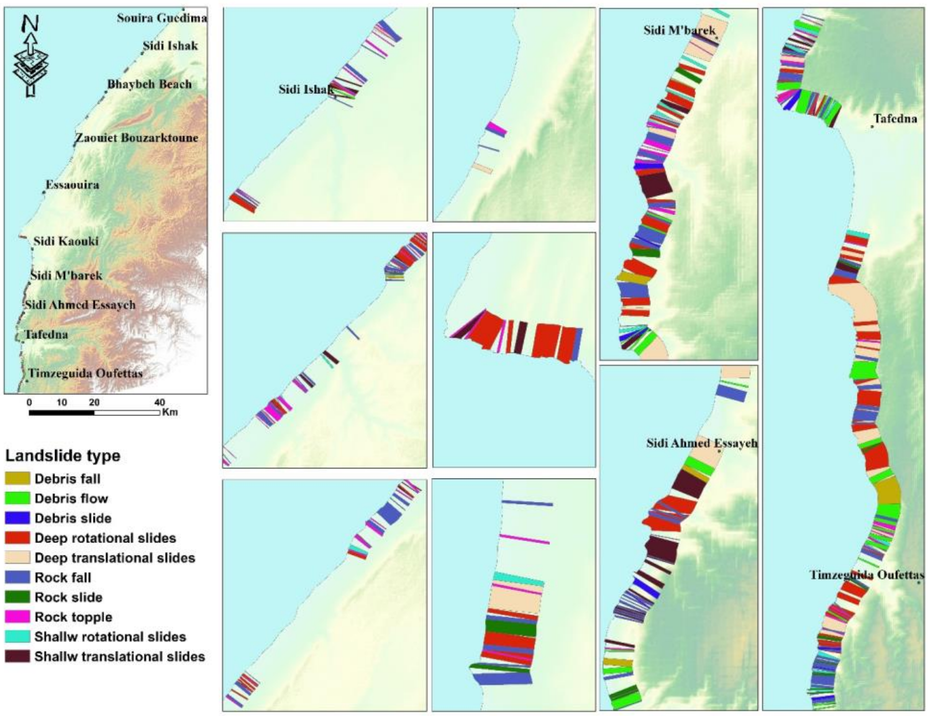


Figure 4: The relative distribution of landslides by type and area in the ETU of the study area

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

Commenté [a69]: -Rev2: Figure 5 – Replace the pie plots by bar or column plots.

Commenté [a70R69]: •Authors Reply: We believe that, by a typo, the reviewer is referring to figure 4 and not figure 5. The pie plots are in figure 4 and not figure 5. Yes, we can replace them by bar or column plots.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Timzeguida Oufettas
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Landslide type
Debris fall
Debris flow
Debris slide
Deep rotational slides
Deep translational slides
Rock fall
Rock slide
Rock topple
Shallw rotational slides
Shallw translational slides
Sidi Ishak
Sidi M'barek
Sidi Ahmed Essayeh
Tafedna
Timzeguida Oufettas

