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Article

Earthquake risks assessment and urban vulnerability: Case of Nador city, northeast Morocco

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Abstract: This study introduces an innovative approach to assessing seismic risks and urban vulnerabilities in Nador, a coastal city in northeastern Morocco at the convergence of the African and Eurasian tectonic plates. By integrating advanced spatial datasets, including Landsat 8–9 OLI imagery, Digital Elevation Models (DEM), and seismic intensity metrics, the research develops a robust urban vulnerability index model. This model incorporates urban land cover dynamics, topography, and seismic activity to identify high-risk zones. The application of Landsat 8–9 OLI data enables precise monitoring of urban expansion and environmental changes, while DEM analysis reveals critical topographical factors, such as slope instability, contributing to landslide susceptibility. Seismic intensity metrics further enhance the model by quantifying earthquake risk based on historical event frequency and magnitude. The calculation based on higher density in urban areas, allowing for a more accurate representation of seismic vulnerability in densely populated areas. The modeling of seismic intensity reveals that the most susceptible impact area is located in the southern part of Nador, where approximately 50% of the urban surface covering 1780.5 hectares is at significant risk of earthquake disaster due to vulnerable geological formations, such as unconsolidated sediments. While the findings provide valuable insights into urban vulnerabilities, some uncertainties remain, particularly due to the reliance on historical seismic data and the resolution of spatial datasets, which may limit the precision of risk estimations in less densely populated areas. Additionally, future urban expansion and environmental changes could alter vulnerability patterns, underscoring the need for continuous monitoring and model refinement. Nonetheless, this research offers actionable recommendations for local policymakers to enhance urban planning, enforce earthquake-resistant building codes, and establish early warning systems. The methodology also contributes to the global discourse on urban resilience in seismically active regions, offering a transferable framework for assessing vulnerability in other coastal cities with similar tectonic risks.

Keywords: seismic risk; urban vulnerability; Nador; seismic vulnerability indices; landslides; risk mitigation strategies

1. Introduction

Coastal cities in the Mediterranean region experience natural disasters, and among these, seismic risks have remained paramount. Nador, indeed, could be regarded as an example of sensitivity to geological events because it is located in the area where active movements of the African and Eurasian tectonic plates are observed. Therefore, the identification of the seismological risks involved when constructing a city like Nador is critical for the public good, as well as in developing a sustainable city for future growth and urban longevity.

Before advancing to the results of this paper, it is pertinent to highlight that the study relies on prior research carried out on seismic risks in Nador (Chaaraoui et al., 2022). Geological surveys documented the location of active faults in the area and estimated urban vulnerability (Marsh, 2011). Historical seismography studies revealed that previous earthquakes tend to repeat concerning the local seismicity (Tsushima and Ohta, 2014). Social scientists simultaneously analyzed building systems for earthquake resistance and the edges of social vulnerabilities in sensitive cities. An assessment approach focusing on individual aspects of Nador's earthquake risk has been used in previous research (Nicholls et al., 2021).

Earthquake risk assessment spans multiple areas. Geology identifies active faults, seismology examines old earthquakes, and social science examines resilience and social vulnerability levels. Although valuable, these factors have operated in isolation, hindering the development of comprehensive mitigation strategies (Yariyan et al., 2020).

Risk analysis entails identifying potential risks, judging the consequences, and estimating the probability of their occurrence (Mao et al., 2024). The concept of risk is widely applied in sectors such as healthcare, industry, and insurance, which heavily rely on accurate forecasting of natural disasters (Brückl et al., 2021). However, the concept of risk differs across sectors like business, finance, and infrastructure (Haldon and Rosen, 2018). Despite these variations, a common thread remains: uncertainty (probability) and loss (likelihood of outcome) are the determinants of risk. The equation Risk = Hazard × Vulnerability × Exposure to Hazard reflects this concept (Bankoff et al., 2004).

Figure 1. Types of stakes.

In this context, Nador presents a particularly high risk due to its location on the Mediterranean coast, in proximity to fault lines. As shown in **Figure 1**, the various stakes of seismic risk, human, property, environmental, system, and spatial stakes are central to understanding the broader implications of earthquake events for coastal cities like Nador. Human stakes refer to direct impacts on individuals, including displacement and injury, while property stakes involve the destruction of infrastructure. The potential damage to essential services, like communication and transportation systems, reflects system stakes, and environmental stakes highlight the risk to natural ecosystems. Together, these components illustrate the multifaceted nature of seismic vulnerability.

This study follows an assessment view of seismic theory that integrates risk assessment approaches, becoming the analytic framework (Fekete et al., 2020). The United Nations Office for Disaster Risk Reduction defines risk as the possibility of a hazardous event occurring at specific times and places (Breaking the Cycle of Risk, 2024). Cohen (1984) further considers risk as one of the possible outcomes that result in damage.

The commonly used term "risk" holds a deeper meaning, particularly in risk evaluation and management (Gibbs, 2015). To answer what constitutes risk, it is necessary to rely on definitions found in literature and to embrace distinctions that imply both quantitative and qualitative dimensions (Hantz, 2021). Gibbs et al. (2015) concluded that risk involves the probability of growth occurring at a particular time and place. Hantz et al. (2021) and Smith (1993) have demonstrated that risk involves the possibility of something undesirable happening. Risk involves uncertainty about the effects of an activity concerning something humans value, such as health, well-being, property, or the environment, often focusing on negative outcomes (Smith, 2013).

These conceptualizations provide an understanding of how historical information, statistics, and modeling can help assess the likelihood of potential risks. These quantitative assessments are the foundation of various approaches used in calculating risks and predicting events with a certain degree of certainty. However, relying solely on probability can lead to an incomplete picture. Recognizing this limitation, Varnes (1984) suggested a complementary perspective, defining hazard as "a condition with the potential for causing an undesirable consequence". This qualitative angle aligns with the definitions proposed by Alexander (1993) and Blaikie et al. (2004), who showed that a threat is a hazard with the potential to cause damage, or a chance with the ability to result in negative effects, respectively (Alexander, 1993; Blaikie et al., 2004).

Embracing both qualitative and quantitative perspectives allow for a deeper understanding of the inherent dangers associated with various phenomena, regardless of their likelihood of occurrence. This broader knowledge is crucial for effectively preparing for and mitigating the potential impacts of unsafe events, even those with low probability.

Vulnerability, often used to describe the potential for harm or susceptibility to adverse events, carries significant weight in scientific discourse across fields such as climate change, poverty alleviation, and natural hazard management (Blaikie et al., 2004). Scientists have worked to refine and define vulnerability more precisely, emphasizing its multifaceted nature and the dynamic interplay of factors contribution.

In theoretical understanding, vulnerability remains somewhat abstract, with definitions often lacking specificity. However, operational definitions and methodologies developed to assess vulnerability provide tangible frameworks for analysis. These methodologies typically fall into three categories: evaluating potential harm under projected future scenarios, assessing the current capacity to mitigate harm, or combining both approaches to offer a comprehensive understanding of vulnerability dynamics.

A focal observation is the disparity between theoretical and operational definitions, highlighting the need for greater coherence and alignment across disciplines.

According to Aksha et al. (2019), vulnerability may be understood as the manifestation of inherent conditions that render a system susceptible to extreme risks, resulting in detrimental effects. Aven (2011) and Wolf et al. (2013) provide a nuanced definition, describing vulnerability as the characteristics that determine a person or group's ability to anticipate, cope with, resist, and recover from the impacts of a hazard. This definition underscores the dynamic nature of vulnerability, shaped by external factors like environmental changes and economic shocks, as well as internal factors such as social inequalities and resource availability (Aven, 2011; Wolf et al., 2013).

From an environmental perspective, Kreimer et al. (2003) expand the concept of vulnerability to include the degradation and subsequent loss of environmental goods and services. This broader perspective highlights the interconnectedness of human societies and their environment, showing how environmental degradation can exacerbate vulnerabilities and increase susceptibility to adverse impacts (Kreimer et al., 2003).

These research studies on risk and vulnerability emphasize the importance of integrating both quantitative and qualitative approaches for effective risk and vulnerability management. Recognizing the dynamic interplay between external and internal factors is crucial for comprehensive assessment and mitigation strategies (Freddi et al., 2021). Quantitative methods provide the empirical data needed to measure risk and vulnerability through statistical analysis, numerical modeling, and probabilistic forecasting. These methods offer precision and the ability to generalize findings across different contexts (Rus et al., 2018). On the other hand, qualitative approaches, such as case studies and ethnographic research, capture the nuanced, context-specific experiences of urban communities, offering insights that quantitative methods may overlook.

In the case of earthquakes, quantitative methods are critical in understanding seismic hazards through geological surveys, seismic monitoring, and probabilistic seismic hazard assessments. These approaches provide essential data on the likelihood of earthquakes, their potential magnitudes, and expected ground-shaking intensity, contributing to seismic risk mapping and the design of engineering solutions to mitigate structural damage.

Qualitative research on earthquakes, however, explores the urban dimensions of seismic events. It investigates how cities experience and perceive earthquake risks, focusing on urban factors that influence preparedness and response in earthquake-prone regions. This perspective is vital for understanding how different urban areas are affected by and respond to earthquakes, which might not be captured solely through quantitative data.

Challenges persist in achieving definitional coherence due to the lack of alignment between theoretical and operational definitions of vulnerability. Theoretical definitions emphasize broad conceptual frameworks, while operational definitions focus on measurable indicators. This divergence can result in inconsistencies in research findings and difficulties in applying theoretical insights to real-world scenarios.

The research and literature review suggest that previous seismic surveys have approached earthquake research from a narrow perspective, without fully integrating environmental and urban dimensions to explain risk and vulnerability assessment. This study addresses these limitations by developing inclusive frameworks that merge the urban context and diachronic seismic analysis to identify the intensity levels of risk and vulnerability in Nador city. This perspective provides a comprehensive understanding of vulnerability by bridging the gap between empirical data and the urban environment. By addressing underlying causes of vulnerability such as urban land cover changes, ground stability factors, and environmental and infrastructural aspects, this approach enhances the resilience of Nador city.

This paper follows a structured approach to assess seismic risks and urban vulnerabilities in Nador, Morocco. It begins with an introduction, outlining the significance of the study and its geographical focus. The literature review builds on existing research regarding seismic risks and urban resilience. The materials and methods section details the data collection, preprocessing, and analysis, using tools like Landsat imagery and Digital Elevation Models (DEM) to create vulnerability maps. The results present high-risk areas identified through spatial analysis. Finally, the discussion and conclusion offer recommendations for urban planning and disaster mitigation, with broader applications for other coastal cities.

2. Materials and methods

The methodological framework of this study is structured into four key phases: data collection, preprocessing, indicator calculation, and spatial analysis. This approach ensures a systematic workflow for assessing seismic risks affecting Nador city. The field study phase focused on verifying landslide inventory maps, refining geological maps, and validating causative factors such as soil types and tectonic features, based on the geological map of Nador city. These are crucial for understanding the underlying risk factors contributing to urban vulnerability in seismically active regions.

Simultaneously, the study involved the preparation of several geospatial maps, including a detailed spatial and temporal seismic intensity map, a refined landslide inventory, and a geological map within a GIS framework. Key data sources such as a Digital Elevation Model (DEM) were extracted to help in the generation of a spatial vulnerability map. These maps serve as fundamental inputs to understanding the physical and environmental dynamics of the study area.

