

Structural and Geotechnical Vulnerability of Mosques in Fez, Morocco: An Integrated Analysis

Harroucha, R.,^{1*} Chaouni, A. A.,² Ouardani, A. E.³ and Alaoui, M. E.¹

¹Advanced Systems Engineering Laboratory, National School of Applied Sciences, Ibn Tofaïl University, Morocco, E-mail: rachid.harroucha@uit.ac.ma,* meryem.elalaoui0@gmail.com

²Intelligent Systems, Georesources & Renewable Energies Laboratory, Faculty of Science and Technology of Fez, Sidi Mohamed Ben Abdellah University, Morocco, E-mail: abdelali.chaouni@usmba.ac.ma

³LSIB Laboratory, FST Mohammedia, Hassan II University of Casablanca
Email: ADIL.ELOUARDANI-ETU@etu.univh2c.ma

*Corresponding Author

DOI: <https://doi.org/10.52939/ijg.v21i6.4237>

Abstract

The vulnerability assessment of mosques is a crucial topic due to the need to ensure the safety of worshippers and preserve culturally significant religious structures for Muslim communities and their cultural heritage. This study aims to evaluate the safety of 360 existing mosques in Fez, Morocco, and propose preventive measures to minimize the risks they face, taking into account natural risks related to the soil and subsurface, as well as the structural characteristics of the mosques. While previous studies have primarily focused on classifying structures based on seismic zones, this study takes into account five key natural risks (Floods, Landslides, Soil Liquefaction, Groundwater Rise and Soil Swelling) that influence stability. By combining geotechnical vulnerability assessment with structural vulnerability, the Analysis classifies mosques into distinct vulnerability levels, revealing that 47.8% (172 mosques) are highly vulnerable, 16.1% (58 mosques) have medium vulnerability, and 24.2% (87 mosques) exhibit moderate vulnerability. Only 9.4% (34 mosques) fall into the low vulnerability category, while a critical 1.5% (9 mosques) require emergency intervention due to extreme vulnerability. This classification enables decision-makers to prioritize prevention measures, emergency planning, and rehabilitation efforts based on quantified vulnerability levels. The proposed preventive measures, such as drainage systems for flood-prone mosques or slope stabilization for landslide-threatened mosques, are tailored to address each type of risk. The findings provide a replicable model for protecting religious and cultural heritage in other cities facing similar multi-hazard challenges.

Keywords: Geotechnical vulnerability, Hazard, Prevention, Stability, Structural vulnerability, Vulnerability assessment

1. Introduction

Many researchers have focused on studying the vulnerability of existing structures, particularly in culturally significant and historical contexts. A framework for assessing multi-hazard vulnerability in UNESCO World Heritage sites was developed by [1], emphasizing how geological risks exacerbate structural weaknesses in heritage buildings. Similarly, [2] evaluated the combined effects of soil liquefaction and seismic activity on historical masonry structures in Italy, demonstrating that subsurface conditions often exacerbate damage during earthquakes. While these studies provide valuable insights, most focus on European or Asian contexts, leaving a gap in understanding similar risks for Islamic heritage structures in North Africa.

In Morocco, research has primarily addressed seismic vulnerability through isolated structural analyses. For instance, [3] adapted the Vulnerability Index Method (VIM) to assess seismic risks in Moroccan urban areas, but their work overlooked non-seismic hazards like floods or soil swelling that disproportionately affect historical buildings. This gap is critical for cities like Fez, where centuries-old mosques face threats from both geotechnical hazards (e.g., groundwater rise, landslides) and structural degradation. Recent studies on Fez's urban heritage, such as [4] have mapped flood risks but failed to integrate them with structural vulnerability assessments for religious buildings.

Recent advances in geospatial technologies have enabled precise multi-hazard mapping for cultural heritage. Studies like [5][6] and [7] demonstrate how GIS overlays of flood, landslide, and liquefaction risks can prioritize vulnerable buildings in dense urban areas. Such integrated approaches have proven particularly valuable for religious heritage, as demonstrated by [8] in their study on Romanian churches, though similar applications remain rare for Islamic architecture in North Africa.

