Landslide susceptibility mapping using the analytical hierarchy process and the Geographic Information System along the Agadir Ida Ou-Tanane province, Morocco.

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Abstract. This study focuses on evaluating the susceptibility to landslides in the Agadir Ida Ou-Tanane province following the significant seismic event on September 8, 2023, employing Geographic Information System (GIS) and Analytical Hierarchy Process (AHP). The region, characterized by tectonic activity and diverse lithology’s such as clay, limestone, and alluvium, coupled with steep slopes, is inherently prone to landslides. Utilizing the AHP methodology, we integrate ten factors influencing landslide vulnerability: lithology, slope, earthquakes zone, rainfall, land cover (LULC), distance from faults, hypsometry, drainage, distance from road, and aspect to map susceptible areas effectively. Pairwise comparison matrices and expert assessments were employed to establish the relative significance of these factors, with the reliability of judgments evaluated through the calculation of the consistency ratio (CR). The resulting map depicting landslide susceptibility illustrates a spatial continuum from very low to very high susceptibility areas. Given the active tectonic setting of the region, lithology and slope emerge as the predominant factors influencing susceptibility. Model validation was conducted using observed landslide occurrences, enhancing the applicability of this mapping for land-use planning and risk management purposes.

1. Introduction

On September 8, 2023, at 23:11 local time (22:11 UTC), a magnitude 6.8 earthquake shook the Moroccan High Atlas, around 75 km southwest of Marrakech. Locally referred as the Al Haouz earthquake, it is the most powerful earthquake ever recorded in the country. Tragically, the event resulted in almost 3,000 deaths and 5,500 injuries over the following weeks [1].

This disaster is a poignant reminder that Morocco lies in a seismically active region, and the province of Agadir Ida Ou-Tanane is particularly prone to earthquakes, inducing landslides, another natural threat. Due to the geological, structural and morphological complexity of the region [2], this research aims to update landslide susceptibility mapping in the province of Agadir Ida Ou-Tanane following the September 8, 2023 event, by integrating two additional crucial factors: earthquakes zone and annual rainfall. We will adopt a qualitative approach based on hierarchical multi-criteria analysis (AHP) and GIS techniques. The data used will include slope, exposure, vegetation cover, lithology, drainage, seismic zones and precipitation. The results of this mapping should reveal the vulnerability of the study area to landslides, highlighting increased susceptibility in certain regions.

2. The study area

Agadir is situated in the north-western part of Morocco's Souss-Massa region. It covers an area of around 2,297 square kilometres, 85% of which is mountainous and rugged, and the remaining 15% a flat plain. The town is located in west-central Morocco, at coordinates 9°13'10 to 9°53'30 west longitude and 30°56'00 to 30°20'50 north latitude [3].

3. Geological setting

In close proximity to Agadir, the South Atlas Fault divides into two branches: the North Atlas Flexure and the South Atlas Flexure. These are the two major faults that define the southern edge of the Moroccan High Atlas and the Saharan Atlas from Agadir to Gabes. They extend under the Atlantic Ocean to the Canary Islands, where their activity has caused volcanic eruptions in recent centuries [4].

The primary faults in the vicinity of Agadir extend from the east-northeast to the west-southwest, characterized as flexures. These flexures exhibit a pliant tectonic style, allowing for bending and deformation without fracture. There are also smaller, more recent faults in the area that run from northeast to southwest. These faults are located in the southern pre-Atlasic zone and include the Kasbah fault, the Tildi fault, and the Lahouar fault [5].
The Tildi and Lahouar faults serve as barriers against the propagation of longitudinal seismic waves into the pre-Atlasic zone. While the Tildi fault has induced some damage, the Lahouar fault has effectively hindered its further extension. The Sous synclinal zone appears to function as a shock absorber, as observable damage is primarily confined to the vicinity of the pre-Atlasic zone [6].

The anticlinal structures in the Agadir region (Tagragra, Ait Lamine, El Kasbah, etc.) are associated with regional faults such as El Kasbah, Tildi offshore, Cap Rhir offshore, Ameskroud, etc. The offshore region of Cape Rhir exhibits intricate structures and notable salt activity, bounded by the El Kasbah boundary. Earthquakes with a magnitude exceeding three are situated north of the El Kasbah system. The primary factor contributing to the 1960 Agadir earthquake is the South Atlas Fault, characterized by its east-northeast to west-southwest orientation [7].