Data processing was conducted using QGIS and Google Earth Engine powerful tools that allowed for the integration, stacking, and extraction of multiscale geospatial data within the study area, notably incorporating the latest urban boundary of Nador city. This integration was crucial for ensuring that the data accurately reflected the current urban form, which is essential when assessing risks in a rapidly evolving urban environment.

A critical aspect of the methodology is the selection of datasets such as Landsat 8–9 Operational Land Imager (OLI) and DEMs. These datasets were deliberately chosen for their complementary roles in the analysis. Landsat OLI offers high-resolution multispectral data, enabling the detection of changes in land cover over time, it's a key factor in understanding surface conditions that influence landslide susceptibility. Additionally, it provides spectral data useful for identifying the geomorphological characteristics of the region, which directly impact the occurrence of natural hazards.

DEMs, on the other hand, supply precise elevation data, critical for calculating topographic factors such as slope, aspect, and hillshade factors that heavily influence both the likelihood and severity of landslides in seismic-prone areas. For example, steeper slopes are often correlated with higher landslide risk, particularly in regions with unstable geological formations. By combining the spectral capabilities of Landsat with the topographic insights from DEM, the study creates a more robust model for geospatial analysis.

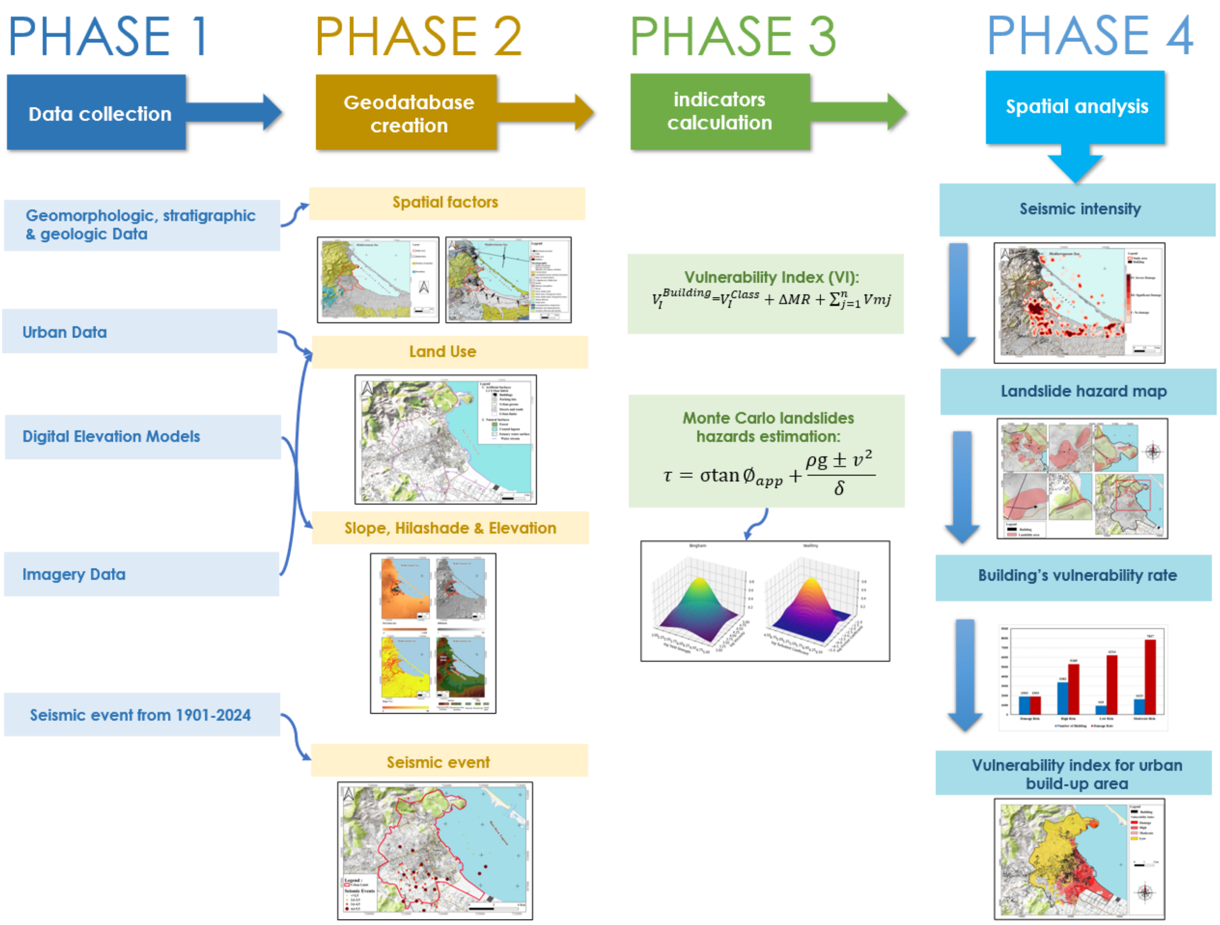

Figure 2. Workflow methodology chart.

The integration of these diverse datasets allows for a multi-dimensional analysis, where both surface dynamics (from Landsat) and subsurface conditions (from DEMs) are assessed in tandem. This approach enhances the granularity of the spatial vulnerability map, making it more accurate for urban planning and disaster preparedness.

The methodological framework is summarized in the **Figure 2**, which illustrates the sequential integration of field and desk-based activities, ensuring that each phase builds upon the previous one to strengthen the overall risk assessment.

2.1. Study area

Nador, a Mediterranean city in north-eastern Morocco, is nestled between the Gourogou mountain to the west and north and the port of Beni Ensar to the west. Stretching approximately 75 km in a generally east-northeast to west-southwest direction, it encompasses the urban areas of Nador city, Arekmane, the Marchica dune lido and Beni N'sar city (see **Figure 3** below).

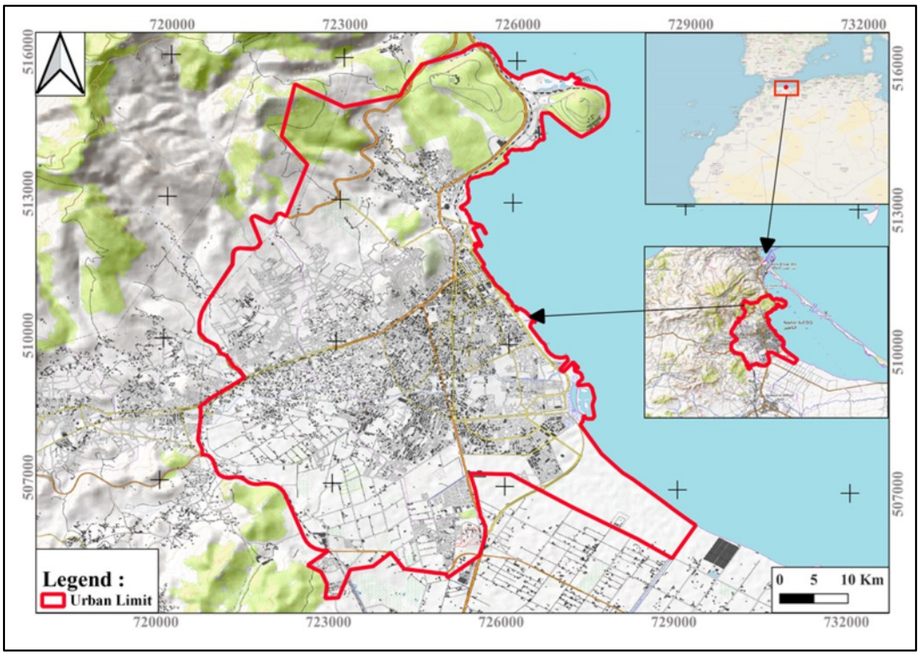

Figure 3. Study area Nador, Northern Morocco.

2.2. Data sources and pre-processing

The data acquisition process in this study is inherently multifaceted, utilizing an extensive array of geospatial, geological, and seismological datasets to establish a rigorous earthquake risk assessment framework. The primary data sources include geological maps and historical seismic records, which provide critical insights into the study area's subsurface geology, tectonic features, and past seismic activities. Geological data, specifically fault line mappings and lithological units, are essential for determining the geotechnical characteristics of the region, while historical seismic data allow for an in-depth understanding of seismic event recurrence, magnitude distribution, and temporal evolution (Meerow et al., 2016). These datasets form the foundation for both seismic hazard evaluation and subsequent vulnerability modeling.

Sophisticated data fusion techniques were employed to integrate geological, seismic, and urban datasets using geospatial overlay analysis, processed primarily through Quantum GIS (QGIS). This integration was achieved by overlaying vector and raster data, including fault line data, topographical models, and seismic intensity layers, creating a comprehensive risk matrix. Temporal seismic data were processed through a time-weighted aggregation method to ensure that both historical seismicity and recent trends were dynamically considered within the model.

The methodology follows a structured geospatial data fusion protocol that aligns various spatial datasets based on their temporal and spatial resolutions. This process is critical for achieving high accuracy in seismic vulnerability mapping, ensuring that heterogeneity in data sources (e.g., different resolutions of topography and land cover datasets) does not lead to analytical discrepancies. The geospatial fusion technique incorporates advanced kernel density estimation (KDE) to evaluate seismic hazard intensity distributions, offering a more granular understanding of high-risk zones.

To ensure the reliability of the data sources, a rigorous cross-verification strategy was adopted. All data obtained from various sources were systematically validated against authoritative databases such as the United States Geological Survey (USGS). Specifically, seismic data from the Volcano Discovery (1901–2024) catalog were compared with Mw-homogenized earthquake datasets to verify both the magnitude and frequency of events. This comparative analysis ensured that no biases were introduced into the risk assessment model.

Topographical accuracy was ensured by cross-validating 30-meter resolution Digital Elevation Models (DEMs) from the USGS with urban planning documents from the Nador Urban Planning Agency. This process ensured the consistency of elevation data, minimizing potential topographical errors that could distort vulnerability assessments. Further validation involved aligning seismic event data with geospatial fault mapping, ensuring logical coherence between fault line proximity and recorded seismic activity.

To enhance the robustness of the methodology, advanced geospatial and statistical techniques were employed to provide a deeper understanding of the spatial dynamics of seismic hazards. Kernel density estimation (KDE) was used to analyze the spatial distribution of seismic events, pinpointing areas of heightened risk with greater precision than traditional methods. Additionally, topographical factors such as slope, hillshade, and elevation were extracted from DEMs and used to model potential landslide zones. These zones were cross-referenced with geological layers to predict areas of compounded seismic and geotechnical risk.

The application of advanced spatial analysis tools enabled the creation of high-resolution vulnerability maps. These maps synthesized seismic, geotechnical, and urban data into a single integrated framework, significantly enhancing the accuracy of identifying vulnerable areas. This methodology provides the granularity necessary to inform urban planning and risk mitigation efforts with a level of precision that surpasses traditional approaches.

Given the reliance on multiple datasets from diverse sources, a comprehensive quality assurance framework was essential. Beyond the verification of seismic data, a multi-layered verification process was employed for all data inputs, including geological and urban land cover data. This process involved triangulating data sources and subjecting the results to error analysis, thereby minimizing inconsistencies in the final models. For instance, geological data from fault maps were cross-checked with historical earthquake records to ensure the consistency of fault activity with seismic trends. Similarly, urban land cover data were validated against urban planning document to ensure spatial accuracy.