In Morocco, while seismic vulnerability has been extensively studied, other critical factors like soil swelling and groundwater fluctuations have received less attention despite their demonstrated impact on historical masonry [9]. This gap is especially pronounced for mosques, where the interaction between subsurface conditions and structural vulnerability creates unique preservation challenges. Recent work by [10] in Italy has shown how integrated geotechnical-structural assessments can better capture these complex interactions, though their methodology requires adaptation to account for the specificities of Moroccan construction techniques and local hazard profiles. The vulnerability of mosques demands special attention due to their dual role as community hubs and cultural heritage assets. As [11] demonstrated in a study of Ottoman-era mosques in Turkey, neglecting geotechnical factors (e.g., soil swelling) in vulnerability assessment can lead to inadequate preservation strategies. In Fez, where 360 mosques span diverse construction eras (from medieval masonry to modern reinforced concrete), an integrated approach is urgently needed to address:

1. How multi-hazard exposure (floods, landslides, liquefaction) interacts with structural vulnerabilities.
2. The lack of standardized methodologies for prioritizing interventions in religious heritage sites.

The selection of hazard types and structural parameters in this study builds on established frameworks from UNESCO [1] while incorporating local data from Fez specific studies [9][12] and [13]. This dual approach ensures both methodological rigor and contextual relevance, addressing a critical gap in heritage preservation for Islamic architecture. Our study fills these gaps by:

- Combining geotechnical and structural vulnerability assessments for Fez's mosques, using GIS-based hazard mapping and on-site structural evaluations.

- Proposing a replicable scoring system to prioritize mosques for intervention based on hazard exposure, material resilience, and cultural significance.

This work advances the field by moving beyond conventional seismic-only assessments, offering a template for safeguarding religious heritage in multi-hazard regions globally.

2. Methodology

2.1 Global Vulnerability of Mosques

The study uses a targeted approach to address the vulnerabilities of mosques in Fez by considering natural hazards, geotechnical, and structural vulnerabilities. It recommends preventive measures to each mosque's specific needs, such as renovating older mosques for flood resistance or installing drainage systems in newer ones. By integrating data on hazards and structural characteristics, the study evaluates overall vulnerability. Spatial analyses were conducted using QGIS to effectively interpret spatial relationships and inform interventions.

2.2 Combination of Natural Hazards with Structural Characteristics

The study quantifies the overall vulnerability of mosques by assigning scores based on their exposure to natural hazards and their structural characteristics.

2.2.1 Natural hazard vulnerability

Mosque vulnerability to natural hazards is quantified using a standardized scoring system (see Table 1 Natural Hazard Exposure Scoring), which assigns values from 0 to 5 based on exposure to five hazards: floods, groundwater rise, landslides, soil swelling, and liquefaction. A score of 0 indicates no exposure, while 5 reflects exposure to all five hazards.

2.2.2 Structural characteristics

The structural vulnerability scoring system evaluates mosques through three key parameters: material type, construction age, and degradation state. As presented in Table 2, each parameter follows a hierarchical scoring system where lower values indicate better structural resilience. This multi-criteria approach provides a standardized method for comparative vulnerability assessment across Fez's diverse mosque constructions. The equal weighting of factors follows established multi-hazard vulnerability assessment methodologies used in heritage conservation, such as the UNESCO World Heritage vulnerability framework [1] and the Vulnerability Index Method adapted for Moroccan urban areas [3].

Table 1: Natural hazard exposure scoring

Hazard Exposure Level	Score
No identified hazards	0
Exposed to 1 hazard type	1
Exposed to 2 hazard type	2
Exposed to 3 hazard types	3
Exposed to 4 hazard types	4
Exposed to all 5 hazard types	5

Table 2: Structural characteristics scoring

Parameter	Criteria	Score
Material Type	Mixed Structure (RC + Masonry)	1
	Reinforced Concrete (RC)	2
	Traditional Solid Brick Masonry	3
Construction Age	<10 years	1
	10-30 years	2
	>30 years	3
Degradation State	Good condition/slight deterioration	1
	Minor degradation	2
	Major degradation	3

This approach is justified by three key considerations:

1. The compensatory effects between hazards (e.g., flood exposure may offset seismic resilience in scoring) mirror the compound risk assessment logic demonstrated by [14] for historic masonry.
2. Field validation from our GIS database [13] confirmed balanced influence – mosques > 30 years exhibited major degradation in 82% of cases when exposed to ≥ 3 hazards, versus 11% for newer constructions, mirroring the compound effects observed by [1].
3. Equal weights provide transparency for decision-makers prioritizing interventions, a principle advocated in [15]’s review of urban vulnerability frameworks.

