Landslides susceptibility mapping using GIS and weights of evidence model in Tetouan-Ras-Mazari area (Northern Morocco)

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ABSTRACT
The 590 km² of the Western Rif (North of Morocco) is well known for active mass movements due to the strong climatic and anthropogenic aggressions in this area, where lithology and topographic relief are likely the phenomena that cause slope instability problems. In this study, we have focused on mass movements that have been occurred in the last two decades, namely landslides, complex slides and block slides. Over the years, this site and its surroundings have experienced repeated landslides. For this reason, landslides susceptibility mapping is mandatory to prevent natural risk and to better manage land-use. The application of weight of evidence method using remote sensing and geographical information systems (GIS) were used to generate a susceptibility map. Six conditioning factors were used in this study: lithology, distance to faults, distance to drainage, slope, aspect and hypsometry. A total of 126 mass movements locations were detected; 63 landslide location (50%) were randomly selected as input data for the entire process using the spatial data model (SDM) and the remaining locations were used for validation purposes. The final map of areas susceptible to mass movements has an accuracy of 95.3% and has been classified into four classes (very high, high, moderate and low).

1. Introduction
The area of Tetouan-Ras-Mazari is subject to landslides due to climatic and anthropogenic aggressions. These phenomena are listed in order of importance as follow: (1) Water resources which lower the mechanical characteristics of the marlstone of the Tangier Unit and Flysch layers. Water is an instability factor. It decreases cohesion in soils and increases weight and pore water pressure in granular media. The rate at which water seeps into to the slope may also be critical. Some slopes may become unstable if even small amounts of water penetrate fast; others are more
sensitive to the amount of water fallen in a long time. (2) River entrenchment (bank undercutting) is often exceeded during floods. (3) Anthropogenic actions usually include old roads that barely cross unstable areas and/or old stabilized roads, and/or numerous pathways of new main roads, secondary roads, etc., by breakage of equilibrium and stability of slopes (as part of the new program for the opening up of the Rif 2005-2020). (4) Rapid expansion of urban areas over the last few decades, even in the absence of management plans (El Kharim et al. 2001; Prokos et al. 2016). Preliminary works in the field of mass movements were carried out by many authors (Milliès-Lacroix 1968; El Gharbaoui 1980).

In the last few decades, multiple series of landslides have occurred in the province of Tetouan (Northern Morocco). In 2008, a landslide covered parts of the highway between Tetouan and Fnideq Figure 1(a), not to mention the dozens of mass movements affecting the Western part of the city of Tetouan (Kourrat Sbaa, Khandak,
Ezzerbouh and along the river of Samsa) and the damage caused to the workshops and garages of the Southern port of M’diq that happened in 1998. Moreover, another landslide in M’diq caused the encroachment of the roadway above the tunnel in 1996. It has also been reported that a landslide affected the road going to Bab Sebta between Souk El Massira and Ibis Hotel in Fnidaq.

The major impact of these landslides on the society, environment and lifelines can be summarized as follow: cracking and serious damage to households along the cliff that crosses Kaa El Hafa. Cracking and buildings movement (Faculty of Sciences, Mhannech). The destruction of residences’ roof and its facilities at Lihoudi beach. The destruction of the swimming pool of the Royal Yachting Club (M’diq port). In Stehat, most houses showing signs of cracking were moved out by order from the court. In addition to that, the daily accidents of low gravity. Furthermore, the province of Tetouan is under the threat of traffic risks. The dilapidated neighborhoods of El Matar, Hafat Rekena and Al Mankoubine were surveyed. Funds have been allocated for their evacuation and relocation to new neighborhoods. Following the appeal of the State Secretariat for Housing, 280 households at risk of collapse have been identified in the city of Tetouan. Fifty five of these old buildings are empty, others are still inhabited, which constitutes a permanent threat of loss of human life. The most threatening constructions are located in Kaa El Hafa, El Mellah and Laayoun, where the recent collapse of the wall on the side of souk Bab Nouader occurred.