Through meticulous integration and validation of diverse datasets, this study presents a scientifically robust and comprehensive model of earthquake risks and urban vulnerabilities. By utilizing advanced geospatial and statistical methodologies, the study delivers a refined and granular analysis that enhances the precision of vulnerability assessments, ultimately leading to more effective risk mitigation strategies. The multi-layered verification approach strengthens the credibility of the results by ensuring data reliability. This methodical approach improves the study's scientific rigor and ensures its applicability and replicability in real-world policy and urban planning contexts (see **Table 1** below).

Table 1. Data sources and their description.

Type	Description	Year	Spatial scale	Source
Raster	Topography	2024	50 m	OpenTopoMap
	Digital Elevation Model	2024	30 m	USGS
	Geology	1978	5000 m	Geojamal
	Geotectonic	1992	5000 m	Geojamal
	Landsat 8–9 Operational Land Imager (OLI)	2024	30 m	USGS
Vector	Land Cover	2024	/	OpenStreetMap
	Siesmic Data	1900–2024	/	Volcano Discovery & Mobarki et al. (2022)
	Urban Boundary	2024	/	ArcGis Hub

2.3. Seismic data

This study analyzed seismic data from the Volcano Discovery database, covering the period from 1900 to 2024 (Mobarki and Talbi, 2022), focusing on 221 earthquake events with magnitudes ranging from 2 to 5 Mw. The selection of this magnitude range was deliberate, aiming to capture both frequent, low- to moderate-intensity earthquakes, which reflect the background seismic activity of the region, and moderate seismic events that pose a tangible threat to infrastructure. This spectrum allows for a more nuanced understanding of the seismic hazard profile, as lower magnitude events can indicate underlying tectonic stress accumulation, while moderate events have the potential to cause significant structural damage. By encompassing these magnitudes, the study provides a robust assessment of seismic hazards and their possible impacts on urban infrastructure in Nador.

Out of the 221 events, 78 earthquake locations in and around Nador city were selected for further analysis. These locations were chosen based on their proximity to active fault lines and high urban population density, which are critical factors in assessing seismic risk. Nador's location at the convergence of the African and Eurasian tectonic plates makes it particularly susceptible to tectonic activity, highlighting the importance of focusing on these areas to better understand earthquake dynamics and their localized impacts. The emphasis on densely populated urban areas ensures that the risk assessment is directly relevant to human safety and infrastructure resilience.

By concentrating on these 78 locations, the study provides a focused evaluation of seismic risk, including the frequency and intensity of earthquakes, within Nador's most vulnerable urban zones. This approach strengthens the practical applicability of the findings, offering valuable insights for urban disaster preparedness and informing regional seismic risk mitigation strategies. Ultimately, the study contributes to more effective regional planning and risk reduction efforts, ensuring that urban development in Nador is aligned with seismic resilience goals (Kreibich et al., 2022).

The ambient vibration data used in this study were derived from field recordings conducted by Chaaraoui et al. (2021). These measurements were taken using three-component CMG-6TD seismometers, with data acquisition and real-time visualization managed through the SCREAM 4.6 software. To ensure the accuracy of the data, in situ validation was performed, where pre-treatment steps, including calibration and noise filtering, were applied directly in the field. This allowed for immediate verification of the recordings, ensuring data quality and reducing potential interference from environmental noise. Any issues encountered during data collection, such as instrument interference or unstable ground conditions, were resolved by adjusting equipment settings or repositioning the sensors. These quality control measures, coupled with the robust methodology from Chaaraoui et al. (2021), provide a reliable basis for the seismic analysis in this study.

The coastal region in northern Morocco is a key area of inter-plate seismic activity, where the African and Eurasian plates converge, specifically at the Alboran domain. The interaction between these plates results in significant seismic activity along the Nador coastline. The Betic Cordillera (southern Spain) and the Rif region (northern, Morocco) are geodynamically connected to the Alboran domain, a tectonically complex zone located between Iberia and Africa (Lummen and Yamada, 2014). This area is part of the Betico-Rifain domain, which was structured during the Alpine orogenic cycle (Scheidel et al., 2020). It is highly fractured, with significant geological contrasts between different tectonic units. The Rif nappes, for instance, overlap the African continental margin to the south (Poujol et al., 2014).

Tectonic stresses in this region are driven by the oblique convergence between Africa and Eurasia, occurring at a rate of approximately 3 to 5 mm/year (Benzaggagh et al., 2014; Nocquet and Calais, 2012). This convergence results in frequent seismic activity and the formation of active crustal faults, which can be traced by the distribution of earthquakes at various depths.

Given this complex geodynamic setting, Nador is particularly exposed to seismic hazards. The interaction between tectonic plates in the Alboran domain directly influences the seismic risk for Nador, as the city lies in proximity to these active fault systems. This geotectonic context not only increases the frequency of seismic events but also amplifies the potential for moderate to severe ground shaking in Nador. Furthermore, the underlying geological characteristics of Nador, including unconsolidated sediments, exacerbate the risk of ground instability during seismic events. Understanding this regional tectonic framework is crucial for accurately assessing the specific seismic risks that threaten Nador, helping to inform both urban planning and disaster preparedness strategies (see **Figure 4** below).

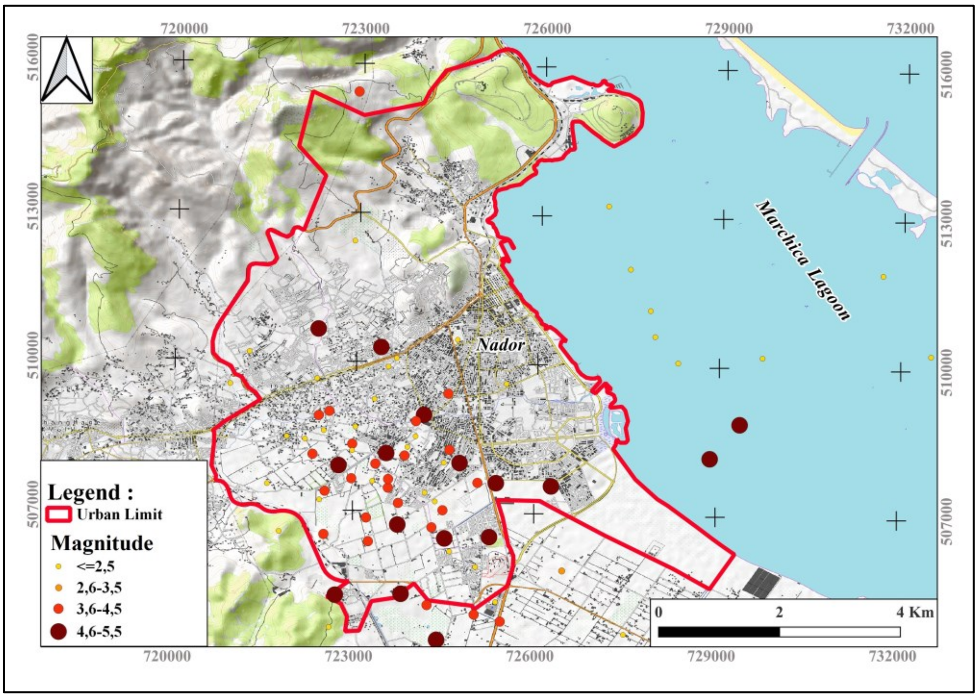

Figure 4. Seismic event Nador city from 1900 to 2024.

2.4. Geomorphologic, stratigraphic and geologic data

The geomorphological, stratigraphic, and geological data used in this study were sourced from the geological map of the Rif Mountains at a scale of 1:500,000. The analysis of geomorphological features provides critical insights into Nador's seismic risk by revealing how tectonic activity has shaped the landscape. Features such as stream networks, terraces, ancient shorelines, and slope landforms (Benamrane et al., 2022) were examined to understand past environmental shifts and identify key indicators of seismic hazards. This examination helps to trace the development of faults and the long-term tectonic forces acting on the region (Nocquet, 2012).

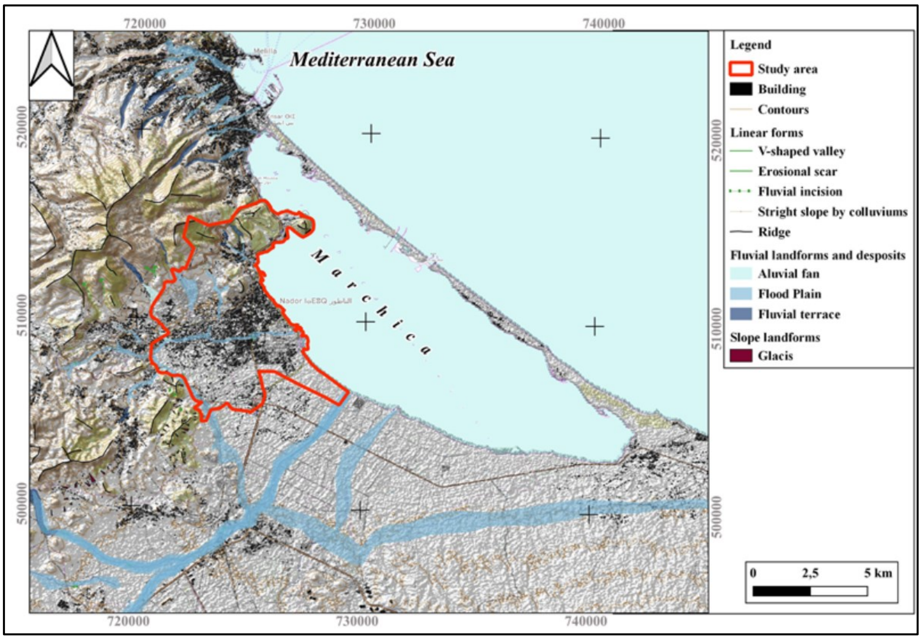

Figure 5. Geomorphological map.

In this study, several significant geomorphological features, such as fault scarps and terraces were identified as direct contributors to seismic risk in Nador's urban areas. These features indicate active tectonic processes and highlight regions prone to ground instability. Additionally, the geomorphological analysis allowed for the assessment of slope stability, identifying areas vulnerable to landslides and erosion, which are critical in predicting the impacts of future seismic events. By integrating these findings into the seismic risk model, we provide a comprehensive framework for anticipating landscape changes and mitigating potential hazards within Nador city (see **Figure 5** above).

Stratigraphic data, on the other hand, enriches our understanding of ground stability and helps identify areas suitable for urban planning based on building engineering regulations. By studying the sequence of layered rocks, stratigraphy offers a window into the history of the underground rock formations (Huggett and Shuttleworth, 2022) (see **Figure 6** below).

