A GIS-based multi-criteria decision analysis framework for landslide risk assessment: A case study in Amathounta, Limassol, Cyprus

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ABSTRACT

Landslides pose significant risks to both infrastructure and environmental systems, making efficient risk assessment and management strategies essential. This research combines Multi-Criteria Decision Analysis (MCDA) with Geographic Information Systems (GIS) to assess landslide susceptibility in the Amathounta region of Limassol Cyprus. Nine key factors influencing slope stability were selected, including slope, aspect, relief, precipitation, land use, proximity to roads, lithology, faults, and streams—sourced from both national agencies and open datasets. A 5-meter resolution Digital Elevation Model (DEM) supported the extraction of terrain-related parameters, while geological and meteorological data were obtained from official sources. Remote sensing and spatial analysis techniques were used to prepare the input layers, and the Analytic Hierarchy Process (AHP) was employed to weight each criterion based on expert judgment and regional studies. These weighted layers were integrated using a structured overlay approach in ArcGIS Pro to generate a detailed landslide susceptibility map. The final output categorizes the study area into five hazard levels, from very low to very high risk. Validation using a local landslide inventory showed strong spatial agreement with the high-risk zones, confirming the robustness of the approach. The research provides important findings for Amathounta land-use planning and hazard mitigation and establishes a transferable method for other areas in Cyprus. The upcoming research will concentrate on expanding the model across the national territory and adding soil characteristics together with socio-economic data and real-time monitoring systems to boost predictive accuracy.

Keywords: GIS, Multi-Criteria Decision Analysis, Analytic Hierarchy Process, Landslide Risk Assessment, Predictive Modeling, Hazard Zonation.

1. INTRODUCTION

Landslides occur frequently and often cause extensive disruption which leads to infrastructure damage and fatalities and prolonged economic and social impacts. Their occurrence is driven by a combination of natural factors—such as geology, slope, and rainfall patterns—as well as human-induced pressures including deforestation, urban sprawl, and changes in land use[1,2]. In Cyprus, this hazard becomes increasingly critical as expanding urban development continues to encroach on geologically unstable areas, particularly in coastal and hilly zones of the Mediterranean[3].

Cyprus as a whole—and particularly the Amathounta region along Limassol's southeastern coastline—illustrates the critical need for landslide susceptibility assessment[4]. The region stands out because it contains both archaeological value and challenging geological formations that link cultural significance to geological dangers[5]. The area contains various active and inactive fault lines together with steep slopes and diverse lithological formations which enhance the likelihood of slope instability. The rising human pressure from tourism developments combined with residential expansion has made the terrain more susceptible to landslides.

Amathounta distinguishes itself through the combination of natural hazard exposure with human-made features that hold historical significance. This unique overlap heightens the need for site-specific hazard assessments that consider both geological conditions and cultural preservation. The combination of periodic intense rainfall and inherent geological instability means that even minor environmental changes can trigger serious slope failures[6,7] .

To address this complexity, the study applies a geospatial multi-criteria decision analysis (MCDA) framework within a Geographic Information System (GIS) environment to map and evaluate landslide-prone zones in the area.

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GIS enables the integration and spatial processing of diverse datasets—such as digital elevation models (DEMs), geological and hydrological layers, land use classifications, and infrastructure networks—into a cohesive analysis. As shown in recent spatial heritage applications in Cyprus[8], GIS plays a pivotal role in managing and visualising risk in areas where natural and cultural landscapes intersect.
By assigning weights to the most influential factors using the Analytic Hierarchy Process (AHP), this methodology offers a structured and transferable approach to landslide risk assessment[9]. The resulting susceptibility map supports targeted mitigation planning and can serve as a model for other high-risk areas across the island.