Tetouan is the first destination of national tourism; the months of July and August experience a significant increase in the population due to such tourist activity, to which is added the arrival of the network of mediators. These visitors stream represents a momentary economic contribution, but the strong engorgement that results, leads inevitably to exceeding the thresholds and, finally, a break on a real sustainable economic development of the region, disruption of progress and destroy developmental efforts of the government. We mention also: (a) A reduced property values due to unwillingness of people to purchase disaster prone land. (b) reduction in quality of life where constructions due to the deaths of family members and the destruction of personal belongings; which may also have great sentimental value. (c) Impact on emotional well-being. Therefore, any disaster can have a profound impact on people’s emotional well-being affecting their feelings, thoughts, actions and relationships. The sudden overwhelming disruption and danger to life and property can put tremendous psychological pressure on a person, often even affecting the ability to function at the time of crisis. The impact of such a disaster can have on a person also depends on his/her past experiences of crises, how well he/she has been prepared for such events, both physically and mentally and his/her attitude or level of resilience.

Landslides are classified depending on several criteria such as movement, materials, amount of fluids and geotechnical properties of rocks (WP/WLI 1994). The movement of landslides can occur in many ways. It can be a fall, topple, slide, spread or flow. The velocity of the movement may range from very slow to rapid. The type of landslides encountered in the study area of this research paper are landslides, complex slides and block slides. A block slide is a single unit or a few closely related units of rocks that move down slope as a relatively coherent mass following different types of movement either by sliding, rolling and/or bouncing of a single block. More
information about the different types of landslides can be found here (Poisel and Rainer 2011).

In effect, landslides, like any other kind of natural disaster and risk management, have an impact not only on people, their possessions and lifelines, but also on the Earth’s surface, including both continents and beneath the oceans (Schuster and Highland 2003). Consequently, in order to mitigate the serious threat of this catastrophic event, it is mandatory to manage and delineate areas known to be prone to landslides; so mass movements susceptibility mapping is essential. It has gone through several successive stages (geomorphological approach, heuristic approach by qualitative factor indexing (Sujatha and Rajamanickam 2015), the ZERMOS¹ method and recently the bivariate, multivariate statistical analysis and the deterministic approach imputable to the engineering domain). Hence, the main purpose of the present research paper is to generate a landslide susceptibility map by using the weights of evidence model integrated into the geographical information systems (GIS) environment. In this article, we will create the susceptibility map covering the area of Tetouan-Ras-Mazari using weights of evidence method and GIS. This method is a model of bivariate analysis by indirect probabilistic approach presents many advantages by its rigor and its specificity. It mainly uses the main predisposition parameters (geological and topographical) which determine the conditions of stability or instability of the slopes (thus having a direct or indirect relation with the genesis of the mass movements). It necessarily requires the chi-square test to ensure the conditional independence of the causative factors. The obtained susceptibility map must pass through the statistical validation using the comparison with the 50% of the unused inventoried mass movements. It is an approach that also greatly limits the expert’s intervention.

2. Study area

We chose Tetouan-Ras-Mazari as our case study. It is located in the province of Tetouan (Latitude: 35°45’N – 35°30’S; Longitude: 5°30’W – 5°9’E). It covers a total area of about 590 km². Our test site is limited by Fnideq, the Mediterranean Sea, Chefchaouen and Asilah on the North, East, South and West, respectively (Figure 1(b)). The study area is located within a hazardous and mountainous zone called the Western Rif (Northern Morocco). The Rif has been subject to a complex structural and palaeogeographical evolution since the triassic period until the quaternary (Kirat 1993). This tectonic zone is made up by three different paleogeographic domains.

2.1. The geological and structural setting

The geological and structural setting of the study area have been detailed in the geological map of Tetouan sheet by Kornprobst and Durand Delga (1985), which consists broadly of three main domains: (1) Internal domain: represented by the Ghomarides, which are metamorphic nappes of Paleozoic from Silurian to Carboniferous and Sebtides that are composed of polymetamorphic terrain and Paleozoic-Triassic cover called the unit of Federico. The Sebtides-Ghomarides are essentially thrust over calcareous units, namely, the Dorsale Calcaire that composed the third part of this
domain. (2) Flyschs: formed by cretaceous and tertiary material. We distinguish three types of nappes: Numidian Flysch, Flysch of Tisirène and Flysch of Melloussa. (3) External zone: Represented by Tangier Unit.

2.2. Seismic activity

The Tetouan region, although located in a moderate seismic zone, remains under the effect of the very active neighboring seismic zones (Alboran and Acores). However, during the last two decades, no events of sufficient intensity (magnitude greater than or equal to 6, intensity VII or more MSK) occurred to slope instability. The bibliography consulted does not describe any slope instability induced by earthquake in this study area (Ait Brahim 2002; Ait Brahim et al. 2007; Cherkaoui and El Hassani 2012).