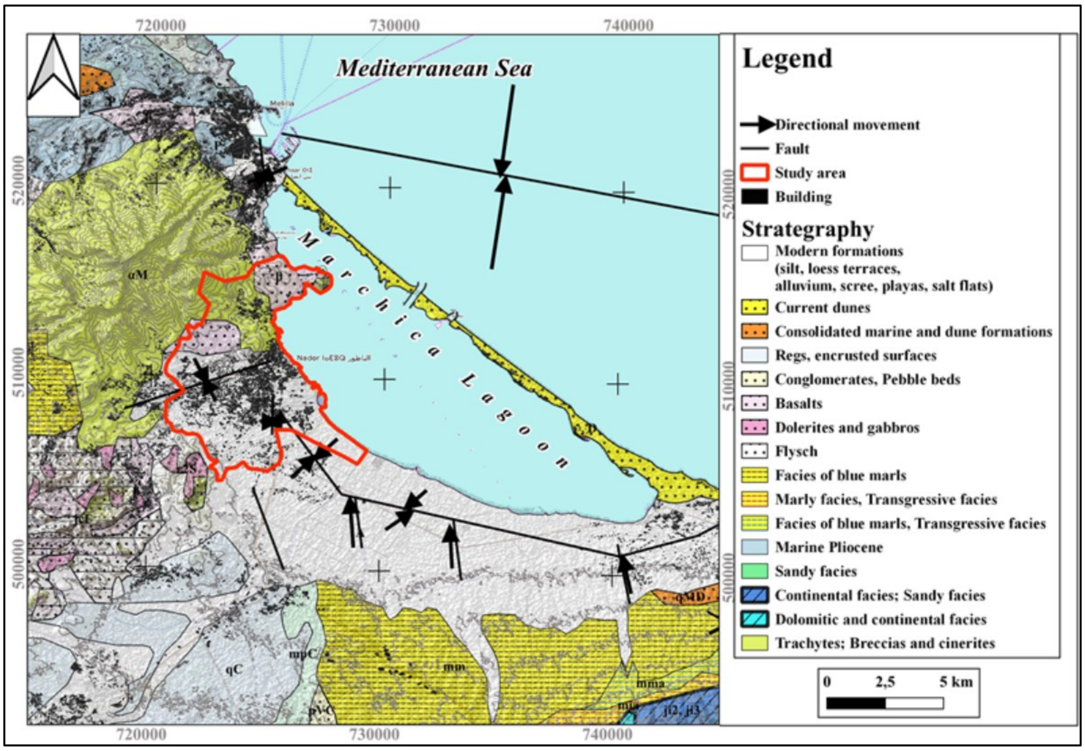

Figure 6. Stratigraphical map.

Geological data, encompassing a broader range of information, provides details about the Earth's features, structures, and processes within Nador. Identifying the types of rocks and minerals, along with seismic activity and gravitational measurements, reveals valuable information about the region's geotechnical history and past seismic events (Naimi and Cherif, 2021) (see **Figure 7** below).

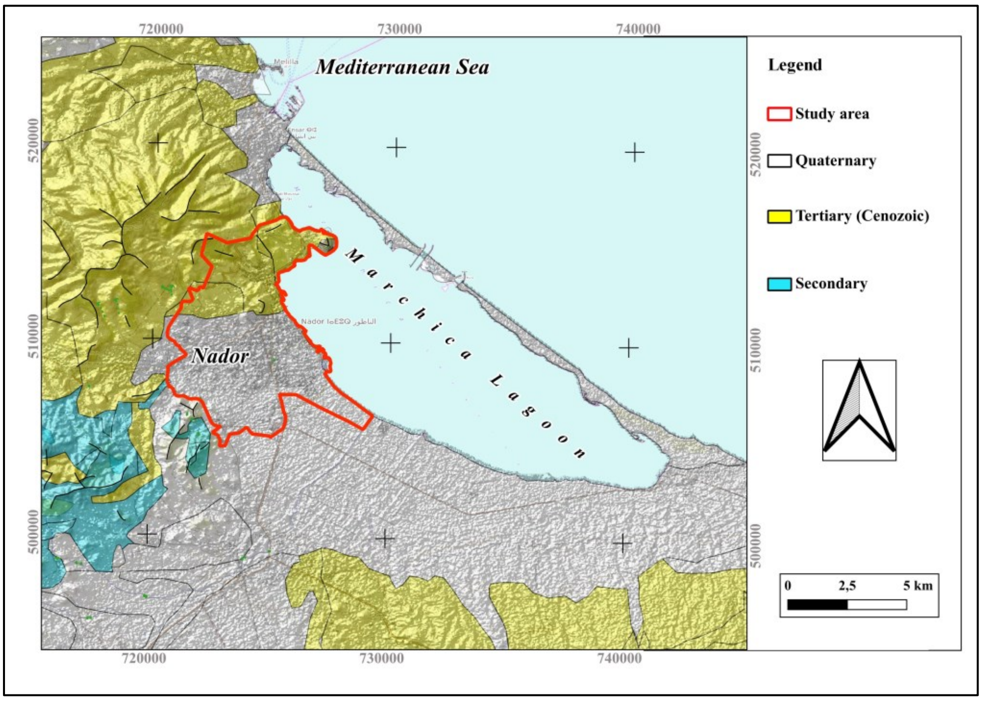

Figure 7. Geological map.

2.5. Topography data

The topographic Map of Nador (1/50,000) provides detailed information about the elevation and terrain features within the Nador study area. Topographic maps are essential tools for understanding landscape variations and serve as a valuable baseline for further analysis (Raji et al. 2018).

Shuttle Radar Topography Mission (SRTM) Data, acquired during the joint mission between the National Geo-spatial Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA) provided comprehensive digital elevation model (DEM) coverage for the entire study area. SRTM data is particularly valuable for its near-global coverage and high-resolution elevation information, making it a crucial resource for various topographic studies.

This data helps us understand the topographic landscape, including factors like elevation, slope and hillshade. These topographic factors play a crucial role in identifying areas susceptible to landslide risks during earthquake events (see **Figure 8** below).

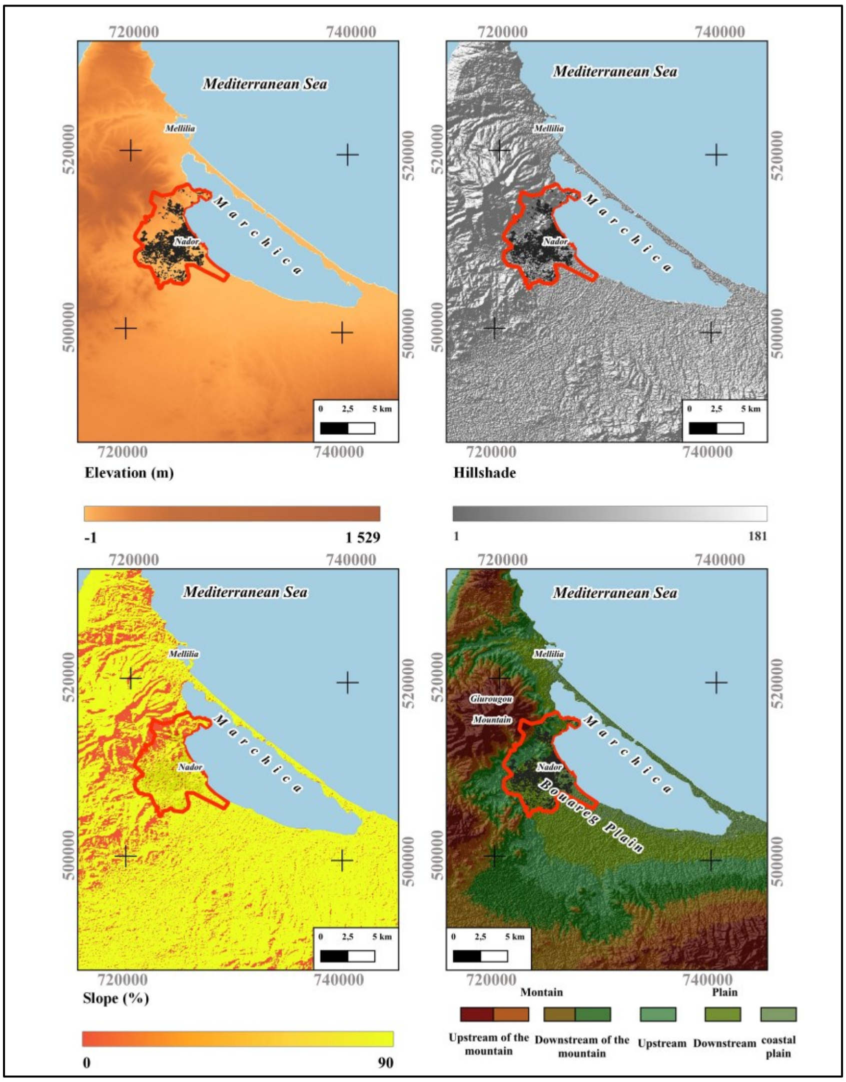

Figure 8. Topography characteristic in the Nador area.

Figure 8 presents a comprehensive visualization of the Nador region's topography, incorporating several key elements. Elevation variations are depicted using a color gradient, with higher areas shown in darker browns and lower plains in lighter yellows transitioning to white, allowing for quick visual identification of mountainous regions and plains. Hillshade adds a three-dimensional texture, highlighting slopes and ridges, revealing subtle variations in topography beyond elevation data. Additionally, explicit slope percentages provide a precise understanding of steepness, crucial for land-use planning, infrastructure development, and hazard assessments like landslide risks. While the specific details of "topographic unity" are not directly evident, it likely refers to the overall uniformity of land forms within a region, such as consistent slope angles, prevalence of specific features, or repetitive ridge and plain patterns.

Key observations from the figure include the mountainous region's steep slopes exceeding 20% (darker tones and steeper labels), suggesting rugged terrain. In contrast, the Bouareg plain exhibits a significantly flatter slope ranging from 0 to 15% (lighter tones and gentler slopes), indicating a more level area potentially suitable for urban development or agriculture.

2.6. Land cover data

The data from the Marchica planning plots, with a spatial scale of 1:5000, was utilized as a key source for assessing and analyzing land cover in the study area. This dataset, in conjunction with satellite imagery, topographic maps, and urban planning documents, provided highly detailed information on the urban landscape around the Marchica Lagoon. To integrate these diverse data sources effectively, GIS techniques were applied to overlay and analyze multiple spatial layers, ensuring a comprehensive risk assessment.

The integration process involved combining the land cover plots, satellite data, and topographic maps into a unified geospatial framework using Quantum GIS (QGIS). The land cover data was specifically weighted according to its influence on seismic vulnerability. For instance, areas with loose or unconsolidated soils, which are more prone to ground shaking during earthquakes, were assigned higher risk values than areas on stable bedrock. This weighting process was essential for refining the vulnerability model and improving the accuracy of the overall risk assessment.

Participatory Learning and Action (PLA) techniques were employed to further contextualize the land cover conditions, particularly focusing on urban and environmental factors (Egenhofer, 1991). A geophysical survey conducted in Nador city also helped delineate open spaces and the boundaries of human activity, adding an additional layer of detail to the spatial analysis.

Figure 9 illustrates how these data layers land cover plots, satellite imagery, topographic maps, and urban planning documents were combined to generate a holistic view of the region's vulnerability (Guo et al., 2024). The figure, based on Corine Land Cover (CLC) rules, highlights the standardized methodology used to map land cover changes, providing a critical reference for assessing spatial dynamics at multiple scales (Egenhofer, 1991).