The compressional focus mechanism oriented WNW-ESE aligns closely with the ongoing convergence of the African and Eurasian plates, indicating a collision between the two plates in a west-northwest to east-southeast direction. In the event of an earthquake in the Agadir region, it has the potential to induce various secondary phenomena, including floods, avalanches, tsunamis, landslides, fires, and soil liquefaction. These phenomena can sometimes cause more damage than the earthquake itself.

4. Methodology

The method used in this study has three main steps:

1. Data collection: This process entails gathering diverse datasets, including digital terrain models (DTMs), satellite imagery, geological maps, earthquake records spanning from 1960 to 2023, road information, data related to terrain instability zones and annual rainfall data for 2020.

2. Data preparation: This process entails utilizing Geographic Information System (GIS) to establish a digital database encompassing predisposing factors for landslides, including lithology, slope, exposure, hypsometry, land use, distance to faults, distance to roads, and drainage density [3]. Moreover, two additional factors: earthquakes zone (1960-2023) and annual rainfall for 2020, have been integrated.

3. Landslide susceptibility mapping: This involves using the analytical hierarchy process (AHP) to structure diverse parameters and allocate weights to them. Initially, weights are assigned to each sub-factor and subsequently to each factor through the AHP pairwise comparison method. Ultimately, GIS is utilized to consolidate the weighted factors, generating a landslide susceptibility map.

4. Validation: This involves validating the landslide susceptibility map using field data to ensure that it is accurate.

5. Results and discussion

In this research, the weighted superposition technique based on Analytical Hierarchy Process (AHP) was utilized to create a landslide susceptibility map for the Agadir Ida Ou-Tanane province. The development of the susceptibility map involved the consideration of ten factors influencing landslides. A comprehensive examination of the previously published article provided a foundation to build upon the eight established causal factors (lithology, slope, land use, distance from faults, distance from roads, aspect, elevation, and drainage) known to contribute to landslide occurrence. Additionally, we introduced two additional factors of significant importance (earthquakes zone and rainfall). The outcomes of the AHP method for the ten factors considered in this study are presented in the subsequent table 1.

The consistency ratio (CR) is equal to 0.08, i.e. below the threshold value of 0.1, meaning that inconsistencies are very low.

Lithology is the most influential factor on landslide susceptibility, closely followed by slope, vegetation cover, and seismicity of the area. These observations are in line with previous studies highlighting that rock type, slope, vegetation cover and regional seismic activity are all significant determinants of landslide risk.

Lithology: Rocks with low mechanical properties and high vulnerability to weathering are more prone to landslides. In the province of Agadir Ida Ou-Tanane, most geological formations are characterized by high proportions of clay, marl and limestone, all of which are prone to landslides [3].

Slope: Steeper slopes amplify the gravitational force acting on slope materials, reducing stability and increasing the likelihood of slope failure [3].

Land use and land cover (LULC) changes, such as deforestation, agriculture, and urbanization, can impact landslide susceptibility by altering soil's hydrological and mechanical properties. For instance, deforestation removes stabilizing vegetation, rendering slopes more prone to landslides. In the Ida Ou-Tanane basin, the moderate vegetation cover in the north-northwest zone suggests a relatively lower to medium risk of landslides.

Due to its seismic activity, our study area is especially susceptible to landslides, triggered by seismic vibrations that induce ground movements. The resultant map, derived from recorded seismic data and following the reclassification of classes into five categories, reveals zones of intense seismic activity (depicted in red) along the coast, where earthquakes of magnitudes 5.9 and 4.4 were recorded in 1960 and 2017, respectively. Over 70% of the region falls within a zone characterized by high to very high seismic sensitivity (Cf., Fig. 1).
Table 1. Weight of each factor in the conditioning of landslides by the AHP model.

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<tr>
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<th>Lithology</th>
<th>Slope</th>
<th>Earthquakes zone</th>
<th>Rainfall</th>
<th>Land use</th>
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<th>Elevation</th>
<th>Drainage</th>
<th>Distance from roads</th>
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Consistency ratio (CR) = 0.08

Fig. 1. Map of earthquake areas between 1960 and 2023 in the province of Agadir Ida Ou-Tanane.

Precipitation is a significant factor in the initiation of landslides. The precipitation map illustrates the annual precipitation patterns in the province for the year 2020. The data are depicted using color gradients divided into five classes, ranging from light to dark green for areas with minimal precipitation to orange and red for regions with higher precipitation levels. Mountainous terrains display heightened precipitation...
values exceeding 216.15 mm per year, indicated by vibrant shades of red. In contrast, coastal zones exhibit more moderate precipitation levels, varying between 166 mm and 116 mm, portrayed in lighter tones (Cf., Fig. 2).