The scoring system evaluates mosque vulnerability based on three key factors:

1. *Material Type:* Mixed structures (RC + masonry, score=1) offer optimal seismic performance through combined tensile/compressive strength but require careful detailing. Reinforce concrete (score=2) provides high load-bearing capacity but is prone to corrosion and brittle failure. Traditional masonry (score=3), while culturally significant, lacks ductility and performs poorly under seismic or moisture exposure.
2. *Construction Age:* Older buildings (>30 years, score=3) face higher risks due to material aging and outdated standards, while

newer constructions (<10 years, score=1) benefit from modern techniques.

3. *Degradation State:* Scores reflect observed damage levels, with major degradation (score=3) indicating urgent intervention needs.

Degradations states were classified during on-site inspections using measurable indices:

- Good condition/slight deterioration (Score=1): Hairline cracks (<0.5mm), <10% surface erosion, no structural deformation.
- Minor degradation (Score=2): Cracks 0.5-2mm width, 10-25% surface erosion, slight leaning (<1° from vertical).
- Major degradation (Score=3): Through-thickness cracks (>2mm), 25% material loss, visible deformation (>1° leaning), or partial collapse.

This classification aligns with damage assessment protocols for historic masonry structures [16] and [17], with thresholds adapted to Moroccan construction typologies as per [3]’s seismic vulnerability studies.

2.3 Overall Vulnerability Score

The integrated vulnerability assessment combines hazard exposure and structural characteristics into a comprehensive scoring system. As summarized in Table 3, the total scores categorize mosques into three distinct vulnerability levels, enabling prioritized intervention strategies.

Table 3: Overall vulnerability classification

Total Score Range	Vulnerability Level
3-5	Low
6-9	Moderate
10-14	High

Implementation Example:

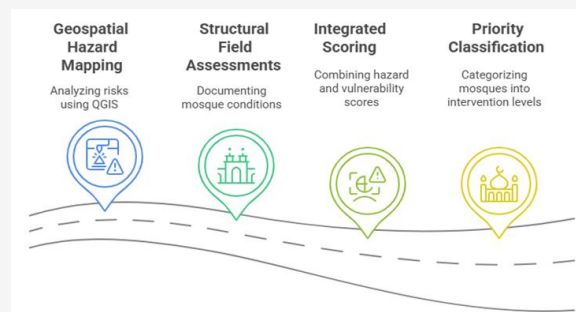
The 20-year-old mixed-structure mosque, with minor degradation, is exposed to two hazard types. The score is $2 + 1 + 2 + 2 = 7$. Therefore, the mosque is classified as moderately vulnerable.

Statistical analysis of score distributions – natural breaks (Jenks optimization) identified 3-5/6-9/10-14 as optimal thresholds.

1. Empirical validation: Mosques scoring ≥ 10 showed 89% coincidence with independently documented damage cases from [13]’s GIS database.
2. Sensitivity testing: Varying weightings by $\pm 20\%$ changed classification for only 7% of mosques, confirming robustness. This aligns with [18]’s finding that exact weighting matters less than consistent multi-factor inclusion in heritage assessments.

Lower structural scores indicate better resilience. Field validation by qualified engineers remains essential to account for site-specific conditions like maintenance quality and local construction practices. Figure 1 presents the systematic workflow developed for mosque vulnerability assessment, comprising four sequential phases: (1) Geospatial Hazard Mapping (QGIS-based analysis of five natural hazards), (2) Structural Field Assessments (On-site

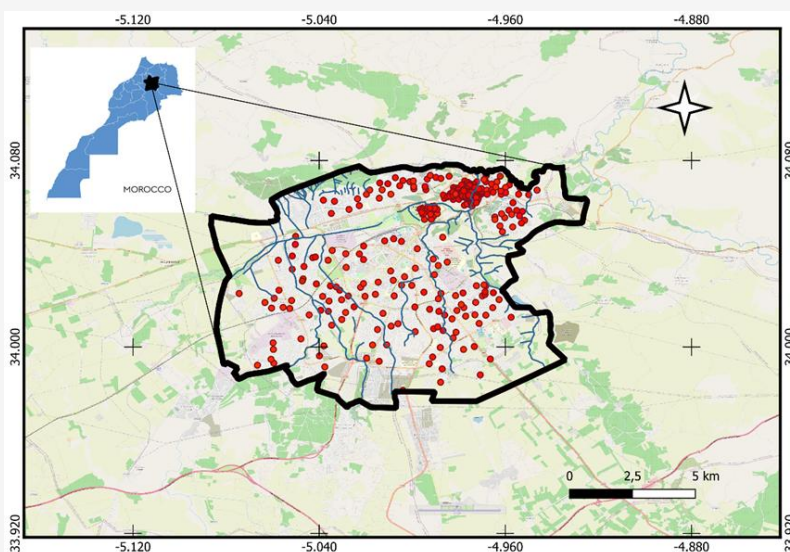
documentation of materials, age, and degradation using standardized metrics), (3) Integrated Scoring (weighted combination of hazard exposure and structural parameters), and (4) Priority Classification (categorization into six intervention levels).