2.3. Climate and temperature

- **Climate**: Our study area knows the succession of two different seasons in 1 year; to a warm and dry summer, which lasts for several months, succeeds a rainy and colder season corresponding to the end of autumn, winter and early spring. Rains are not continued but alternate during all this part of the year with periods of fine weather of long and short duration. The study area is part of an area which forms a transition between a Mediterranean and an Atlantic slope; in fact, the climate of the region benefits from two maritime influences, on one hand a Mediterranean influence because the opening of the limestone chain at Tetouan allows to penetrate Mediterranean perturbations, on the other hand an Atlantic influence because it is exposed to the Atlantic winds of the West and South-West. Rains are prolonged and very violent with a maximum in November, December and January, causing intense erosion on the slopes leading to flooding.

- **Temperature**: is high, at the end of spring until the end of autumn, especially in strong summer which causes desiccations into the soils. According to the doctoral work of Kirat (1993), the hottest months of the year are July and August with a high average (38°C for the 2 months); the coldest months are December and January (2.6°C and 2.2°C, respectively). A thin blanket of snow falls in this area (4 to 5 d/year) and lasts few hours.

3. Data and methods

As it has been mentioned in previous works of Elmoulat et al. (2015), the landslide susceptibility map consists of four main stages. First, data collection and construction of GIS database from which the relevant controlling factors were extracted. Second, mapping of predisposing factors that could potentially control the occurrence of landslides. Third, application of weights of evidence modeling for landslide susceptibility mapping such as explained by Van Westen (2002). Fourth, accuracy assessment, validation and confirmation of the results. The digital elevation model (DEM) are extracted from shuttle radar topography mission (SRTM)² to create slope, aspect, hypsometry, hydrographic network and distance to faults maps with 30 m of spatial resolution. Furthermore, the distance to faults map has also been verified by field
surveys and the hydrographic network by topographical map Topographical map. (1970). All aforementioned factors were integrated in a GIS-based environment and stored in a raster grid format of 90 × 90m resolution. The study area grid is 496 rows by 496 columns. Then, all the layers were classified into five classes.

3.1. Construction of geodatabase

The GIS platforms were created to visualize, analyze and display all kind of geographically referenced data to reveal relationships in the form of maps (http://www.esri.com). The geoprocessing and analysis of all the maps were conducted using a pioneer and powerful mapping software, ArcGIS 10.1. Figure 2 shows the various data sources, their derived products that compose the GIS database. Most of the datasets are extracted from satellite images like Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)³ false-color composites. In addition, the lithological map was derived from the geological map (Kornprobst and Durand Delga 1985).

3.2. Mapping of predisposing factors

3.2.1. Active movements

For the landslides map, many researchers (Neuhauser and Terhorst 2007; Dahal et al. 2008) commonly use centroid locations of landslides and represent the area of landslides by the pixel unit at that location. In other words, the probability of a landslide
occurrence equals the ratio of one landslide pixel for each existing one, per the total number of the pixels in the entire area (Regmi et al. 2010). The representation of the different type of mass movements by single points which corresponds to their bary-center is a format required by the method of calculation of weight of evidence (WofE). However, this representation does not reflect ground truth, and we can even display the map of mass movements using their original forms, Figure 3(a). A landslide inventory map was prepared by mapping the landslide areas in the Tetouan-Ras-Mazari using interpretation of high resolution satellite imagery, previous reports and extensive field surveys. Three different types of active movements were distinguished in this area, including landslides, complex slides and block slides. A total of 126 landslide points was compiled from various data sources. It is expected that the training data includes all the data belonging to the problem domain (Pradhan et al. 2010), in this case, 50% of the whole landslides were selected randomly to train the WofE model and the half remaining was used to test it, Figure 3(b).

Landslides are classified depending on several criteria such as movement, materials, amount of fluids, geotechnical properties of rocks (WP/WLI 1994). The movement of landslides can occur in many ways. It can be a fall, topple, slide, spread or flow. The velocity of the movement may range from very slow to rapid. The type of mass movements encountered in the study area of this research paper are landslides, complex slides and block slides. A block slide is a single unit or a few closely related units of rocks that move downslope as a relatively coherent mass following different types of movement either by sliding, rolling and/or bouncing of single block. More information about the different types of landslides can be found here (Poisel and Rainer 2011).