2. METHODOLOGY

Nine conditioning elements were identified for the assessment of landslide risk in the Amathounta region: slope, aspect, relief, precipitation, land use, proximity to roads, lithology, closeness to faults, and proximity to streams (Table 1). These characteristics are acknowledged as significant contributors to slope instability in Mediterranean settings and have been thoroughly utilized in prior regional susceptibility studies, especially in Cyprus. The Department of Lands and Surveys (DLS) provided a 5 m Digital Elevation Model (DEM) to calculate slope, relief, aspect and drainage networks while the Geological Survey Department (GSD) provided lithology and fault information. The precipitation data from 2011 to 2020 was obtained from the Cyprus Department of Meteorology and interpolated into a continuous raster surface with a resolution of 5.5 km. Road network data were obtained from the national cadastral database, and land cover classifications were generated using the ESA WorldCover 2021 dataset (10 m resolution).

Each criterion was reclassified into ranked subcategories reflecting its relative contribution to slope instability. The classification thresholds and ranking scheme were adapted directly from Alexakis et al. (2014) for the Paphos district of Cyprus, with adjustments for the geomorphological context of Amathounta. For example:

• Slope was divided into seven classes (0–5°, 5–10°, 10–20°, 20–30°, 30–40°, 40–50°, >50°), with higher ranks assigned to steeper slopes.

• Precipitation was classified into 750–1150 mm/year ranges, with higher rainfall values ranked as more susceptible.

• Fault proximity was ranked with higher susceptibility near definite faults (≤500 m) and lower ranks at greater distances.

• Stream buffers were classified according to Strahler order, assigning higher susceptibility to areas close to higher-order streams (reflecting erosion potential).

• Land use classes were ranked based on vegetation cover and human disturbance, with bare soils assigned higher susceptibility and dense vegetation lower.

This ranking system ensured comparability with previous Cypriot studies while being calibrated to the local conditions of Amathounta.

The Analytic Hierarchy Process (AHP) was used to assign relative weights to the nine conditioning factors. This study adopted the weighting scheme developed by Alexakis et al. (2014)[8] for the Paphos district of Cyprus, as it is based on a comparable Mediterranean geological and geomorphological setting on the same island. In their methodology, expert-based pairwise comparisons were applied to the nine factors, with the consistency ratio (CR) confirmed below the acceptable 0.1 threshold, ensuring reliable judgments. The normalized weights derived in that study were directly integrated into the present analysis to maintain consistency with established regional practices. Lithology, slope, and precipitation were identified as the dominant factors. Table 1 presents the ranked subcategories, data sources, and final AHP weights used in this study. This approach ensured comparability with previous Cypriot studies while allowing the Amathounta susceptibility assessment to follow a tested and validated framework.

Table 1: The nine criteria used for landslide susceptibility mapping, including data sources, spatial resolution, classification categories, and assigned AHP weights.

A/A	Criterion	Source	Type	Resolution (m)	Ranked Subcategories (→ increasing risk)	Weight
a	Precipitation (mm/year)	Department of Meteorology	Raster	5500	750 mm (Low) → 850 mm → 950 mm → 1050 mm → 1150 mm (High)	0,043
b	Aspect (cardinal direction)	D.E.M. - Department of Lands and Surveys (DLS)	Raster	5	NW–N (Low) → SW–W → NE–E → SE–S (High – windward/rain-exposed slopes)	0,026
c	Land Use (class)	ESA Worldcover Version 2	Raster	10	Water (Low) → Vegetation → Urban → Bare soil (High)	0,119
d	Faults (distance in m)	Cyprus Geological Survey Department (GSD)	Vector	N/A	>500 m (Low) → ≤250 m (Undefined fault) → ≤500 m (Definite fault, High)	0,176
e	Roads (distance in m)	Department of Lands and Surveys (DLS) (distance in m)	Raster	5	>150 m (Low) → ≤100 m → ≤50 m (High)	0,079
f	Relief (m a.s.l.)	D.E.M. - Department of Lands and Surveys (DLS)	Raster	5	180 m (Low) → 280 m → 380 m → 480 → 580 → 680 → 780 → 880 → 980 → 1180 m (High)	0,013
g	Streams (buffer distance in m, by Strahler order)	D.E.M. - Department of Lands and Surveys (DLS)	Raster	5	>500 m (Low) → ≤250–500 m (5th–6th order) → ≤100 m (3rd–4th order) → ≤50 m (1st–2nd order, High)	0,094
h	Lithology (formation type)	Cyprus Geological Survey Department (GSD)	Raster	50	Lavas (Low) → Limestone/Sandstone → Mélange → Alluvium → Marl (High)	0,245
i	Slope (°)	D.E.M. - Department of Lands and Surveys (DLS)	Raster	5	0–5° (Low) → 5–10° → 10–20° → 20–30° → 30–40° → 40–50° → >50° (High)	0,200