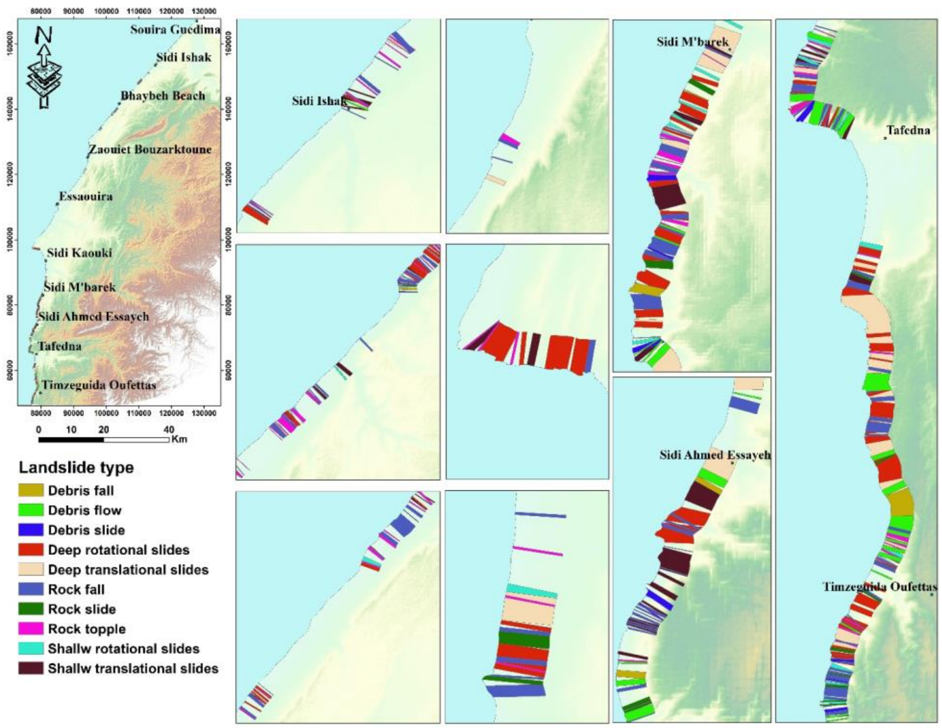


Figure 5: Spatial distribution of landslide types in study area

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 ~~most~~ 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

Commenté [a71]: Rev1: L. 412-413: Like it is written, it does not make much sense.
Do you mean "... Calcareous crusting and Essaouira sandstone-calcarenite are the two lithological formations most found in the majority of ETU…"?

Commenté [a72R71]: •Authors Reply: Yes. In the study area, we have 1534 ETU and in each ETU it could be found more than one lithology type. We rewrite the phrase to turn clear: "Regarding the number of ETU per lithology type, Calcareous crusting and Essaouira Sandstone-calcarenite are the two lithological formations most founded in the majority of ETU (total ETU = 1534), these lithologies are present in 1216 and 1270 ETU, respectively."

Commenté [a73]: Rev2: L 417 – What is "limestone barre"? Clarify.

Commenté [a74R73]: •Authors Reply: It is a cretaceous formation with limestone, looks like a continuous barre (band or visible layer) in the cliff area.

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 ~~part~~ 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 ~~part~~ section (from log 1 to log 13), while there is no much variation in the northern ~~part~~ 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~~'s~~ 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.

Commenté [a75]: Rev1: L. 435: that's – please, avoid word contractions.

Commenté [a76R75]: •Authors Reply: - Done. The new phrase will be "that is why we consider them important, especially because some of them are in contact with springs,"