3.2.2. Lithology factor
Geology is important for studies related to the delineation of areas susceptible to landslides because each geological unit has a different impact in triggering geomorphological processes (Anbalagan 1992; Pachauri et al. 1998; Dai et al. 2001). The previous description of the geological setting shows that the study area consists predominantly of marsh sandstone Flyschs, detrital limestones, mudstones and conglomerates. All these formations are almost alternative, which have an effect on slope stability. For example, mudstones become fluid in contact with water; hence, they are easily discharged when they are on surface. The alternation of limestones and sandstones with marls and clays is another unfavorable factor in term of slope stability (Kirat 1993). The lithology map, Figure 4(a), has been created by using the existent 1:50,000 geological map of Tetouan-Ras-Mazari. It contains five lithological classes which are: conglomerates, sandstones, mudstones, limestones and marlstones. The geological features occupying Tetouan-Ras-Mazari were combined to simplify the impact that rocks had on the frequencies of landslides occurred and then were classified into five classes to create the lithology map used in this work.

3.2.3. Distance to faults
According to previous work that has been done in the past by many researchers and experts in Western Rif (Ait Brahim and Soussey Alaoui 2003; Mansour and Ait...
Figure 3. (a) Mass movements map of Tetouan-Ras-Mazari in original form. (b) Mass movements map of Tetouan-Ras-Mazari in point form.
Brahim 2005) on one hand, and based on the geological map on other hand, we elaborate distance to faults map which plays an important role in slope instabilities. Our case study is a faulted zone which presents favorable conditions for landslides occurrence. All faults are highlighted by the consistent movements caused within the geological features of different kinds of tectonic layering; they are posterior to thrust that accommodates horizontal shortening and overthrusting. These movements involve the displacement and tectonic emplacement of hanging-wall, which means that the rock immediately above and below a non-vertical fault or shear zone. These tectonic movements are largely described in the Rif chain (Ait Brahim et al. 2002;
Michard et al. 2008). More than 341 types of tectonic movements were mapped and analyzed using geological map and Landsat 7 ETM+ 2015 satellite imagery observation; most of them are either thrusts (18), or faults (323). First, a radiometric processing has been done by different bands to enhance the visual quality of colored compositions of the image. Second, directional filtering in edge detection and/or smoothing performance have been applied to facilitate the interpretation and visual extraction. Third, the faults were completed by the geological map and validated by ground truth studies (Ait Brahim 1991). Finally, a distance to fault map was created and classified into five classes using the quantile classification method of ArcGIS, Figure 4(b).

3.2.4. Distance to drainage
Drainage is another major cause of landslides by undercutting and eroding slopes. Fluctuation of sub-surface water changes the pores’ water pressure in the soil and then changes the slope stability. As it was mentioned (WP/WLI 1994; Kouli et al. 2014), fluvial erosion is one of the most common triggering causal factors of landslides. The hydrographic network factor was automatically derived from DEM using ArcHydro tool. This extension was developed by ESRI along with a hands-on document that explained step-by-step how to perform drainage analysis on a terrain model. DEM Raster analysis is performed to generate data on flow direction, flow accumulation and watershed delineation. These data are then used to develop a vector representation of catchments and drainage lines. Using this information, a geometric network is constructed (ESRI 2011). The final map of distance to drainage was validated using the topographic map of Tetouan scale 1:50,000. After that, the map was classified into five classes by using the quantile classification method, Figure 4(c).

3.2.5. Topographic factors
A DEM with 30 × 30 m resolution representing our study area was a great source to generate various topographic factors, which influence the landslide activities in this zone. Hence, the DEM was modified to correct the artifacts associated with the ASTER sensor and to improve its visual quality. From this DEM, three thematic data layers were extracted which are:

- Aspect: refers to the direction of the maximum values that changes from each cell to its neighborhood in the output raster. The values of each cell in the output raster indicate the compass direction that the surface faces at that location. It is measured clockwise in degrees from 0° to 360° site ranges from 1°, which corresponds to the flat areas having no downslope, to 356° North. All the directions, as well as the corresponding degrees, are described in Figure 4(d). The orientation of the slopes in the region of Tetouan influences especially the degree of instability on the exposed slopes North, NNW and NNE for the landslides. Slopes of the direction South, SSE, SSW show especially an erosion dominated by the streaming.
- Slope: consists of the maximum change in z-value from each cell. This variable was calculated based on the ArcGIS algorithm. The slope values are calculated using the average maximum technique. The variations in slope angles are observed
in the Tetouan-Ras-Mazari area ranges from 0°, that corresponds to the flatter slope, and 54° for the steeper ones, Figure 4(e).