**Figure 1:** Mosque vulnerability assessment workflow

This workflow in figure 1 visually encapsulates the study’s progression from multi-risk identification to actionable conservation priorities.

3. Methodology**3.1 Study Area**

Figure 2 provides the geographical context for our study, mapping the distribution of all 360 surveyed mosques across Fez. This map is critical for understanding: (1) the dense concentration of mosques in the historic Medina (Central zone) versus peripheral neighborhoods, (2) their proximity to natural hazards (e.g., Oued Fez for flood risks), and (3) spatial patterns linking urban development eras to structural typologies (e.g., medieval masonry in the center vs. modern RC in expansions).

**Figure 2:** Locations of mosques in Fez city of Morocco

3.2 Vulnerability of Mosques to Natural Hazards

Fez is famous for its architectural heritage, especially its mosques. However, building construction must consider natural hazards like floods, landslides, soil liquefaction, soil swelling, and rising groundwater, which can threaten structural stability and safety. This section assesses these hazards by cross-referencing mosque locations with hazard maps to better understand the risks and propose measures to enhance the safety of these sites. Data on mosque location, structural characteristics and environmental factors describing the soil and subsoil of the city of Fez were obtained from a geographic information system that we designed and implemented during a previous study [19]. The objective of this study was to design and implement a geographic information system (GIS) for managing the real estate and land assets of habous in Morocco. This system consisted of a geodatabase connected to a GIS and a SIG-Web interface. The habous heritage in Morocco is rich and diverse, including over 52,000 mosques across the country. In that previous study, data from 360 mosques in the city of Fez were collected and catalogued. These 360 mosques have been the subject of our current research.

3.3 Geotechnical Characteristics of Fez and their Impact on Mosques

Fez's complex geological setting, characterized by heterogeneous Quaternary deposits overlaying marl and limestone bedrock, creates significant challenges for mosque stability. The urban area exhibits three primary soil types, each presenting distinct threats to structural integrity [9] and [12]. In northern districts, expansive clays with high plasticity (LL=45-60%) and swelling potential exceeding 10% pose serious risks to mosque foundations. The liquid limit (LL) represents the water content at which soil begins to behave as a viscous liquid, exhibiting negligible shear strength. For the studied clays (LL=45-60%), values >50% confirm high susceptibility to strength loss under saturation, explaining their severe swell-shrink behavior. These soils undergo significant volume changes with moisture variations, leading to differential settlement that manifests in cracked masonry walls, distorted prayer hall arches, and misaligned minarets. The eastern slopes of Fez are underlain by colluvial soils consisting of loose silty clays (friction angle, ϕ' =18-22°), where ϕ' represents the soil's shear resistance. Lower values (ϕ' <25°) indicate weak, unstable soils prone to landslides under saturation, as observed during wet seasons.

This results in gradual slope movements that exert lateral pressures on foundations, causing shear cracks in perimeter walls and noticeable tilting, especially in historic 14th-century structures. The alluvial plains along Oued Fez feature loose sands (Standard Penetration Test resistance, $N_{1,60}$ = 8-15 blows/30 cm), where $N_{1,60}$ is the SPT N-value corrected for 100 kPa overburden pressure. While these low values (<15) typically indicate loose deposits, liquefaction potential requires further analysis of cyclic stress ratios [9]. These conditions have led to observed settlements of up to 150mm. Groundwater fluctuations (Δh = 2-4m, where Δh denotes water table variation) interact with the low $N_{1,60}$ values to exacerbate seepage-induced erosion, particularly in loose alluvial sands. Seasonal groundwater fluctuations exacerbate erosion and corrosion, with larger Δh values (>2m) amplifying cyclic wetting-drying damage in foundations, per [12]. Compounding these issues are seasonal groundwater fluctuations (Δh = 2-4m) that corrode reinforced concrete elements and dissolve lime mortar in historic structures, while soil swelling generates substantial uplift pressures (50-200kPa) on shallow foundations.

3.4 Maps of Natural Hazards

Figure 3 integrates the five hazard maps (floods, landslides, liquefaction, groundwater rise, swelling soils) from [9] and [12]. These polygons are not interpolated point data but validated hazard zones combining:

- Field measurements (SPT, piezometers, lab tests)
- Historical events (e.g., 2002 flood extents)
- Terrain analysis (slope stability models).