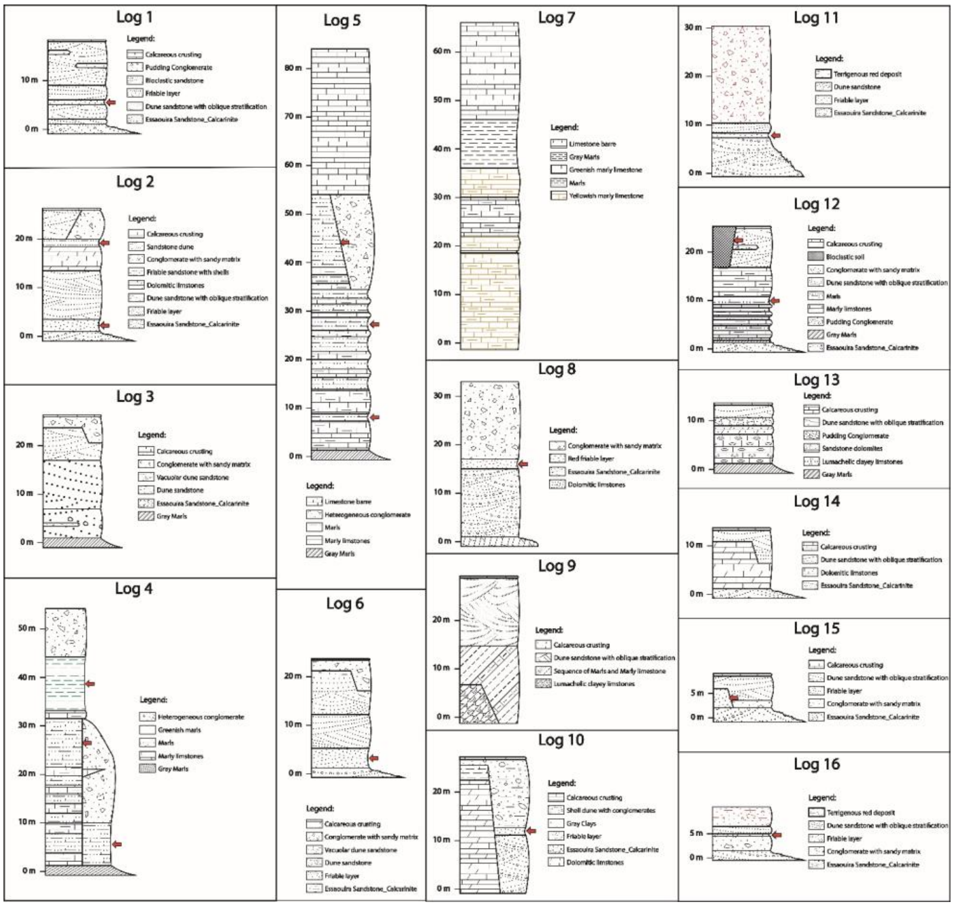
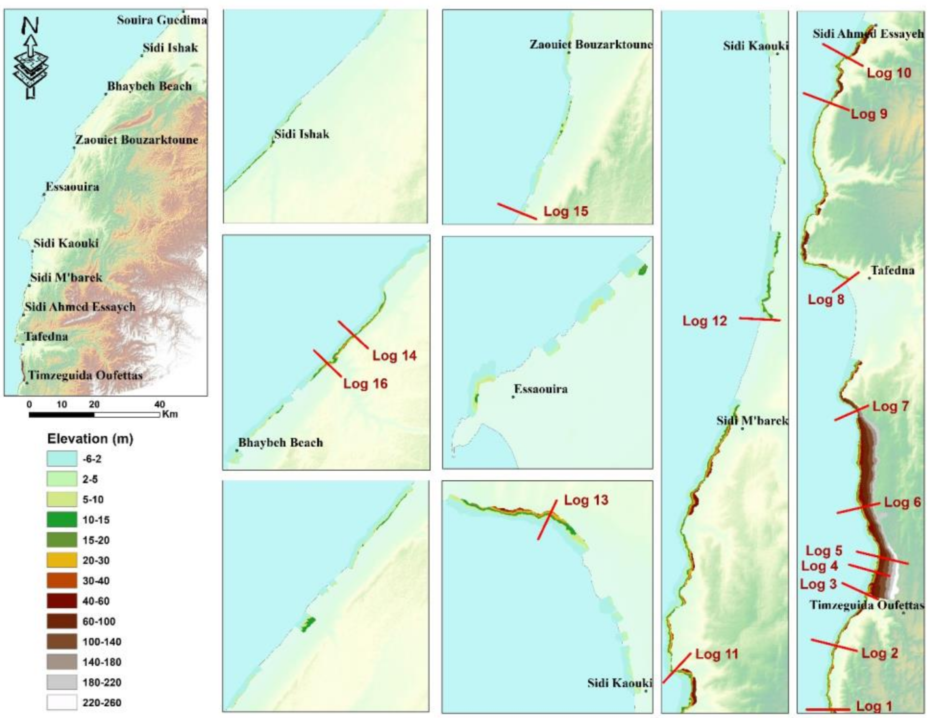


Figure 6: Stratigraphic columns for Essaouira coastal area

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 ~~part~~ section cliffs present higher elevation, for the reason that those area are more closed to the High Atlas mountains feet.

Commenté [a77]: Rev1: Figure 6: This figure is very low. Please make the fond size readable. The legend and the vertical scale are not readable.

Commenté [a78R77]: •Authors Reply: We acknowledge your comment, the figure's resolution is good, it is because of the logs number that we couldn't rise the size, but we suggest splitting it in two pages or figuring it in one page landscape format, as illustrated bellow.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Timzeguida Oufettas
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Elevation (m)
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2-5
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Log 16
Bhaybeh Beach
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Log 13
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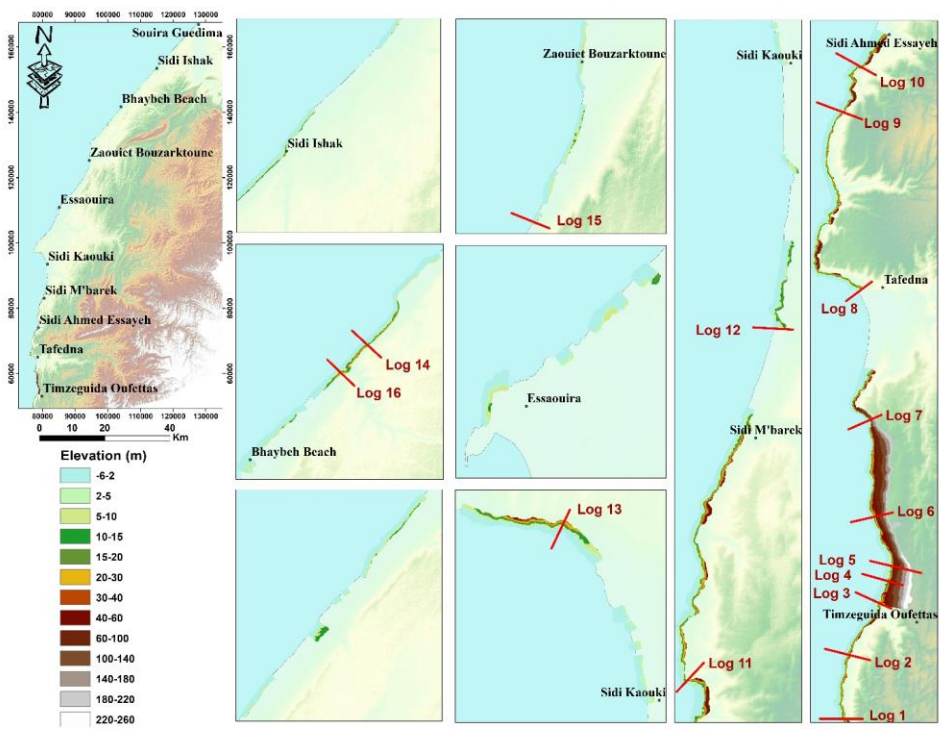