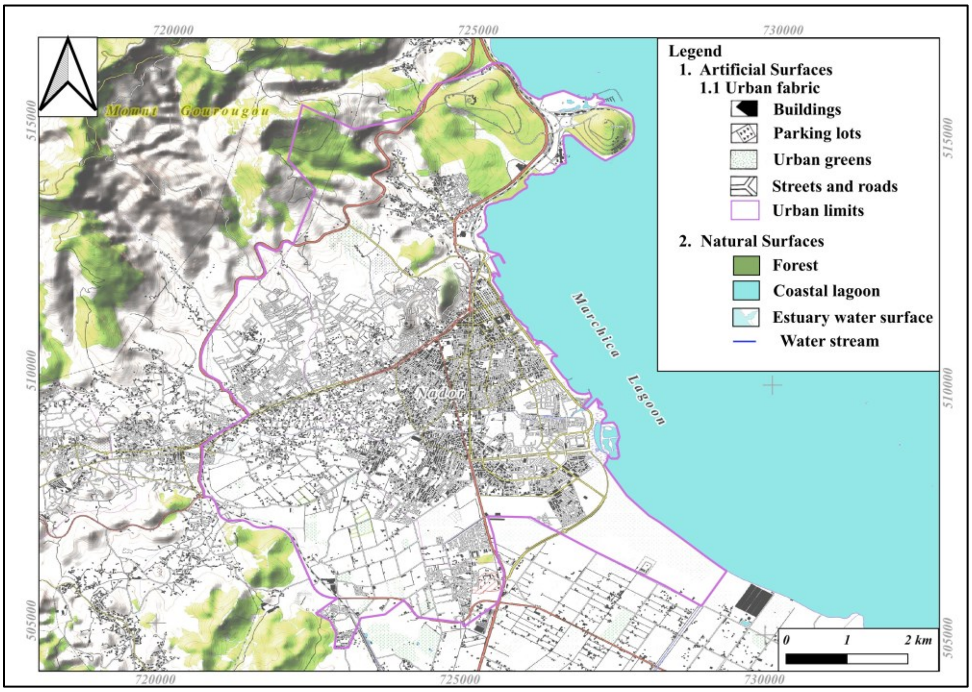

Figure 9. Land cover map of Nador city.

This mapping approach, encompassing forests, urban areas, wetlands, and more, is valuable for assessing seismic risk. By identifying vulnerable areas with land cover data, it can pinpoint locations susceptible to earthquake damage. For instance, buildings on loose soil are more prone to shaking compared to those on bedrock. Furthermore, Corine Land Cover data is primordial for emergency planning, allowing for assessments of potential infrastructure damage and prioritization of areas requiring emergency response after an earthquake. So, incorporating land cover data into risk modeling helps scientists create more accurate models to predict potential earthquake impacts (see **Figure 9** above).

2.7. Method for estimating seismic risks intensity

Seismic risk intensity estimation involves a comprehensive approach integrating seismic hazard analysis, vulnerability assessment, and exposure analysis. Generally, seismic intensity measures are divided into continuous (seismic acceleration, velocity, and response spectrum) and discrete (macroscopic seismic intensity) types (Petrișor et al., 2020). Initially, seismic hazard is evaluated, considering historical data and geological studies to determine earthquake probabilities and potential ground shaking. Concurrently, vulnerability assessment examines the susceptibility of structures and populations to seismic hazards, analyzing the construction quality and fragility of various elements. Exposure analysis identifies elements at risk, such as buildings and critical infrastructure, accounting for population density and economic assets. Integrating these assessments yields an overall seismic risk intensity estimation. Visualization through risk maps aids in the communication of results to decision-makers and the public, facilitating informed mitigation strategies including infrastructure strengthening, land use planning, and emergency preparedness. This assessment approach aims to reduce the impact of earthquakes on communities and infrastructure.

Many scientists have developed a statistical model of seismic intensity measures. Li (2024) considered the impact of multiple seismic risk factors on structural seismic risk, and vulnerability and proposed a ground motion prediction equation considering site conditions for large-scale seismic risk assessment, as expressed in Equation (1) below:

$$log(IMa, b) = E[log(IMa, b) \mid \mu r, m, \theta i,] + \eta b + \varepsilon \tag{1}$$

The equation represents the seismic intensity measured under the influence of an earthquake hazard (b) and the geologic features of the study area (a). The term represents the mean of the logarithm of the intensity measure (IMa, b) considering the distance (μr) between the epicenter source and the impacted urban area surfaces (i). The term (m) refers to the magnitude degree, ηb refers to the seismic event average per year, and ε represents the error of the residual variability values and θ represent Gaussian residual coefficients for areas that were affected by earthquake hazards (b), respectively.

The criteria used to create seismic risks intensity maps are based on a comprehensive integration of geospatial datasets, seismic activity records, and geological features.

Several key factors were considered in classifying the different levels of seismic risk:

- Seismic Intensity and Historical Earthquake Data: The spatial distribution of seismic events, including magnitude, depth, and frequency, was analyzed to model areas of high ground-shaking intensity. Historical earthquake data, particularly from the 2004 El Hoceima event, played a critical role in validating the accuracy of our risk model. This allowed us to ensure that high-risk zones identified in the maps align with areas previously affected by seismic activity.
- Topographical and Geological Conditions: The study used Digital Elevation Models (DEMs) to assess slope gradients and terrain stability. Regions with steep slopes and unconsolidated sediments were marked as highly susceptible to landslides during seismic events.
- Urban Land Cover and Building Vulnerability: The classification also incorporated urban expansion and land cover data, emphasizing the vulnerability of buildings in densely populated areas. Buildings located on unstable soils, especially those made with less earthquake-resistant materials, were categorized as high-risk. This is critical for identifying sectors where structural failure is most likely in the event of an earthquake.

Based on these factors, risk levels were categorized into three distinct zones:

- High Risk: Areas with intense seismic activity, unstable geological conditions, steep slopes, and high population density, where both human and structural vulnerabilities are elevated. The southern part of Nador is an example of such a high-risk area.
- Moderate Risk: Zones where seismic activity is less frequent or severe, but vulnerability still exists due to either geological instability or the presence of vulnerable infrastructure.
- Low Risk: Regions with minimal seismic exposure, stable ground conditions, and lower population densities, where the likelihood of significant damage is much lower.

2.8. Method for estimating probabilstic landslide risks

Probabilistic mapping methods have become increasingly vital in the field of landslide susceptibility assessment, particularly in seismically active regions such as Nador. The primary strength of probabilistic approaches lies in their ability to incorporate spatial and temporal uncertainties associated with highly variable parameters, including hydrological, seismic, geological, geotechnical, and geomorphological factors (Xu et al., 2024). These methods represent a substantial advancement over traditional deterministic models, which often struggle to account for the inherent unpredictability of natural systems. Given Nador's high seismicity and complex geomorphological context, adopting a probabilistic framework enhances the precision and relevance of risk assessments.

The methodology proposed in this study is centered around a probabilistic approach designed to capture the uncertainties associated with slope stability in response to seismic activity. This approach builds on a modified slope model that integrates critical shear strength parameters, topographical characteristics, and geotechnical properties (Zhang et al., 2022). Traditional models often rely on fixed parameters, limiting their flexibility and reducing their effectiveness in dynamic environments. By contrast, our probabilistic model allows for the dynamic consideration of variable factors, significantly improving the reliability of landslide hazard predictions.

A key innovation of this study is the integration of Voellmy and Bingham models to simulate ground movement (McDougall, 2017), both of which offer distinct advantages in representing the behavior of landslides under seismic stress. The Voellmy model characterizes the landslide as a turbulent flow, while the Bingham model treats it as a viscoplastic flow, capturing the dual nature of landslide movements. This dual-model approach provides a more comprehensive understanding of the physical processes driving landslides, thus improving predictive accuracy.

The Monte Carlo simulation framework employed here further enhances the scientific rigor of the analysis (see **Figure 10** below). By generating multiple probabilistic distributions for shear stress (τ) based on uncertainties in input parameters, this method transcends the limitations of deterministic approaches. The governing equation (Equation (2)) demonstrates how probabilistic variations in normal stress (σ), friction angle ($\emptyset_{app}$), bulk density (ρ), and velocity (v) can lead to a more nuanced risk assessment:

$$\tau = \sigma \tan \emptyset_{app} + \frac{\rho g \pm v^2}{\delta} \quad (2)$$

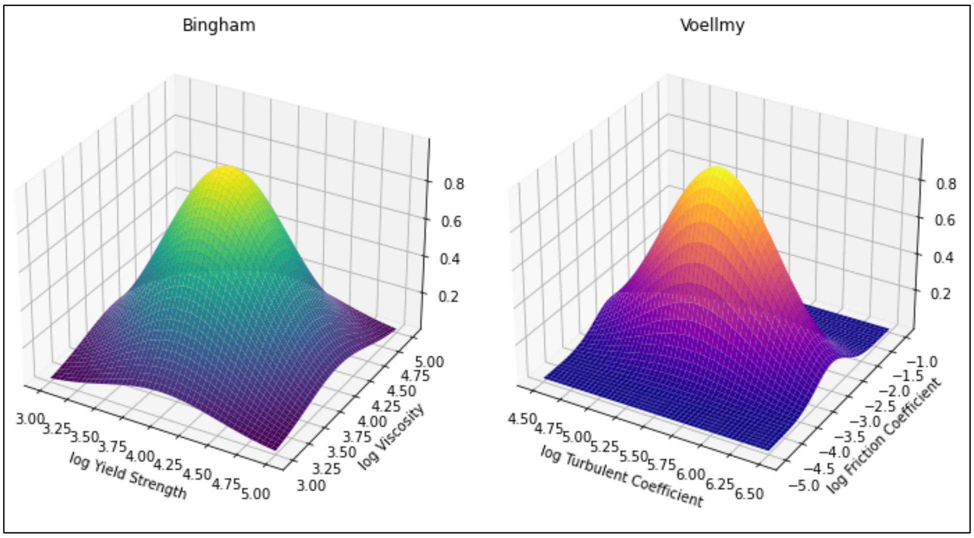

Figure 10. Landslide mass estimation using two models Bingham and Voellmy.

This probabilistic formulation provides a more realistic depiction of the landslide process by capturing the range of possible outcomes rather than a single, deterministic result (Gatto et al., 2022). Such advancements are essential for high-stakes urban environments like Nador, where the accuracy of risk assessments has direct implications for public safety and infrastructure resilience.

Beyond improving the scientific understanding of landslide mechanisms, this probabilistic approach contributes to practical applications. The spatial distribution of landslide risks, visualized through probabilistic hazard maps, offers local authorities and planners a crucial tool for informed decision-making. These maps are not constrained by symmetrical or simplified assumptions, making them highly adaptable to the complexities of real-world geotechnical landscapes. The absence of such constraints allows for a more realistic representation of the diverse and unpredictable conditions that influence landslide susceptibility.

Furthermore, the application of the Monte Carlo method allows for simulating probability density functions across different locations, ensuring that local variations in topography and material properties are adequately captured (Cepeda et al., 2013). This level of detail is indispensable for regions like Nador, where the interaction between seismic activity and geomorphology creates a highly heterogeneous risk landscape. By utilizing historical landslide inventories, such as those from the 2004 El Hoceima earthquake, we validated the model's predictive capacity, thereby confirming its robustness and applicability.

The implications of this research extend far beyond academic interest. The generated probabilistic seismic landslide hazard maps provide an invaluable resource for local governments and infrastructure planners. In contrast to conventional hazard maps, these probabilistic maps account for the full range of possible outcomes, allowing policymakers to implement more targeted mitigation strategies. This capability is critical in regions where urban expansion and seismic activity intersect, as it enables land-use planners to avoid high-risk areas while focusing on reinforcing structures in zones identified as particularly vulnerable.

This approach underscores the need for a paradigm shift in how we approach landslide hazard assessments in seismically active regions. The ability to integrate probabilistic models that account for both material and seismic uncertainties represent a significant leap forward in disaster risk management. In a rapidly urbanizing world, where natural hazards pose ever-greater risks to human populations, such advancements are not only scientifically valuable but also socially imperative. By adopting this approach, cities like Nador can better protect their populations and infrastructure from the potentially devastating impacts of earthquake-induced landslides.