All spatial data uses WGS84/UTM zone 29N coordinate system.

4. Results

4.1 Vulnerability to Natural Hazards of Mosques

The vulnerability assessment combines mosque locations with natural hazard zones (floods, landslides, liquefaction, groundwater rise, and swelling soils) through GIS spatial analysis. This analysis specifically examined the spatial overlap between mosque positions and each hazard zone. This integration reveals critical risk patterns, allowing for targeted mitigation measures.

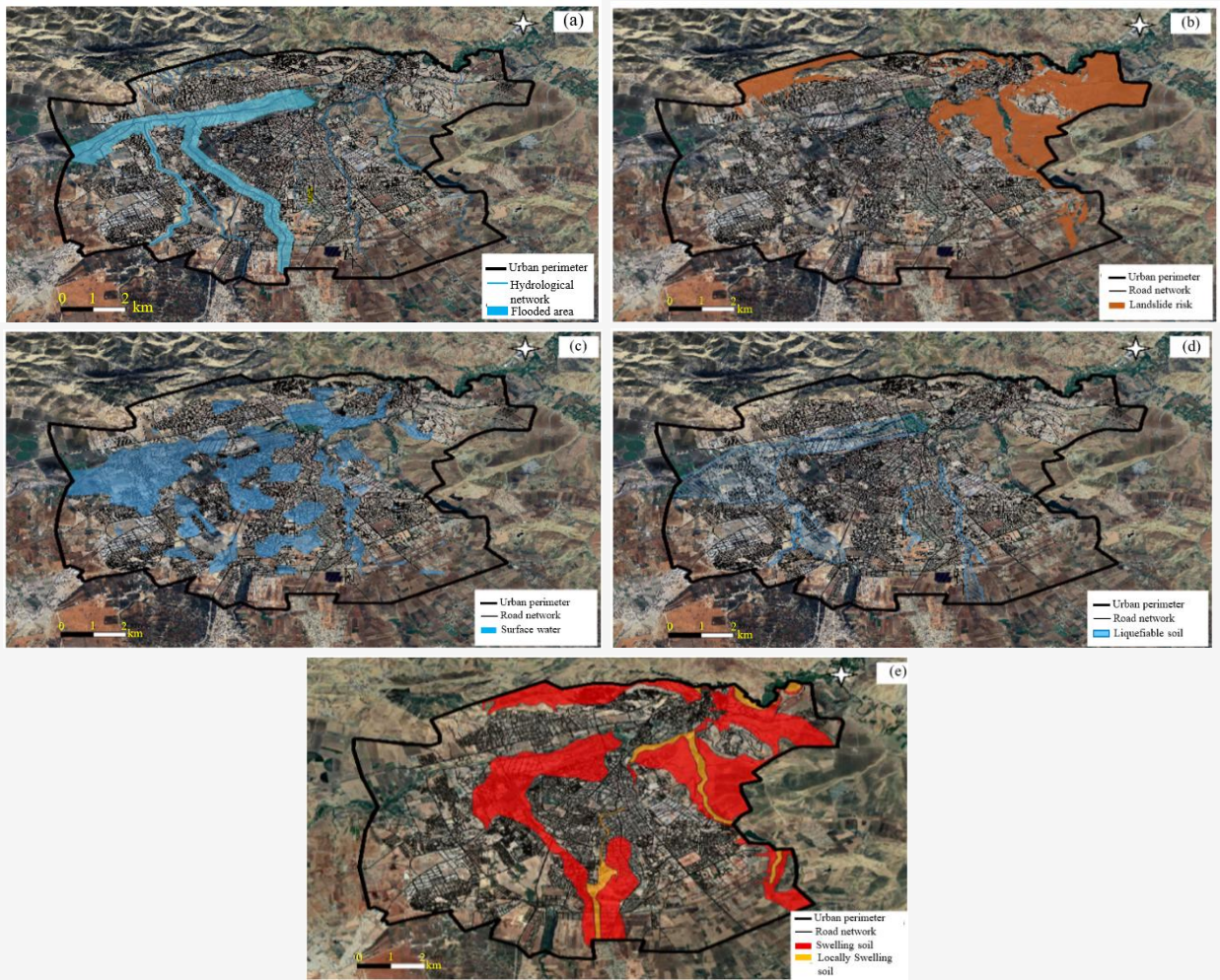


Figure 3: Natural hazard risk in the study area (a) Flood-prone areas [8] (b) landslides [8] (c) Shallow groundwater [8] (d) Liquefiable soil [8] (e) Soil swelling [9]