Figure 7: The spatial distribution of elevation factor in the study area with the profiles emplacement.

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 ~~part~~ 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 ~~movements of landslide in the~~ post-failure movements~~phase~~, especially where we have marls or clays.

Commenté [a79]: Rev1: L. 452-453: Please revise the sentence. As it is does not make much sense.

Do you mean this? - "These considerably affect the mechanical processes that lead to slope failure and to the subsequent post-failure movements, especially where there are marls or clays."

Commenté [a80R79]: •Authors Reply: Yes, thank you for the suggestion. We change it to “These considerably affects the mechanical processes that lead to slope failure and to the subsequent post-failure movements, especially where there are marls or clays.”

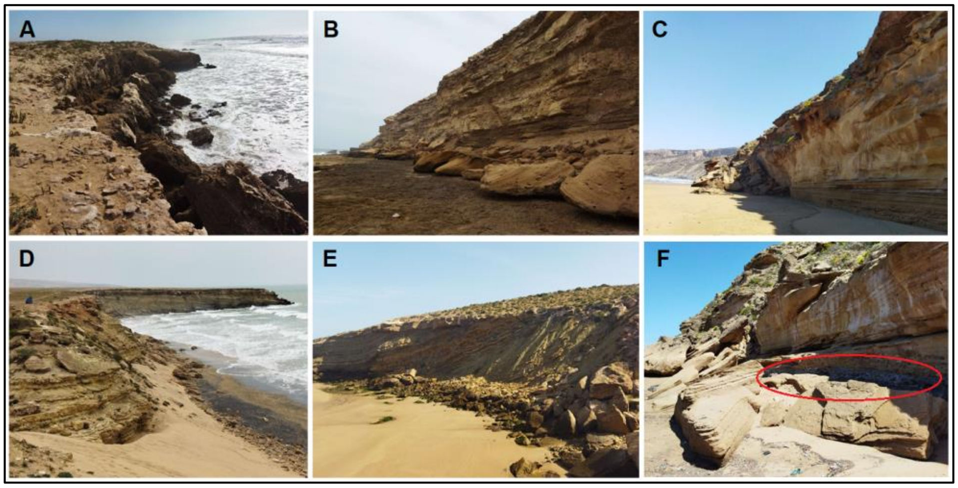


Figure 8: Examples of some conditioning factors; A: Absence of toe protection, B: Rock platform protection, C: Beach protection, D and E: tilted layers towards sea, F: Cliff toe lithology effect.

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 types 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 slopy 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 slopy 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.