2.9. Method to evaluate vulnerability index

The Vulnerability Index (VI) is a tool that can be used to measure the vulnerability of a coastal area in terms of its socioeconomic development (De Risi et al., 2019; Rosso et al., 2022). It is considered an index that reflects the intensity of each parameter on the territory and population of the coastal zone of the northern part of the Eastern region.

Vulnerability index method helps evaluate the impact of earthquake hazards on humans and goods. This indicator assesses the impact levels. Understanding vulnerability help to analyze spatial extension and how can urban areas be managed to enhance their resilience and ensure the safety of citizens and their property. The evaluation of vulnerability index is based on Equation (3). As proposed by Iervolino et al. (2023), a higher value of score signifies higher vulnerability. After normalization of all variables between 0 (least vulnerable building) and 1 (highly vulnerable building), the vulnerability index was calculated for the urban sector in Nador city by integrating the score of seismic intensity variable (V_I^{Class}).

$$V_I^{Building} = V_I^{Class} + \Delta MR + \sum_{j=1}^{n} Vmj \tag{3}$$

The vulnerability index ($V_I^{Building}$) corresponding to the class of built-up area considers a regional modifier based on building age and land characteristics (topography, soil, slope, geomorphology, and geology) that influence the seismic performance of the area. The vulnerability indices for different building typologies in **Table 2** were derived based on the Risk-UE project methodology (Milutinovic and Trendafiloski, 2003).

In the case of Nador city, the regional modifier was determined based on historical earthquake data. Applying the vulnerability index method helps identify the main urban areas susceptible to seismic hazards.

Our model, based on building type, age, and building position within its environment, was used to map the urban vulnerability index in Nador (see **Table 2** below). We conducted a deep analysis of building characteristics and their positions within the environment.

Table 2. Vulnerability indices for buildings typology. (Milutinovic and Trendafiloski, 2003).

Typology	Description	VImin, BTM	VI−, BTM	VI, BTM	VI+, BTM	VImax, BTM
M1.1	Rubble stone, fieldstone	0.62	0.81	0.873	0.98	1.02
M1.2	Simple stone	0.46	0.65	0.74	0.83	1.02
M1.3	Massive stone	0.3	0.49	0.616	0.793	0.86
M2	Adobe	0.62	0.687	0.84	0.98	1.02
M3.1	Wooden slabs	0.46	0.65	0.74	0.83	1.02
M3.2	Masonry vaults	0.46	0.65	0.776	0.953	1.02
M3.3	Composite steel and masonry slabs	0.46	0.527	0.704	0.83	1.02
M3.4	Reinforced concrete slabs	0.3	0.49	0.616	0.793	0.86
M4	Reinforced or confined masonry walls	0.14	0.33	0.451	0.633	0.7
M5	Overall strengthened	0.3	0.49	0.694	0.953	1.02
RC1	Concrete Moment Frames	−0.02	0.047	0.442	0.8	1.02
RC2	Concrete shear walls	−0.02	0.047	0.386	0.67	0.86
RC3.1	Regularly infilled walls	−0.02	0.007	0.402	0.76	0.98
RC3.2	Irregular frames	0.06	0.127	0.522	0.88	1.02
RC4	RC Dual systems (RC frame and wall)	−0.02	0.047	0.386	0.67	0.86
RC5	Precast Concrete Tilt-Up Walls	0.14	0.207	0.384	0.51	0.7
RC6	Precast C. Frames, C. shear walls	0.3	0.367	0.544	0.67	0.86
S1	Steel Moment Frames	−0.02	0.467	0.363	0.64	0.86
S2	Steel braced Frames	−0.02	0.467	0.287	0.48	0.7
S3	Steel frame + unreinf. mas. infill walls	0.14	0.33	0.484	0.64	0.86
S4	Steel frame + cast-in-place shear walls	−0.02	0.047	0.224	0.35	0.54
S5	Steel and RC composite system	−0.02	0.257	0.402	0.72	1.02
W	Wood structures	0.14	0.207	0.447	0.64	0.86

3. Results

The results reveals that the frequency of the interactions between continental features and the Mediterranean drive the release of energy as seismic events (Dong and Shan, 2013). Nador's foundation rests upon a precarious amalgamation of sedimentary and alluvial rocks, including silt, alluvium, and salt flats. These loose and unconsolidated materials lack the robustness of harder rocks, rendering them more prone to ground shaking during seismic activity. Furthermore, their susceptibility to liquefaction exacerbates the risk, as saturated sediments can transition into a fluid-like state during earthquakes, causing structural damage and ground instability.

3.1. Seismic intensity in Nador compared to other regions

The proximity of Nador to the plate boundary between the African and Eurasian plates increases the likelihood of seismic activity in the region, as evidenced by the frequent occurrence of earthquakes. Damage areas are divided into three levels (No damage, significant damage, and severe damage). The modelling of seismic intensity shows that the susceptible impact area is located in the southern part of Nador city, where 50% of the urban surface "1780.5 hectares" is at risk of earthquake disaster (see **Figure 11** below).

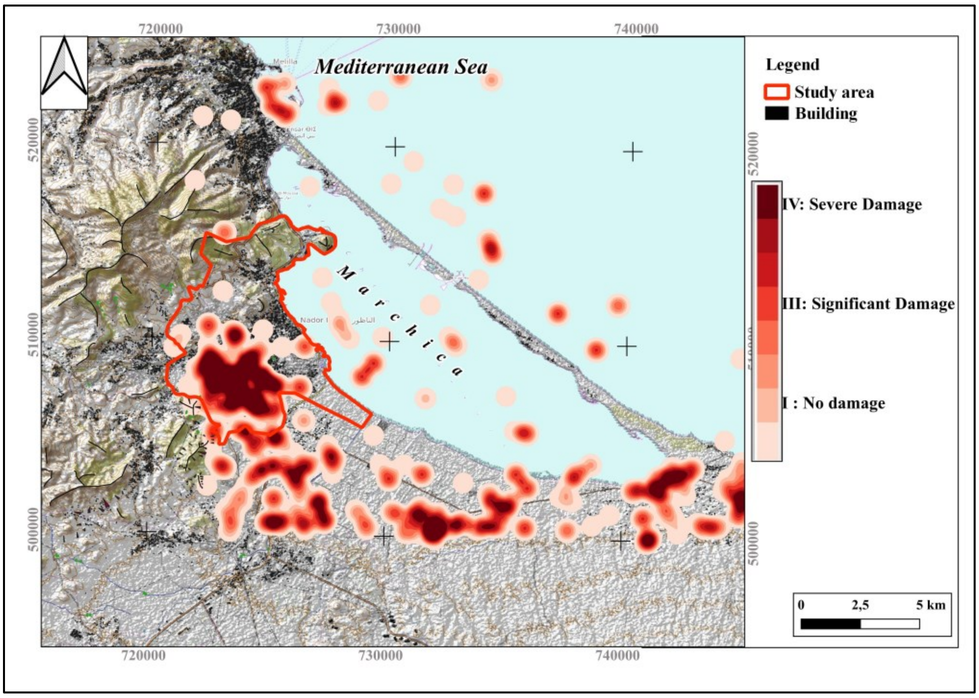

Figure 11. Seismic intensity map.

An analysis of seismic event frequency in the Nador region reveals that over 260 events have registered magnitudes exceeding 5 on the Richter scale. Additionally, 200 tremors have been recorded with magnitudes exceeding 4 on the Richter scale. This high frequency of seismic activity suggests that Nador, a Mediterranean city, is situated within an active geotectonic zone hazard (see **Figure 12** below).

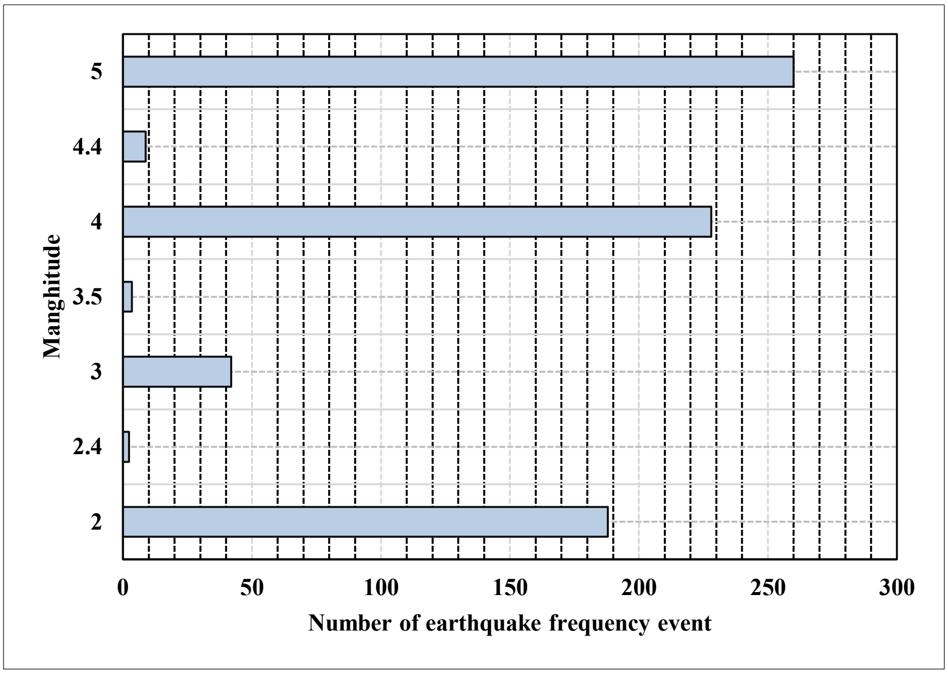

Figure 12. Seismic frequency event.

In comparing Nador's seismic intensity with other regions, Al Hoceima, Morocco, offers a particularly relevant case study. Like Nador, Al Hoceima is located within the Alboran Sea tectonic domain, making it highly susceptible to earthquakes. The 2004 Al Hoceima earthquake (Mw 6.3) caused extensive damage, particularly due to the poor structural integrity of many buildings. This event underlined the need for stricter building regulations and reinforced the importance of seismic-resistant infrastructure. Al Hoceima's experience serves as a critical reminder for Nador, where similar seismic risks require an urgent focus on retrofitting vulnerable structures and adopting more stringent building codes.

Analyzing Nador with Japan, a region that experiences some of the most frequent and powerful earthquakes globally, provides further insights. Japan has long been a leader in seismic risk mitigation, largely due to its stringent building codes, advanced early-warning systems, and community preparedness programs. Japanese cities regularly incorporate probabilistic seismic hazard assessments, similar to those used in this study, into urban planning and disaster preparedness. While Nador is at an earlier stage of implementing such systems, Japan's comprehensive approach especially the integration of real-time monitoring systems and building retrofitting strategies offers a model for Nador to follow.

3.2. Landslides risks

Earthquakes, soil structure, and aggressive slopes are the primary factors contributing to active ground sliding. Spatial analysis reveals that several areas in the north part of Nador city are susceptible to landslide hazards. Construction on hard, uneven topography leads to the accumulation of damage in these areas. The spatial analysis identified 10 critical zones, covering 459.6 hectares, where landslides are most likely to occur. These areas are characterized by aggressive slopes and construction on uneven terrain, which exacerbate the potential for ground sliding during seismic events. (see **Figure 13** below).