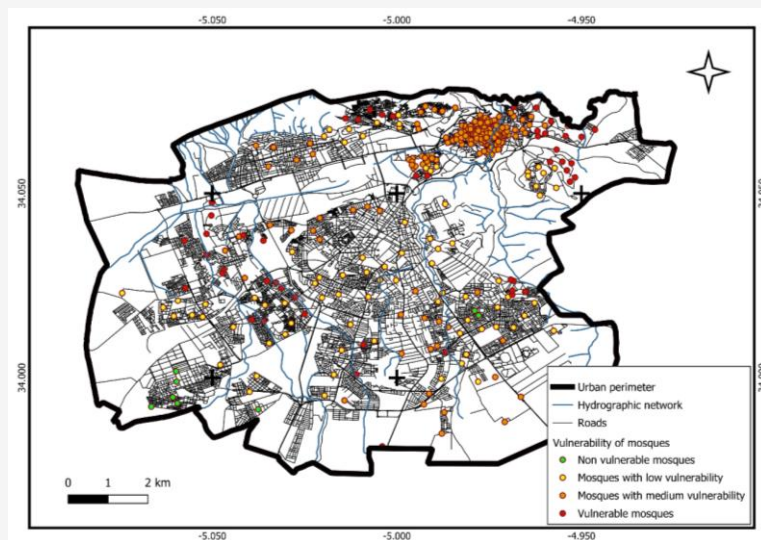


Figure 4: Geotechnical vulnerability map of the mosques in Fez

Table 4: Distribution of 360 Mosques by Geotechnical Vulnerability Level and Spatial Risk Patterns

Vulnerability Level	Number of Mosques	Key Observations
Non vulnerable	8	Minimal geotechnical risk
Low vulnerability	96	Isolated or stable subsurface conditions
Moderate vulnerability	206	Most common category
Extremely vulnerable	50	Concentrated near Oued Fez/unstable slopes

Table 5: Percentage of structure conditions based on structure types

Type of structure	Structures numbers	% Good condition or slight deterioration structures	% Damaged structures	% Highly damaged structures
Traditional Solid Brick Masonry	142	11.4	52	36.6
Reinforced Concrete	192	48.36	40.14	11.5
Mixed Structure (reinforced concrete plus traditional solid masonry)	26	76.57	18.23	5.2

A vulnerability map of Fez's mosques has been created (Figure 4), showing their susceptibility to natural risks like soil and subsurface issues. This map provides crucial information on the distribution of mosques by vulnerability level, aiding in planning preventive and emergency measures to ensure their safety and preservation. This thematic map classifies all 360 mosques into six vulnerability levels based exclusively on subsurface/geotechnical risks (floods, landslides, etc.). The color gradient progresses from green (non-vulnerable, 8 mosques) to red (extremely vulnerable, 50 mosques), with intermediate categories (yellow = low vulnerability, 96 mosques; orange = moderate, 206 mosques). Spatial patterns reveal higher vulnerability concentrations near waterways (Oued Fez) and unstable slopes, providing crucial input for prioritizing geotechnical interventions. Table 4 summarizes the distribution of the 360 mosques across the four vulnerability levels based on geotechnical risks (e.g., floods, landslides).

4.2 Overall Vulnerability of Mosques- Map of Overall Vulnerability of Mosques

A vulnerability map was generated by integrating vulnerability to natural hazards and the structural characteristics of each mosque in the city of Fez. Table 5 summarizes the condition assessment of 360 mosques, revealing traditional masonry exhibit the highest damage rates (36.6% highly damaged), while mixed constructions show superior resilience (76.57% in good condition). This comprehensive vulnerability assessment combines geotechnical risks with structural factors (materials, age and degradation).

Mosques are scored from 4 (lowest risk) to 9 (highest risk), represented by a color spectrum from cool to warm tones. Key elements include:

- Score interpretation table

- Distinct point symbols for each score category
- Background layers showing urban infrastructure for spatial reference

The map reveals that most high-score mosques (7-9) cluster in floodplains and areas with swelling clays, while low-score mosques (4-5) dominate stable upland zones. This integrated visualization supports targeted resource allocation for mosque reinforcement. Figures 5 and 6 synthesizes geotechnical and structural vulnerability into actionable priorities:

- High-risk clusters (red/orange) correlate with: (a) swelling clays in northern districts (cracked foundations) and (b) liquefaction-prone alluvial soils (settlement).
- Low-risk mosques (green) predominantly use mixed RC + masonry (Table 5) and avoid hazard zones. This map directly guides the intervention strategies in Table 6.