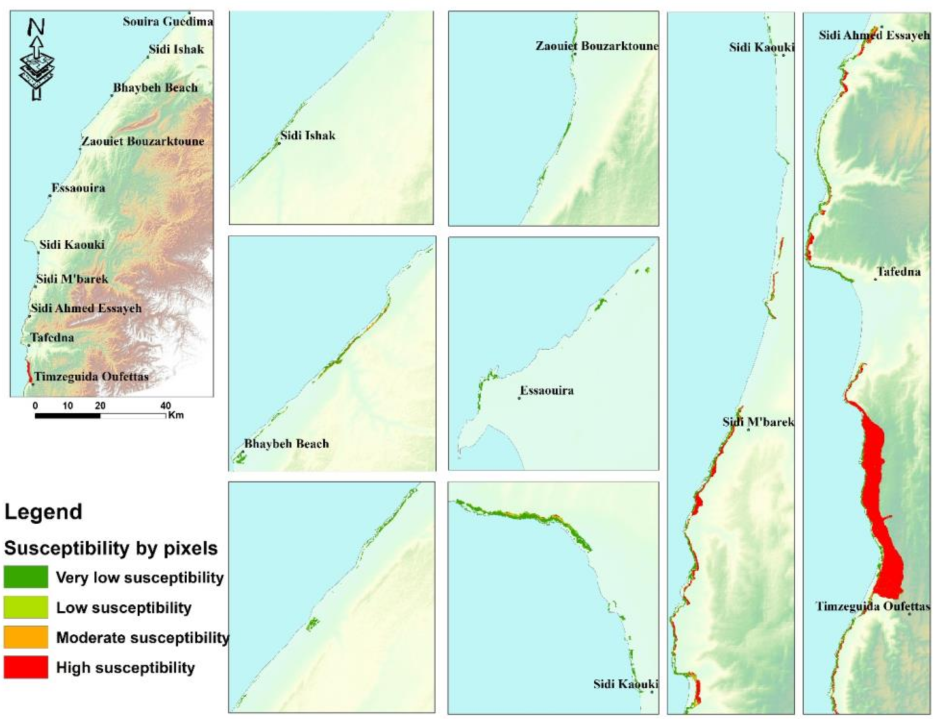
-Debris fall and flow (Model 13 and Model 14) - the lithological material with grain size Sand 51-66 % and Silt 11-23 % are more favorable to the occurrence of debris falls and debris flow in Essaouira coastal area, and the Slope angle factor class 0-2 ° is less favorable with IV score = -4.822.

Commenté [a81]: Rev1: f) You also mention that slope angle is one of the most influent factors (lines 481-482). However, table S1 shows that some types of landslides do not fit in this assumption.
- What does contribute for the low IV score for the highest slope classes (> 35º) for models 10-13, and 15? In the case of rock topple, slopes >15º have negative scores. This should be discussed.

Commenté [a82R81]: •Authors Reply: We understand the reviewer doubt, and it could be possible to rank susceptibility that way from lower to higher scores of IV using breaks in the ROC curves. Nevertheless, we adopt this criterion sustained on the IV values due to their simple meaning. According to Zêzere et al (2017), for example, the relevance of any independent variable to discriminate stable and unstable areas is as greater as its distance from the 0 value of IV. When the score is negative it means that the presence of the variable Xi is favorable to slope stability. Positive scores mean a positive relationship between the presence of the variable and the landslide occurrence, as high as the higher the score. Information values equal to zero means no clear relationship between the variable and the landslide occurrence. We will improve this aspect, according this description in the new version of the manuscript.

- 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 slopy 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 ~~part~~ section of the study area, while the southern ~~part~~ section present higher susceptibility to the occurrence of landslides, especially, due to the weight of the translational and rotational slides in those areas.



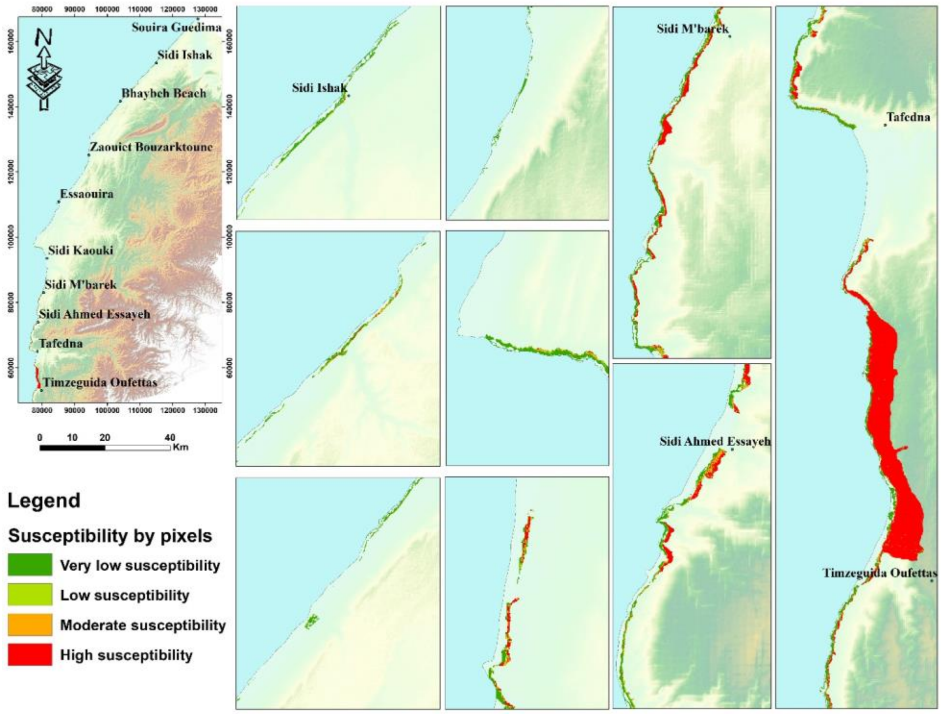


Figure 9: Landslides susceptibility map by pixels method

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).