All datasets were spatially aligned, projected, and standardized in ArcGIS Pro. Geospatial analysis tools were employed to extract or generate thematic layers relevant to landslide-influencing factors. For each of the nine criteria, spatially processed maps were produced—either derived from the DEM (e.g., slope, relief, aspect, streams) or obtained directly from source datasets (e.g., faults, precipitation, land use)—to visualize and quantify their contribution to slope instability (Figure 1). Each factor was then reclassified into susceptibility classes following thresholds adapted from Alexakis et al. (2014)[8], ensuring comparability with established approaches. Within each criterion, subcategories were assigned ranking values from 0 (very low susceptibility) to 10 (very high susceptibility), reflecting their relative contribution to landslide occurrence (e.g., flat slopes ranked closer to 0, while very steep slopes ranked closer to 10). The AHP methodology was then applied to assign relative weights to each factor. Pairwise comparison matrices were created and normalized, with the consistency ratio (CR) maintained below the acceptable threshold of 0.1 to ensure methodological reliability. Finally, the weighted layers were integrated through a structured overlay process to generate the Landslide Risk Index (LRI), categorizing the study area into five levels of hazard: very low, low, moderate, high, and very high susceptibility.

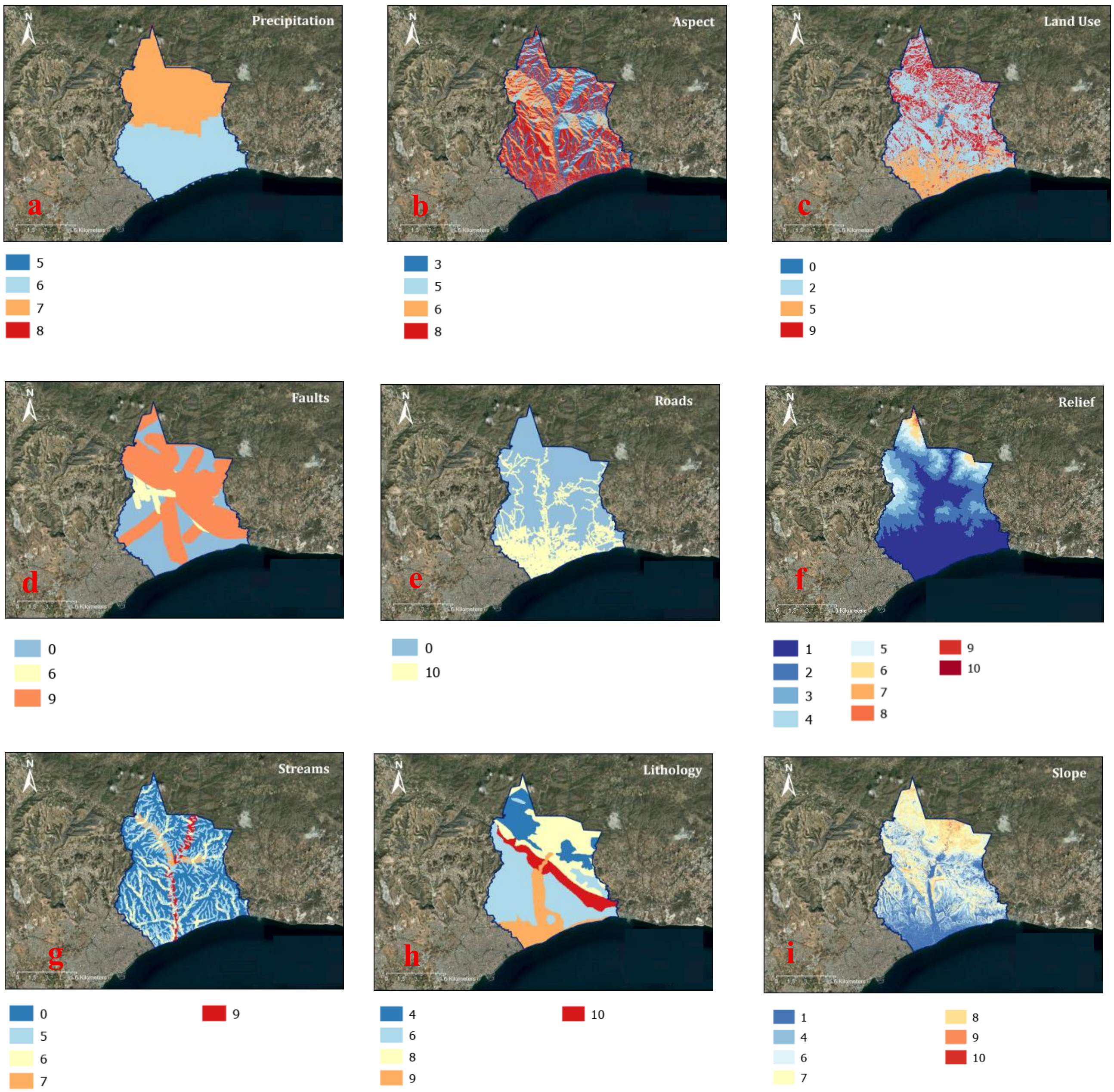

Figure 1. Spatially processed maps of the nine input criteria used in the landslide susceptibility assessment for the Amathounta region: (a) Precipitation, (b) Aspect, (c) Land Use, (d) Faults, (e) Roads, (f) Relief, (g) Streams, (h) Lithology, and (i) Slope.

3. RESULTS

A landslide susceptibility map of the Amathounta region demonstrates varying hazard distributions because it combines geological, hydrological and topographic factors. The study area received a susceptibility classification of very low, low, moderate, high and very high for its five classes. The classes resulted from a MCDA framework applied to nine geospatial criteria in a GIS environment to determine them.