The proximity to faults is a crucial element contributing to landslide susceptibility. Faults have the potential to introduce zones of vulnerability in slopes, rendering them more prone to failure. Additionally, faults can disrupt drainage patterns and trigger seismic activity, further elevating the risk of landslides. The remaining factors, including hypsometry, drainage density, road density, and slope aspect, hold relatively lower weights, yet they remain recognized as impactful in landslide susceptibility according to other studies. It is essential to emphasize the interconnected nature of these factors, as their interactions can collectively influence landslide susceptibility density [3].

Our model encompassed a diverse range of factors, enabling a thorough evaluation of landslide susceptibility in this region characterized by tectonic activity. Our results align with prior studies [3], underscoring the significance of specific factors in landslide susceptibility. Lithology, slope, earthquakes zone, rainfall, and land use emerged as the most critical factors in our study, collectively constituting over 72.08% of the overall importance in landslide susceptibility. Furthermore, these factors have consistently been recognized as key contributors to landslide susceptibility in various other studies.

It is crucial to recognize that the precise weights and rankings of these factors can vary based on the local geological, geomorphological, and environmental conditions of the study area.

The landslide susceptibility map was drawn up by incorporating the ten factors and their respective weights determined by hierarchical multi-criteria analysis (Cf., Table 1). The map shows the spatial distribution of landslide susceptibility in the study area, ranging from areas of very low susceptibility to those of very high susceptibility (Cf., Fig. 3). The region’s most susceptible to landslides (34.90% of the study area) are predominantly situated in the southern and eastern areas, extending north of Agadir, and in proximity to drainage systems like Oued Souss and Oued Tamri. These areas feature steep slopes conducive to erosion and landslides, coupled with high seismic activity and proximity to faults within the province. In contrast, the north-western zone exhibits a low to very low landslide risk (covering 21.96% and 23.92% of the study area, respectively) and is characterized by moderate vegetation cover and an elevation ranging from 800 m to 200 m.

Landslides are primarily observed in clay and limestone formations, aligning with findings from other studies that have highlighted these lithology’s as notably prone to landslides [8, 9].

The landslide susceptibility map was validated by comparing the locations of landslides observed in the field (see Map 10). A total of 53 landslides were identified. The conclusions are as follows: Areas with very high and high susceptibility to landslides comprise 94.3% of observed landslides.
Areas with medium susceptibility to landslides account for 5.7% of observed landslides. These results confirm that the region is highly prone to landslides due to a combination of factors. They also demonstrate that the integration of variables such as lithology, slope, land use, earthquakes zone, rainfall, and distance from faults, hypsometry, drainage density, road density and aspect can effectively identify landslide-prone areas. Comparison of our results with existing literature [3, 10, 11, 12, 13, 14, and 15] confirms the validity of the factors used in our study.

Fig. 3. Landslide Susceptibility Map using the AHP Model, showcasing several identified landslides.

6. Conclusion

Landslides in seismic zones represent a complex and potentially dangerous hazard, often linked to poorly understood direct causes. That's why it's crucial to identify areas at risk of landslides and map their susceptibility. The province of Agadir Ida Ou-Tanane, due to its seismic activity and the unstable nature of its terrain, is particularly exposed to this type of hazard. The region's topographical features and lithological materials increase the likelihood of landslides. In this study, the Analytical Hierarchy Process (AHP) was used to spatialize and locate landslide-prone areas in the province of Agadir Ida Ou-Tanane. This approach integrates factors observed in the field and causative elements, including lithology, slope, altitude, slope aspect, land use, drainage density, earthquakes zone, rainfall, distance from roads and faults. These factors were assessed using AHP and GIS techniques.

Based on the landslide susceptibility map, we have identified five classes with a surface area of 15.69%, 19.22%, 19.22%, 21.96% and 23.92% of the entire Agadir Ida Ou-Tanane province, respectively very high, high, medium, low and very low.

The very high to high sensitivity is mainly located in the southern and eastern regions, extending north from Agadir, and close to drainage systems such as Oued Souss and Oued Tamri. These areas feature steep slopes conducive to erosion and landslides, associated with high seismic activity and the proximity of faults in the province.

They are controlled by the nature of the clay, limestone and alluvial formations, which have the highest landslide density. Hilly topography has a direct influence on landslides, as doe’s proximity to drainage and fault density, as well as human activities such as road and house construction, quarrying and mining of building materials. The resulting map was validated on the basis of landslides identified during fieldwork. The landslide susceptibility map is of vital importance for land-use planning in general and urban development in particular. It provides more information on present and future landslides, which makes it viable.

References

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