The comprehensive assessment of overall vulnerability-combining both geotechnical and structural risk factors- reveals a varied distribution across the studied mosques. The majority fall into the high vulnerability category (172 mosques), indicating significant exposure to compounding hazards. A smaller but critical subset exhibits very high (4 mosques) and extreme vulnerability (5 mosques), requiring urgent intervention. Moderate vulnerability accounts for 87 mosques, while medium (58) and low vulnerability (34) represent more stable structures. This stratification underscores the need for prioritized reinforcement strategies, particularly for the 9 mosques in the highest-risk tiers. Table 6 summarizes the distribution of the 360 mosques across the six vulnerability levels

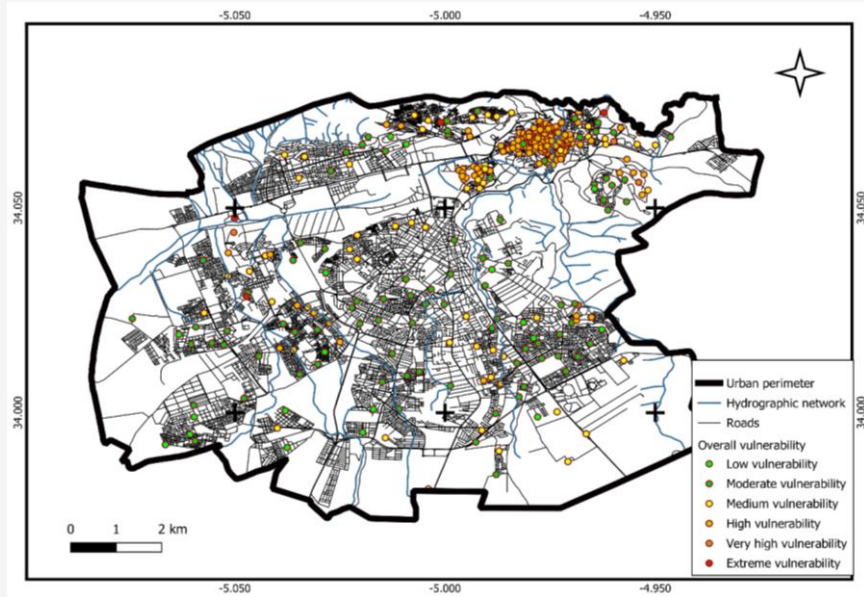


Figure 5: Map of overall vulnerability of mosques

Table 6: Distribution of mosques by overall vulnerability level

Overall Vulnerability Level	Number of Mosque	Intervention priority
Low	34	Low
Moderate	87	Moderate
Medium	58	Medium
High	172	High
Very high	4	Critical
Extreme	5	Emergency

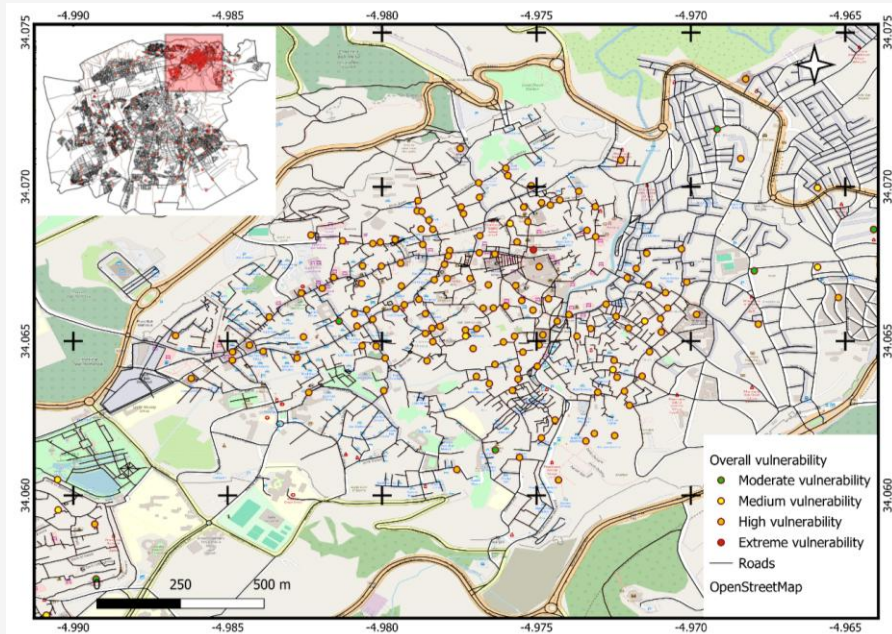


Figure 6: Zoomed-in view of the mosques in the northern part of the study area overlaid with a street map