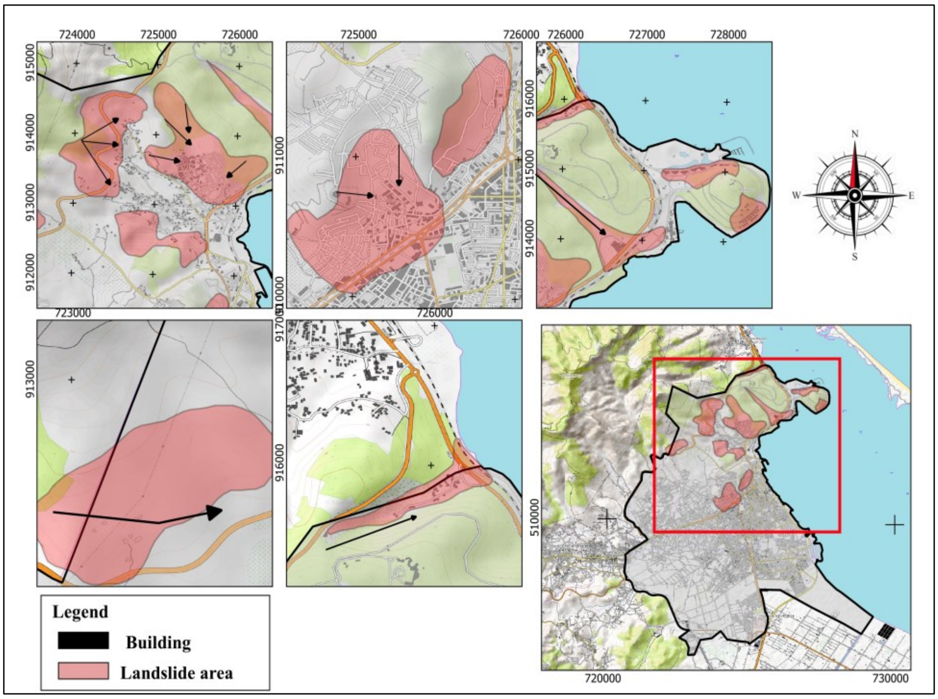

Figure 13. Landslides hazards distribution.

Landslide susceptibility in Nador is driven by steep slopes, seismic activity, and the region's loose soil composition. These conditions are similar to those in Chiang Rai, Thailand, and Al Hoceima, both of which experience frequent landslides due to similar geomorphological and seismological conditions. Al Hoceima, following the 2004 earthquake, has faced numerous challenges in managing landslide risks, particularly in rural areas with steep terrain. However, government initiatives in slope stabilization and public education on building safety in landslide-prone zones have begun to mitigate these risks.

In Japan, the combination of earthquakes and heavy rainfall frequently triggers landslides, particularly in mountainous areas. Japan's proactive approach includes advanced landslide early-warning systems and stringent zoning laws, which restrict construction in high-risk areas. Nador could benefit from adopting similar strategies, particularly by improving early-warning systems and enforcing land-use policies that discourage construction on unstable slopes. Japan's integration of geotechnical data into urban planning offers a valuable example for Nador, especially as urban expansion increases pressure on vulnerable terrains.

3.3. Spatial vulnerability index

An analysis of building materials and locations in Nador, Morocco, revealed that approximately 70% of recent constructions utilize reinforced concrete. Residential buildings typically have ground floor areas ranging from 80 m^2 to 140 m^2. Land surveys indicate that all buildings are constructed with reinforced concrete structures, categorized as reinforced concrete moment frame (RC1), regular reinforced concrete structures with masonry infill walls (RC3.1), and irregular moment frame structures

(RC3.2), aligning with the building typology matrix proposed by Milutinovic and Trendafiloski, 2003 (see **Table 2**).

Vulnerability index methods suggest that buildings located on active ground are highly susceptible to severe seismic events (see **Figure 14** below). Spatial vulnerability analysis shows that 5285 buildings are located in high vulnerability zones, while 1623 residential buildings fall within moderate vulnerability areas. Additionally, 929 buildings are considered outside of high vulnerability zones (see **Figure 14** below).

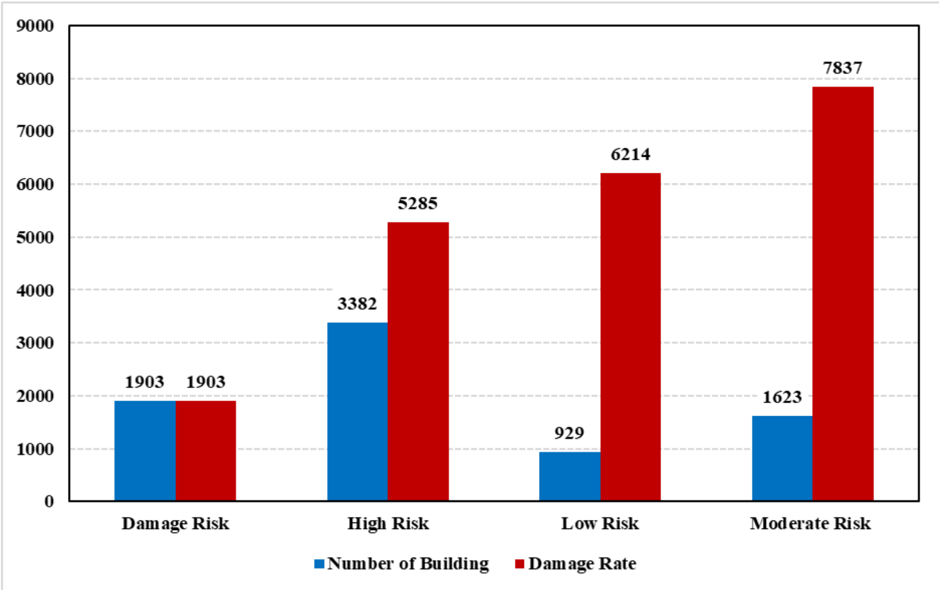

Figure 14. Building's vulnerability rate.

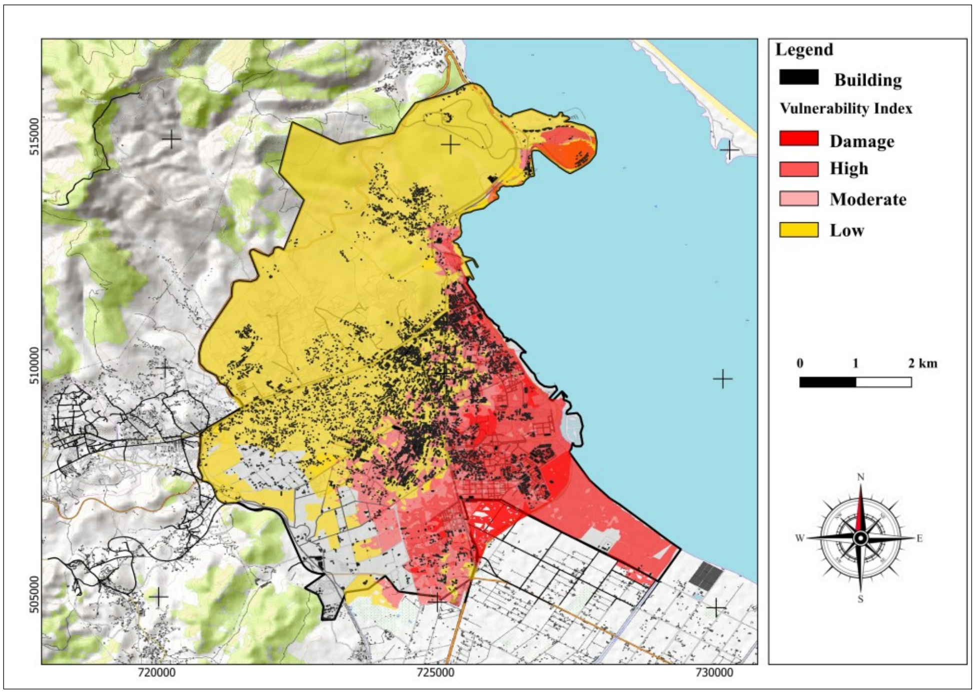

Figure 15. Vulnerability index for urban build-up area.

The risk maps, as shown in **Figure 15**, offer practical, data-driven insights that can be used by various stakeholder groups to support their decision-making processes:

- Urban Planners can leverage these maps to guide future development by avoiding construction in high-risk zones and enforcing earthquake-resistant building codes in areas with moderate risk.
- Policymakers can prioritize urban infrastructure investments in high-risk areas and enact policies that mandate strict building regulations in vulnerable zones. These maps are crucial for long-term urban resilience planning.
- Emergency Response Teams can use the maps to plan evacuation routes and emergency shelter locations in safer areas, ensuring that their strategies are aligned with the most vulnerable parts of the city.
- Environmental Agencies may utilize the maps to protect ecosystems that could be affected by both seismic activity and human development, particularly in areas where landslides are a significant risk (see **Figure 13**).

3.4. Broader implications for risk management in Nador

The evaluation of Nador's seismic and landslide risks, in comparison with regions such as Al Hoceima, Japan, Istanbul, Messina, Chiang Rai, and San Salvador, offers critical insights that can be applied to improve disaster risk management strategies. These comparative examples highlight key approaches to mitigating risks, emphasizing the need for Nador to adopt a comprehensive framework that integrates both local and global best practices for disaster resilience.

Key lessons from these regions include:

- Al Hoceima's 2004 earthquake experience illustrates the vital importance of retrofitting buildings and enforcing stricter seismic codes. In Nador, where urban growth is rapid, immediate action is required to implement similar building retrofitting programs, particularly in older and structurally vulnerable areas. By enhancing the structural resilience of buildings, Nador can significantly reduce the potential for catastrophic damage during future seismic events.
- Japan's approach to disaster management provides a model of integrating advanced seismic and landslide early-warning systems, coupled with rigorous building regulations. Japan's commitment to public education on disaster preparedness ensures that communities are not only aware of the risks but are also well-prepared to respond. Nador must prioritize the installation of real-time monitoring and warning systems while fostering a culture of preparedness among its residents.
- Istanbul's urban retrofitting programs demonstrate the effectiveness of upgrading infrastructure to modern seismic standards. As Nador continues to develop, it is crucial to incorporate resilient infrastructure into urban expansion plans. Istanbul's investment in upgrading older structures and implementing resilience-driven urban policies can serve as a blueprint for Nador's modernization efforts.
- Messina's post-earthquake reconstruction underscores the importance of rebuilding with a focus on resilient infrastructure. For Nador, which faces the dual threats of seismic activity and landslides, future urban development must

prioritize resilience in both design and construction, ensuring that infrastructure can withstand natural hazards while enabling rapid recovery post-disaster.

- Chiang Rai and San Salvador's success in adopting community-based landslide monitoring systems and slope stabilization projects provides a valuable lesson for Nador. The integration of local knowledge, community participation, and scientific monitoring is key to managing landslide risks. Nador should consider the implementation of similar systems, especially in its northern regions where slope instability is prevalent.