565 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

Commenté [a83]: Rev1: g) In table 5 you have the same percentage of landslide susceptibility for translational and shallow translational landslides. What is the explanation? Is it an error or are you assuming all translational landslides as shallow translational?

Commenté [a84R83]: •Authors Reply: Thank you for the comment. No, it was just an error. We correct Table 5 as illustrated bellow.

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	~~61.08~~74.35	~~2.42~~3.41	~~2.07~~3.02	~~34.43~~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)

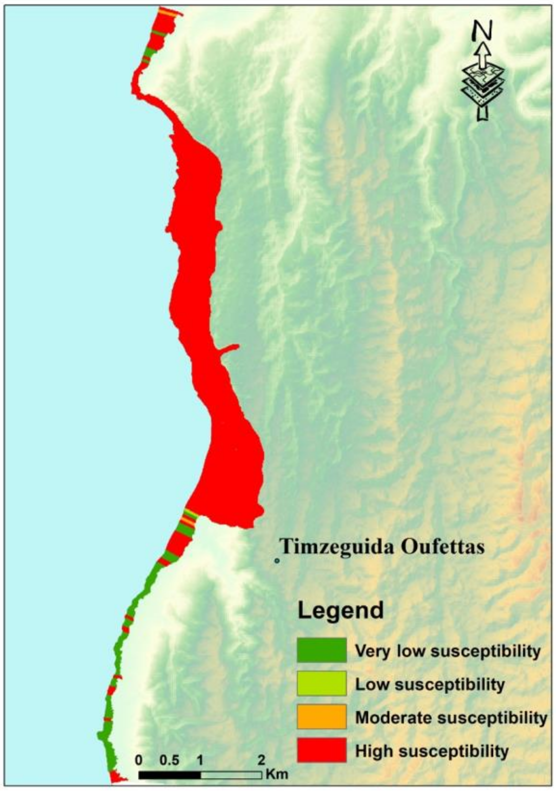
In general, the susceptibility assessment is carried out by classifying the elementary terrain units into two classes: stabilized (37% of ETU) and non-stabilized (63% of ETU). The approach was done individually for each type of landslide studied, and shows that, for all type of landslides, the unstable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

To represent the ETU landslide susceptibility results, we present a zoomed section of the southern ~~part~~ 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.

Mis en forme : Police :10 pt, Couleur de police : Automatique, Police de script complexe :10 pt

Commenté [a85]: L 528 – Clarify “the respective average of the unstable area, are located more to the souths of study area.”

Commenté [a86R85]: •Authors Reply: - Done. This phrase in the new version of the manuscript will be placed as “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.”

585 
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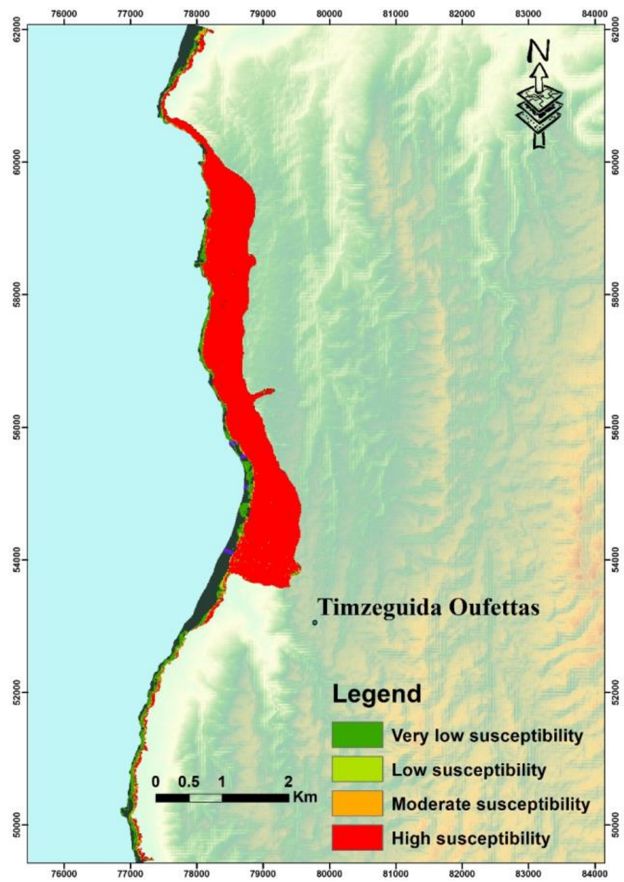

Figure 10: Landslide susceptibility map by ETU method for Model 1

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.