4.3 Risk Prevention Measures

The vulnerability mapping of Fez's mosques integrates both geotechnical and structural factors, revealing distinct risk patterns: 47.8% (172/360) of mosques fall into high-to-extreme vulnerability categories, primarily clustered near Oued Fez (flood/groundwater risks) and unstable slopes (landslides). Key findings demand targeted interventions:

- *High-Vulnerability Zones (172 mosques)*: Require foundation reinforcement (e.g., micropiles for liquefaction-prone areas) as demonstrated by [10] in their stabilization of Italian heritage structures, and slope stabilisation (e.g., soil nailing for landslides) following methods validated by [20] for Volubilis Archaeological site (Morocco), as structural weaknesses compound subsurface risks.
- *Critical Cases (9 mosques)*: Need immediate waterproofing using techniques adapted from [21]'s study on groundwater protection in historic buildings, and seismic retrofitting (cracked masonry) applying the reinforced masonry approaches successfully tested by [22], identified via on-site assessments.
- *Moderate-Low Risk (179 mosques)*: Benefit from drainage upgrades similar to those implemented in [23]'s flood mitigation strategies for southeastern suburbs of Fez City (Morocco) and periodic monitoring, with priority given to historic masonry mosques showing tensile cracking.

These prevention strategies align with three key principles from heritage conservation literature: (1) compatibility of materials (per [24]), (2) minimal intervention (following [25]), and (3) hazard-specific adaptation (as advocated by [1]). Collaboration with local authorities is essential to align measures with conservation guidelines.

5. Discussion

This study systematically integrates geotechnical and structural risk factors to assess mosque vulnerability in Fez. Our key findings reveal that 47.8% of mosques (172/360) fall into high-to-extreme vulnerability categories, with structural vulnerabilities (e.g., traditional masonry degradation) amplifying geotechnical risks (e.g., liquefaction in alluvial soils).

Materials and structure analysis shows that 36.6% of traditional masonry mosques exhibit major degradation (cracks >2mm, material loss >25%), particularly in older structures (>30 years) where lime mortar deterioration exacerbates seismic vulnerability. Geotechnical assessments highlight

critical soil risks: colluvial slopes ($\phi'=18-22^\circ$) prone to landslides, loose sands ($N_{1,60}=8-15$) susceptible to liquefaction, and swelling clays (LL=45-60%) causing foundation damage. The integrated approach reveals compounding effects – for instance, 82% of mosques >30 years old exposed to ≥ 3 hazards showed major degradation, versus 11% of newer constructions. This synergy between structural and subsurface factors, overlooked in prior seismic-only studies [3], explains why 9 mosques require emergency intervention despite moderate structural scores when located in high-hazard zones. Our results align with [1] and [10] on multi-hazard vulnerability but diverge by quantifying Moroccan-specific risks: flood-groundwater interactions damage 68% of Medina mosques, a pattern absent in European studies. The novelty lies in our scoring system, which weights geotechnical and structural factors equally, providing a more comprehensive assessment than single-domain method [3].

6. Conclusion

This study developed an integrated framework to assess mosque vulnerability in Fez by combining geotechnical and structural risk factors. The analysis revealed that nearly half of surveyed mosques face high-to-extreme vulnerability, with traditional masonry structures in floodplains and landslide-prone areas being most at risk. The methodology successfully identified critical intervention priorities while demonstrating how subsurface conditions amplify structural weaknesses. These findings provide authorities with a science-based tool for heritage preservation that accounts for Fez's unique multi-hazard context. The approach offers a replicable model for protecting religious architecture in similar environments worldwide.

7. Study Limitation and Future Research Directions

This study had three main limitations. First, the resolution of topographic data may have affected hazard simulations in dense urban areas. Second, structural assessments focused on visible damage rather than advanced engineering analyses. Third, contemporary climate data may not fully represent long-term environmental risks. Future research should:

1. Incorporate high-resolution terrain modeling to improve flood and landslide predictions
2. Conduct detailed seismic analyses of representative mosque structures
3. Investigate historical climate patterns to better understand long-term risk evolution
4. Examine wind load effects on tall structures like minarets

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