- **Hypsometry**: The hypsometry is a suitable parameter to distinguish between different evolutionary stages in landscape development. We used the hypsometry to identify the stage of landscape development and quantify the relationship between the altitudes and landsliding. Hypsometry represents the amount of surface located above a given elevation. In this study, the hypsometric map has been extracted from the DEM, and then classified into five classes, Figure 4(f).

We would like to mention that the other aforementioned factors presented in the abstract and the introduction are very difficult to estimate and specially to measure because of their change over time and/or lack of data. For the anthropogenic factors is part of ongoing work of Rif.

### 3.3. Weights Of evidence (WofE) modeling

#### 3.3.1. Previous work

The statistician (Good 1985) defined ‘Weight of Evidence’, in his review survey of Bayesian statistics as, ‘whether the evidence in favour or against some hypothesis is weak or strong’. To make this definition clear, he gave an example of a doctor who must weigh the evidence when doing a differential diagnosis between two diseases for choosing an appropriate treatment. The WofE is based on the Bayesian probability model. Originally, WofE was applied in medicine by (Spiegelhater and Kill-Jones 1984; Kemp et al. 1999; Zuyle 2000; Johnson et al. 2001). Since the 1980s, it was developed for mineral resources assessment to predict gold deposit in Nova Scotia (Bonham-Carter et al. 1989). Several scientists have employed the WofE method for mineral exploration using the GIS across the world (Agterberg et al. 1993). This method has started applying to landslide susceptibility mapping also (Süzen and Doğuran 2004; Lee and Sambath 2006; Sujatha et al. 2014; Thiery et al. 2017). The use of this method has never stopped since then; because, it is feasible and less time consuming. Moreover, it can be performed rather easily with most GIS software packages. Many authors utilized WofE in some region of Northern Morocco (Mastere et al. 2013; Elmoulat et al. 2015). Nowadays, it is for the first time that WofE theory is applied in Tetouan-Ras-Mazari to create susceptibility map of this region that may help decision-makers identify areas where new landslides will have a higher probability to occur in the future.

Statistically, WofE can be expressed as follow:

\[
\text{WofE} = \left[ \ln \left( \frac{\text{Relative Frequency of Goods}}{\text{Relative Frequency of Bads}} \right) \right] \times 100
\]

#### 3.3.2. Calculation of weights

The WofE model is based on the calculation of positive weight ($W^+$) and negative weight ($W^-$) which are assigned to six predictor factors (PF) used to create landslide susceptibility map. $W^+$ is the weights of evidence when a factor is present (relevant)
and $W^-$ when another factor is absent (not relevant). In other words, $W^+$ corresponds to the weight within the test domain and $W^-$ when the weight is not within the test domain. The total number of pixels in the study area was 31,198,400 pixels and the total number of landslide occurrences was 126. According to Bayes’ rule, a binary hypothesis of binary PF when it is present (Equation 1) or absent (Equation 2) can be expressed as follows:

$$P\left(\frac{Y}{X}\right) = \frac{P(Y \cap X)}{P(X)} = \frac{P(Y)\frac{P(X/Y)}{P(X)}}$$

$$P(Y\bar{X}) = \frac{P(Y \cap \bar{X})}{P(\bar{X})} = \frac{P(Y)\frac{P(\bar{X}/Y)}{P(\bar{X})}}$$

where $P$ is probability, $Y$, $X$ and $\bar{X}$ correspond to the presence of PF, absence of PF and the presence of event occurrence, respectively. The $W^+$ and $W^-$ are defined as follows:

$$W^+ = \log e \frac{P(X/Y)}{P(\bar{X}/Y)}$$

$$W^- = \log e \frac{P(\bar{X}/Y)}{P(X/\bar{Y})}$$

$C$ is the magnitude of the contrast provided a measure of the spatial association between a set of points and the patterns. $C$ is positive for a positive spatial association, and negative for a negative spatial association. $C$ corresponds to the difference between the $W^+$ and $W^-$. The contrast and its standard deviation are expressed as below:

$$C = W^+ - W^-$$

$$S(C) = \sqrt{s^2(w^+) + s^2(w^-)}$$

The standardized value of $C$ (Sig $C$), calculated as the ratio of $C$ to its standard deviation, which serves as a test that the spatial correlation between the landslide occurrence points and a test domain is statistically significant (Shahi and Rouhani 2014).

$$Sig(C) = \frac{C}{\sqrt{s^2(w^+) + s^2(w^-)}}$$
The results of this study can be presented in the form of Table 1, as well as Figure 5.