Commenté [a87]: Rev2: One other aspect to address is the validation method: using one part of the inventory to build the model and the other part for validation is a statistically sound method of validation, but it only indicates that the landslide inventory is robust enough and that the inventory partitions are representative samples of the total inventory and have similar relations with the landslides predisposing factors. However, as showed in Queiroz and Marques (2019) a temporal partition of a cliff failure inventory (1947-1980 and 1980-2012) led to very high success ROC AUC values, but to poor prediction rates, which raises fundamental doubts for the true prediction of future evolution behavior of sea cliffs based on its past evolution (as in Guilham et al., 2018). It is the reviewer opinion that this matter should also be subject of discussion and a subject for future work.

Commenté [a88R87]: •Authors Reply: We acknowledge the reviewer comment, and we totally agree. In fact, the temporal resolution of landslides in our coastal landslide inventory do not allow to apply a temporal partition of the inventory dataset. That is the reason for which we apply a random partition to generate training and validation landslide groups. This is a potential source of uncertainty and will be properly addressed and discussed on the results section. We will use the reviewer comment/description, which we thank, to better address/guide this potential source of uncertainty. this aspect,

Commenté [a89]: Rev2: The validation process is also a matter of debate in the discussion part of the paper.

Commenté [a90R89]: •Authors Reply: We acknowledge the reviewer comments. The landslide inventory partition in training and validation groups were selected randomly. The 70/30 partition was chosen because is in agreement with the commonly used partitions used for landslide susceptibility models training and validation (as an example please see: https://www.mdpi.com/2220-9964/9/12/696). And the time dependent validation was not possible with the available dataset.

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.

Commenté [a91]: Rev2: In the various model results classification why were used the IV values instead of a classification based on the ROC curve results, with limits of unstable areas of, for example 50%, 65%, 80%, 95% of the correctely predicted unstable terrain units.

Commenté [a92R91]: •Authors Reply: We understand the reviewer doubt, and it could be possible to rank susceptibility that way from lower to higher scores of IV using breaks in the ROC curves. Nevertheless, we adopt this criterion sustained on the IV values due to their simple meaning. According to Zêzere et al (2017), for example, the relevance of any independent variable to discriminate stable and unstable areas is as greater as its distance from the 0 value of IV. When the score is negative it means that the presence of the variable Xi is favorable to slope stability. Positive scores mean a positive relationship between the presence of the variable and the landslide occurrence, as high as the higher the score. Information values equal to zero means no clear relationship between the variable and the landslide occurrence.

Commenté [a93]: Rev1: i) In L. 549-550, you found that eliminating precipitation and TWI of your analysis you get better results (Fig. 11). This is statistically valid. However, considering that this is a dry climate, the effect of humidity and precipitation, when they occur, may be very important for slope instability, but your analysis cannot identify it. It would be important to discuss the limitations of this statistical analysis.

Commenté [a94R93]: •Authors Reply: According to the spatial distribution of rainfall in this study area, the most rainy zone is the middle part near Essaouira city and around it (Sandy coast), and rainfall values decrease towards the two study area extremities, which is totally against the spatial distribution of the landslide inventory. With the statistical constrains that could overcome using a statistical method sustained on landslide density in each ...

Commenté [a95]: Rev1: d) The most frequent phenomena are Rock fall (149 events). However, translational and rotational slides occupy 85% of the unstable area, mainly occurring in the southern section, where they have higher weight on landslide susceptibility. Is there a higher landslide susceptibility in the southern section because of a higher number of these landslide events or is it ...

Commenté [a96R95]: •It is uncertainty related with the age of these landslides and with the uncertainty related with the triggering factor (rainfall, earthquake). This is a purely space dependent modeling and we are not considering the time scale of the events.