3.5. Method comparison and robustness

The method employed in this study demonstrates considerable robustness by integrating a wide array of data sources and analytical techniques to assess seismic risks and urban vulnerabilities in Nador. Unlike traditional methods that typically focus on isolated factors such as seismic frequency analysis or building vulnerability assessments. This approach synthesizes multiple variables, including seismic data, geomorphological characteristics, urban land use, and building quality (Romero-Andrade et al., 2023). By combining these diverse factors into a cohesive framework, the study provides a more comprehensive understanding of how geological, topographical, and urban elements interact to exacerbate or mitigate seismic risks (Lungu and ksendal, 2001). To ensure the robustness and reliability of this integrated methodology, we employed the R-squared mean as a key metric in our method comparison. The R-squared mean was used to evaluate the fit of different models, and it served as a benchmark for comparing the performance and robustness of various methods. As illustrated in the figure below, the "Present Method" demonstrates a superior performance with a higher R-squared value of 0.94, compared to traditional methods (R^2 = 1.00) and other researchers' methods (R^2 = 0.97). This integrated approach allows for a nuanced assessment of vulnerability that is more aligned with the complex realities of urban environments subject to seismic hazards (see **Figure 16** below).

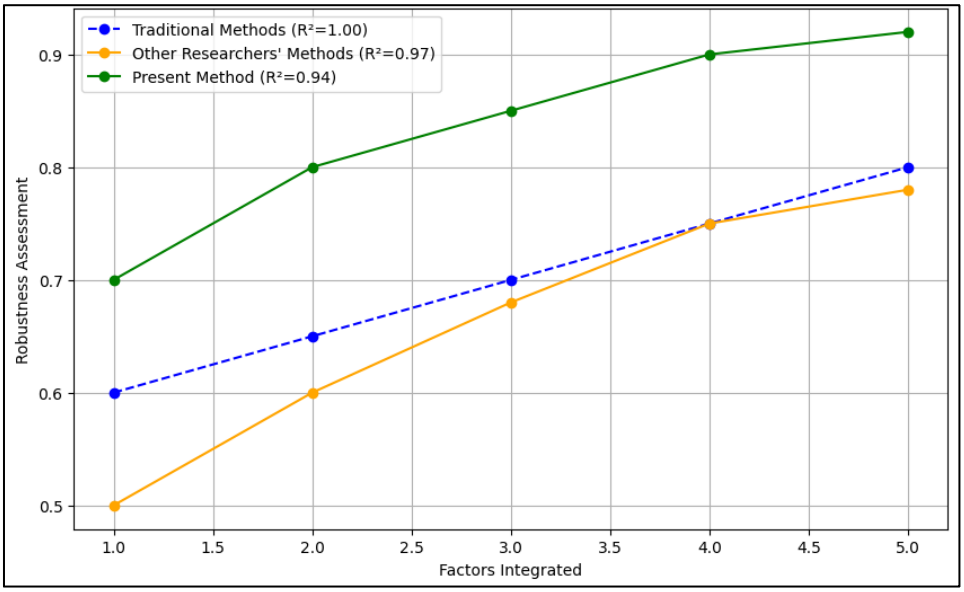

Figure 16. Models' accuracy and robustness.

In comparison to conventional approaches, the method used in this study offers a significant advancement in accuracy and applicability (Menget al., 2024). Traditional seismic analysis often emphasizes the mapping of fault lines and historical earthquake occurrences but may neglect the critical role of urban factors, such as building materials and land use patterns (Hung et al., 2013). Conversely, urban vulnerability assessments may focus solely on human-made structures without adequately accounting for the underlying geological conditions (Rashed and Weeks, 2003). The present method bridges these gaps by producing high-resolution risk maps that incorporate both natural and urban factors. This approach not only enhances the reliability of risk assessments but also provides more actionable insights for urban planners and policymakers, enabling them to develop more targeted and effective mitigation strategies.

3.6. Policy and practice implications for urban planning and risk resilience in Nador city

These large scale evaluation emphasize that Nador must adopt a multi-layered, holistic approach to disaster risk management. This strategy should incorporate advanced scientific methods alongside strong community engagement and effective policy enforcement. The key components of this approach include:

- Enforcing seismic building codes: Immediate strengthening of Nador's building codes is essential. Drawing on lessons from Al Hoceima and Istanbul, policymakers should implement stringent seismic-resistant construction standards and prioritize the retrofitting of existing vulnerable buildings. Enforcing these measures will reduce the risk of structural collapse in high-risk zones.
- Establishing early-warning systems: Advanced seismic and landslide early-warning systems, as seen in Japan, must be integrated into Nador's disaster preparedness framework. Such systems will provide crucial lead time for evacuations and emergency response, mitigating the human and infrastructural impact of disasters. Coupling these systems with public education campaigns will further ensure community readiness.
- Risk-informed urban planning: Nador's urban development must align with probabilistic risk assessments. Land-use regulations should restrict construction in areas identified as high-risk for landslides and seismic activity, while simultaneously promoting slope stabilization techniques in vulnerable regions. Lessons from Messina and Chiang Rai show that urban planning grounded in risk assessments can significantly reduce exposure to natural hazards.
- Community engagement and capacity building: Public awareness and preparedness are critical to disaster resilience. As demonstrated in Japan and San Salvador, involving local communities in disaster preparedness and response planning ensures a more robust defense against natural hazards. Nador should foster community-driven initiatives, such as neighborhood-based early-warning programs and localized response plans.

4. Discussion

The assessment of Nador's urban vulnerability to seismic and landslide risks highlights significant exposure to geological hazards, primarily due to the city's proximity to the convergence of the African and Eurasian tectonic plates. These findings align with previous research on the heightened risks in regions near plate boundaries. For instance, Yariyan et al. (2020) emphasized the amplified seismic risks in areas of tectonic convergence, particularly in coastal cities, which are more prone to earthquakes due to complex interactions between landforms and tectonic activities. Similar patterns of vulnerability have been observed in the broader Mediterranean region, as discussed by Nicholls et al. (2021), where urban growth exacerbates risks in geologically sensitive zones. Our findings build upon these studies by underscoring that Nador's vulnerability is further compounded by its specific geological makeup, particularly the unconsolidated sedimentary and alluvial deposits that increase susceptibility to both seismic shaking and landslide risks.

In comparison to the work of Chaaraoui et al. (2022), which also focused on seismic risks in Moroccan urban areas, our study contributes a more detailed spatial analysis through the integration of advanced geospatial tools such as Landsat 8–9 imagery and Digital Elevation Models (DEM). This allowed for a granular mapping of critical risk zones, particularly in Nador's northern sectors, where construction on steep slopes elevates the potential for landslides triggered by seismic activity. By contrast, Chaaraoui et al. relied heavily on historical seismic records without considering the dynamic effects of rapid urban expansion, which our study shows can significantly alter vulnerability patterns. This methodological distinction emphasizes the novel contribution of our research in capturing evolving risks associated with both urbanization and natural hazards.

Our vulnerability index, developed using these advanced geospatial techniques, echoes global findings, such as those by Brückl et al. (2021), which highlight the importance of integrating seismic hazard assessments with urban planning and strict enforcement of building codes. However, unlike earlier studies that focused predominantly on seismic activity, our model incorporates the additional complexity of landslide risks, presenting a more holistic approach to hazard mitigation. This multidimensional perspective aligns with global best practices, such as those outlined by Gibbs et al. (2015), which advocate for combining slope stabilization efforts, early warning systems, and adaptive land-use planning to mitigate the cascading effects of natural hazards like landslides.

Additionally, the frequent seismic tremors exceeding magnitudes of 4 and 5 on the Richter scale, as recorded in Nador's historical seismic data, underscore the city's vulnerability to significant seismic events. Our findings align with seismic studies from other Mediterranean regions, such as the work of Tsushima and Ohta (2014), who observed similar earthquake recurrence patterns in tectonically active coastal cities. These seismic events, coupled with Nador's geological fragility, suggest that the city is at an elevated risk of catastrophic damage, necessitating immediate attention to both seismic preparedness and resilient urban planning.

Our research not only builds upon existing literature but also sets a comprehensive framework for future studies. For example, the integration of socioeconomic factors and demographic trends, as recommended by Aven (2011) in his exploration of natural hazard risk management, could further enhance the accuracy of vulnerability assessments. Such an approach would strengthen the resilience of Nador by addressing both infrastructural vulnerabilities and community preparedness, ensuring that mitigation strategies are robust, adaptive, and socially inclusive.

This study provides a compelling scientific argument for the high vulnerability of Nador to seismic events and landslides. The findings underline the need for:

- Earthquake Preparedness: Developing and enforcing robust building codes tailored to seismic zones, launching public awareness campaigns, and implementing comprehensive emergency response plans;
- Landslide Mitigation: Identifying high-risk areas for landslides and addressing them through slope stabilization, land-use regulations that avoid risky zones, and the establishment of early warning systems;
- Vulnerability Assessment: Continuously evaluating the vulnerability of buildings and infrastructure by assessing construction materials, building types, and their locations relative to identified hazard zones.

Furthermore, this study contributes to the global discourse on urban resilience in seismically active regions, offering a replicable framework that can be adapted by other cities facing similar risks. By combining science-based decision-making with proactive community engagement and strict policy enforcement, Nador can develop a more resilient urban infrastructure capable of withstanding both seismic and landslide hazards. The adoption of these strategies will not only mitigate immediate risks but also support long-term sustainable development, safeguarding the well-being of its population and the continuity of its economic activities.

Proactively addressing these vulnerabilities, Nador can take significant steps toward reducing the risks associated with seismic activity and landslides, thereby enhancing the city's overall resilience and safeguarding its urban population.

5. Conclusion

This study has conducted a thorough assessment of the seismic risks and urban vulnerabilities facing Nador city, focusing on the complex interactions between geological factors, urban infrastructure, and seismic hazards. The findings indicate that Nador's location on the Mediterranean coast, its proximity to active fault lines, and its foundation on unconsolidated sediments significantly increase its susceptibility to seismic events and landslides. Over 50% of the urban area, particularly in the southern part of Nador city, is identified as being at high risk for severe earthquake damage. This underlines the urgent need for comprehensive risk management strategies.

To mitigate these risks, several policy recommendations have been proposed. First, the implementation and strict enforcement of earthquake-resistant building codes are crucial, particularly in high-risk zones. These codes should focus on enhancing the structural resilience of buildings to withstand seismic activity. Second, Urban planning must be improved to restrict construction in landslide-prone areas and promote slope stabilization through nature-based solutions. Third, establishing robust early warning systems and conducting regular public awareness campaigns are essential to ensure community preparedness and effective response to seismic events.

Continuous monitoring and risk assessment are also vital to adapt and refine these strategies over time.

While this study offers significant insights, it is not without limitations. The research primarily focuses on historical seismic data and current urban vulnerabilities, potentially overlooking future urban expansion and environmental changes that could alter risk levels. Additionally, the study's reliance on available geological and topographical data may have limitations in accuracy, which could affect the precision of the vulnerability assessments. These factors highlight the need for ongoing data collection and refinement of risk models.

Future research should address these limitations by incorporating dynamic models that account for urban growth, land cover change and other evolving factors that may impact seismic risk. Additionally, interdisciplinary studies that integrate socio-economic factors with geological assessments would provide a more holistic understanding of urban vulnerability. This could lead to more targeted and effective mitigation strategies that are adaptable to changing conditions.

In conclusion, the findings of this study emphasize the need for proactive policy implementation and continuous risk assessment in Nador. By addressing the identified vulnerabilities through improved infrastructure, land-use planning, public awareness, and ongoing research, Nador can enhance its resilience to seismic hazards and better protect its population. These steps are crucial not only for Nador but also for other zones facing similar risks in the African countries.

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Abbreviations

CLC	Corine Land Cover
SVI	Socioeconomic Vulnerability Index
Vi	Vulnerability Index
Mw	Moment magnitude

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