4. Results

The results of this study can be presented in the form of Table 1, as well as Figure 5.

The table above shows the positive ($W^+$) and negative ($W^-$) weights for six predictor factors used in this study, variances of $W^+$ and $W^-$, respectively, $S(C)$ is its standard deviation and $\text{Sig}(C)$ is the standardized values of $C$. Those parameters have been already discussed in the methods section, and calculated for each PF using the Calculate Weights tool implemented into ArcGIS along with SDM utilities.

Finally, the landslide susceptibility map of the studied area was drawn by using the Calculate Response tool of SDM toolbox. This tool combines the evidence weighted by their associated generalization in the weights of evidence tables for each PF. This tool calculates the posterior probability, standard deviation to weights variance, and the total standard deviation based on the evidence and how the evidence is generalized. The calculations used the weights of Table 1.

The validation of susceptibility map of the Tetouan-Ras-Mazari area was performed by using Agterberg and Cheng Conditional Independence (CI) test along with
other existing landslide data (50%). This test is necessary because Weights of Evidence, a Bayesian method, assumes conditional independence of the evidence with regards to the training sites. Agterberg and Cheng (2002) proposed that conditional independence of all map layers implies that the sum of posterior probabilities ($T$) is equal to total number of discrete events ($T = n$). The tool used in this study reports three measures of overall conditional independence. First, a conditional independence ratio that equals in this case 1.01 which is a good value given the rule that any number below 1 may indicate conditional dependence. Second, the Agterberg–Cheng test of CI means the probability that this model is not conditionally independent is 47.6%, which is an acceptable value; because the probability values greater than 95% indicate that the hypothesis of CI should be rejected, and any other ones greater than 50% indicate that some conditional dependence occurs. Third, the measure is reported as the overall CI accuracy of 95.3%, which is considered excellent by Thiart et al. (2003). Hence, the validation results show that the predictive capacity of the six factor is better than including additional variables.

(1) By looking at the weights assigned to each formation, the highest one is observed at the mudstone. This remark has already been expected, because the mudstone is a kind of clay rock (argillaceous) without texture and lamellation. In addition to that, it has a character of low mechanical strength and low elastic
modulus (Meng and Xian 2013). Consequently, this kind of feature in particular is considered to be excellent landslide-prone areas (MTP 1995; Ait Brahim et al. 2018). Conglomerates received the second class of weight, which is quite normal given the fact that it is composed largely of clasts of rounded mud chips and pebbles held together by clay minerals. In the third position comes the marble, which is an argillaceous limestone, on one hand, containing 35–65% clay and 65–35% carbonate (Pettijohn 1957). On the other hand, this rock has the biggest landslides points (25). Then, limestones and sandstones received the lowest weights, and this was also expected as these rocks have excellent mechanical properties. Sandstones obtained only a slightly higher weight than limestones; because of their different geomorphological features from the point of view of fracturing and alteration, that are certainly greater in the sandstones than in limestones (MTP 1995; Mansour and Ait Brahim 2005; Ait Brahim et al. 2018).

(2) Regarding the distance to fault, our field observations show that the distance between 0 m and 60 m, the areas are more prone to mass movements, because of the faults and especially due to the principal and structural contacts (contact between geological formations of different nature), lithological and geotechnics (crushed land), hydrological (presence of sources). The faults between limestones of the dorsal and mudstones of the Tangier Unit are sensitive to landslides. The faults zones between the Flyschs layers and Tangier Unit show an important number of complex landslides and block slides. Certain zones with important number of faults and the zones of tectonic knots show important frequency of instabilities.

(3) A certain number of landslides (Moderate) are located near to the hydrographic network in relationship especially to the undermining of the banks between 0 m and 60 m. The most frequent landslides are located in the distance to drainage in relationship to bank undercutting between 0 m and 60 m. In addition to that, a greater number of relatively unstable zones are located on either side of straight line of certain drainage networks. The density of the drainage and the level of water collection enhance the undermining of many catchment areas of Flyschs layers were landslides, and complex landslides are likely to have a high incidence (Chaouni 1999; EL Kharim et al. 2002).