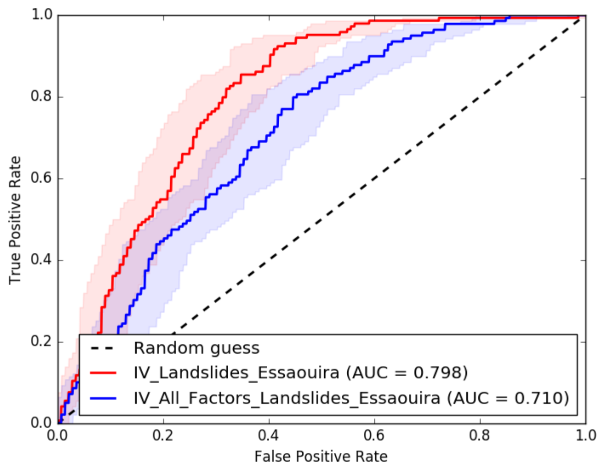

Figure 11: ROC curves of susceptibility model for all landslides with all factors (AUC = 0.710) and without TWI and rainfall factor (AUC = 0.798).

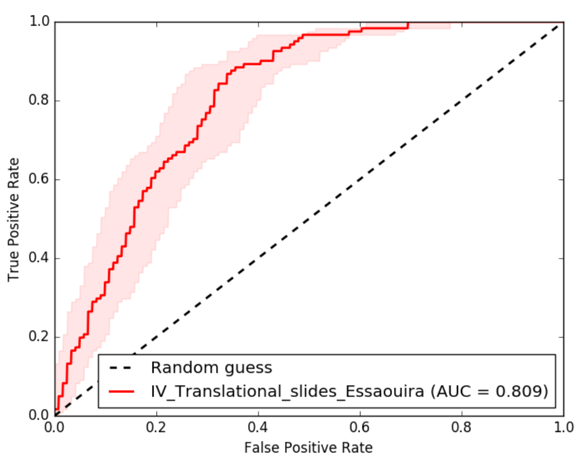

Figure 12: ROC curves of susceptibility model for translational slides (AUC = 0.809)

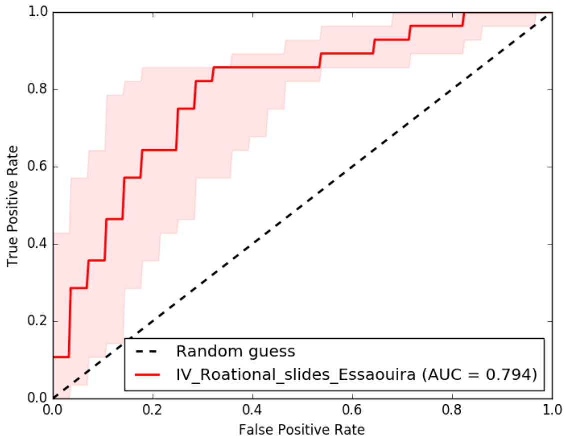

Figure 13: ROC curves of susceptibility model for rotational slides (AUC = 0.794)

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 ~~part~~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 ~~part~~ section because it's topographic characteristics, mainly next to Sidi M'bark, Sidi Ahmed Essayeh, the northern ~~part~~ section Tafedna and Timzguida Oufettas, while the less susceptible areas are more located in the middle and northern ~~part~~ 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

Commenté [a97]: Rev1: j) Given your results and considering the two approaches (Pixel-based and ETU) used in this work, which is the most suitable one for representing the landslide susceptibility in the area?

Since ETU are defined based on the morphometry of the area, there is a more "guided" analysis in this approach, comparing with pixel-based that is more "random", some differences between both modelling should be expected.

Commenté [a98R97]: •-We acknowledge the reviewer comment. Since ETU are more close 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 inconvenients. 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.

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.

Commenté [a99]: Rev1: h) You state that the precipitation is not a "decisive conditioning factor" (L. 588). From a pure statistical point of view, it is true. The reason why you don't see great differences may be because you are using annual average values of precipitation. However, in drier areas, rainfall intensity may be more important than the annual average amount. Since precipitation is an important triggering factor, it would be expected an increase of landslide events during the rainy season. Didn't you find any variation? Considering precipitation is not a permanent factor as the others, is it proper to treat it as a conditioning factor based on its (low) annual average?

Commenté [a100R99]: •Authors Reply: We agree with you, but we didn't use the annual average, I used the monthly cumulative values, even though, to use the intensity it's to have close stations to the cliffs, which is not the case for the study area, the stations are a little far from the cliff, we just opted the interpolation method to estimate it in the cliffs. We could also describe something about the relationship between the landslide dates and the critical rainfall thresholds that trigger them, which are unfortunately not known.

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 ~~part~~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 more close 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.

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