The classification results show that 60% of the total study area belongs to moderate to high susceptibility zones (Figure 2). The central and northern areas of the region have the highest concentration of steep slopes which intersect with active fault lines. The very high susceptibility class occupies 16% of the area which includes unstable lithologies close to fault structures and road networks because these conditions increase slope failure risk significantly. The low-risk category covers about 17% of the region while very low risk areas represent 4% of the total area. The study area features safer zones which occupy its flat coastal regions because stable geological formations and minimal hydrological activity reduce the risk of landslides.

The observed spatial distribution matches the documented geomechanical behaviors of the region in locations that have shown previous slope instability. The susceptibility map shows agreement with theoretical slope failure models while also accurately depicting real-world landslide occurrences. The validation of the model utilized landslide data from the GSD. The superposition of historical landslide occurrences onto the susceptibility results indicates that 74% of documented landslides took place in high or very high-risk zones. The MCDA-AHP approach demonstrates strong spatial agreement with its high level of match between predicted and actual results.

The model achieves its performance because the study used regionally calibrated classification thresholds together with expert-based criterion weights. The GIS-based method uses ArcGIS Pro's structured workflow for future improvements and expansion. The system maintains flexibility to add daily precipitation data along with high-resolution soil characteristics and real-time environmental monitoring for predictive enhancement. The susceptibility map delivers vital information which helps local authorities and urban planners make informed decisions for managing land use and infrastructure development and risk reduction in the Amathounta region and other potential areas.