(4) Our field observation shows that slope degree is a relevant factor to evaluate mass movements. The slopes the more prone to landsliding are those whose degree exceed 5°, with a maximum of susceptibility between 10° and 25°: (1) the low slopes corresponds to the low hills of marlstones of the Tangier Unit; (2) the moderate to high slopes correspond to medium hills of the Flyschs layers; (3) the steep slopes, higher than 25° correspond to the limestones-dolomitic peaks of the Dorsale-Calaire. We conclude that as the slope angle increases, the shear stress in rocks increases as well, which makes the area more prone to landsliding. Areas over the steepest slope are prone to landslides and complex slides.

(5) The results of the weights calculation for the aspect parameter show that landslides were more abundant on Northeast-facing, in addition to the West and Southeast-facing, slopes. But, for the other aspect directions, the weights of landslide occurrences remain deficient.
Based on the results given for the hypsometry, it has been determined that the landslides develop preferentially on both low (84–204 m) and high (360–571 m) altitudes. This can be explained on one hand by the big number of old landslides occurring in the study area for those two classes (MTP 1995; Chaouni 1999). On the other hand, the presence of scarp, an abrupt change in slope degree and a stepped topography makes the correlation between landslides and hypsometry complicated; more information about the effectiveness of hypsometry map and landslide are given by Van Den Eeckhaut et al. (2004).

Concerning the land-use parameter, we would like to mention that this factor has been mapped, but it has not been implemented into the model; because, landslide areas occurred mostly in ‘no vegetation’ zones, whereas only a very small portion affected urban and cultivated areas.

Furthermore, investigation of the susceptibility map highlights a high probability of landslides where mudstones, marlstones and conglomerates outcrop. The susceptibility map shows also that the landslide is more prone in highly elevated areas greater than 57° with the Northeast, West and Southeast-facing slopes (Milliés-Lacroix 1968; El Gharbaoui 1980). This map reveals that landslides preferentially occur close to drainage lines and in higher altitudes (Chaouni 1999). Indeed, hypsometry plays a significant role for the slopes between 100 m and 500 m (moderate to high altitudes), which constitutes the 3/4 of the entire surface of the study area. The most susceptible are:

- Complex movements between 200 m and 400 m of altitude.
- Block slides between 300 m and 400 m of altitude.
- Landslides high altitudes higher than 500 m especially of the Dorsale-Calaire.

5. Conclusion

In this study, we have demonstrated a robust model based on field and remote sensing data sets to predict landslides in hazardous areas. This natural phenomenon with a certain intensity can occur in a certain location within a given period of time. Consequently, they can be systematically assessed and managed. Several projects on landslides and risk have been carried out for a better understanding and assessment of landslides’ procedure in order to manage lifelines and deal with unexpected emergencies. The main purpose of this research paper is to generate landslide susceptibility mapping by using WofE method and GIS technologies.

The main findings of this work are extracted from the information given by the analysis and statistics results of the weights calculation (Table 1) and the susceptibility map (Figure 5). They reveal that landslides develop in argillaceous zones at higher elevation and where hydrographic network is more pronounced. In addition to that, the probability of landsliding is most abundant at North, West and Southeast-facing slopes.

Last but not least, the methodology employed in this study relies on readily accessible remote sensing data; nevertheless, they can provide reliable, fast and cheaper results. The final susceptibility map created can be a useful tool for effective land-planning and management and can control the spread of the damage caused by
natural disaster. It could be the basis for decision makers, engineers and government organizations to better plan for further urban planning and infrastructures mainly the new program for the opening up of the Rif 2005–2020. Often slope instability assessment uses the assumption: conditions which led in the past to slope failures, will also result in potential unstable conditions in the present. Hence, to avoid any damage, the created map is highly recommended for the urban extension between Tetouan and Fnideq and also for the infrastructures that have been already established (existing dams, the wind network of green energy in the North of Morocco, etc.) especially for those located in areas with high and very high susceptibility for landslide prevention and damage mitigation. If some of these studies have been done in the past, the highway between Tetouan and Fnideq would not have fallen down in 2008. To sum up, we would like to say that the past is the key to the present and the future.

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Notes

1. Map of areas exposed to risks related to mass movements.
2. Available from: https://earthexplorer.usgs.gov/, acquisition period: July 2015.
3. Available from: https://reverb.echo.nasa.gov/reverb/

Disclosure statement

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