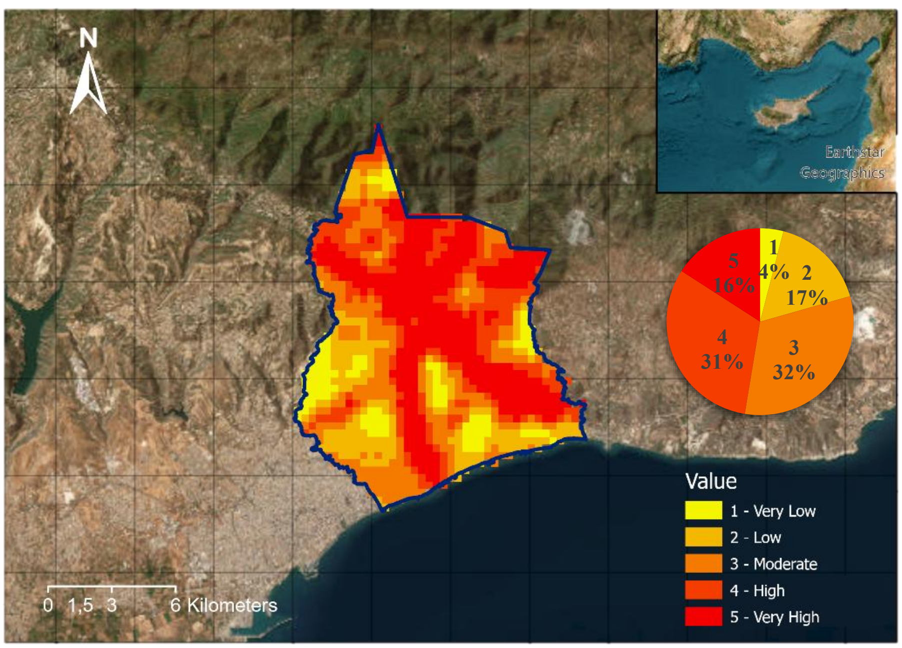

Figure 2. Landslide susceptibility map of Amathounta and corresponding hazard class distribution shown in a pie chart.

4. CONCLUSIONS & FUTURE WORKS

The research implemented a GIS-based MCDA framework with AHP support to evaluate landslide susceptibility in the Amathounta region of Limassol Cyprus. The risk map produced by the study effectively pinpointed regions with high to very high susceptibility levels which matched both existing terrain instability patterns and documented landslide occurrences. The combination of nine spatially processed criteria provided a detailed risk assessment for slope failure which integrated environmental data with structured decision-making systems. The proposed method provides an operational system for local authorities to use when planning land use and building infrastructure and managing disaster risks.

The model demonstrated reliable performance through its validation against GSD historical landslide data which proved its effectiveness for practical applications. The model serves policy development by pinpointing essential areas which need either mitigation measures or monitoring systems or development restrictions. The model's clear framework enables decision-makers and local authorities to add new data points which maintains its effectiveness during environmental changes.

The framework requires expansion to a national level through the integration of detailed data sets that include daily and seasonal precipitation records and soil geomechanical properties and social-economic vulnerability metrics. The methodology benefits from satellite-based observations through the use of advanced InSAR analysis to generate displacement maps.

The research team plans to evaluate machine learning algorithms including random forests and support vector machines to boost predictive accuracy while reducing the AHP weighting process subjectivity. The AHP method depends on expert judgments to determine weights but machine learning algorithms extract feature importance from landslide-environment relationships found in training datasets. The data-driven method reduces dependence on human judgment during ranking while providing better reproducibility and enabling the analysis of complex non-linear factor relationships that traditional MCDA methods struggle to handle.

Environmental risk assessments that focus on coastal vulnerability can help create integrated hazard models to connect geomorphological threats with valuable residential and cultural areas that face development pressures and climate change impacts[10,11].

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