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Journal of Asian Geography, 2025, Volume 4 (Issue 2), 32-36
https://doi.org/10.36777/jag2025.4.2.4

GIS-based Multi-Criteria Landslide Hazard Zonation in Cameron Highlands: An AHP Approach for Disaster Resilience

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Received: 19 Aug 2025; Revised: 4 Sep 2025; Accepted: 15 Sep 2025; Published 30 Sep 2025

Abstract Landslides are among the most frequent and destructive hazards in Malaysia's highland regions, posing threats to communities, infrastructure, and ecosystems. This study aims to develop a GIS-based Landslide Hazard Zonation (LHZ) map for Cameron Highlands using a Multi-Criteria Decision Analysis (MCDA) approach integrated with the Analytic Hierarchy Process (AHP). Five conditioning factors—slope, aspect, rainfall, land use/land cover (LULC), and Normalized Difference Vegetation Index (NDVI)—were derived from remote sensing and spatial datasets. Each factor was reclassified and weighted through AHP, with a consistency ratio (CR = 0.027 < 0.1) confirming reliable judgments. The weighted overlay produced five hazard classes ranging from very low to very high. Results show that approximately 56% of the study area (365 km²) falls within high to very high hazard zones, while only 7% (46 km²) is categorized as low hazard. The findings highlight that unregulated agriculture, slope cutting, and deforestation significantly influence landslide occurrence. This study demonstrates the potential of integrating GIS and AHP for landslide risk assessment and provides an evidence-based tool to support land use planning, slope management, and disaster resilience strategies in highland environments.

Keywords: GIS; landslide; Cameron Highland; MCDA; AHP; disaster

1.0 Introduction

Landslides are a recurring natural hazard in Malaysia, particularly in mountainous and highland areas, threatening the stability and safety of infrastructure, settlements, and key sectors such as tourism and agriculture. Heavy rainfall is the primary factor contributing to this phenomenon. A report by the Public Works Department indicates that from 1973 to 2007, 440 landslide incidents were recorded, resulting in 31 fatalities, while nearly 600 deaths due to landslides have been documented since 1973 (Public Works Department, 2009). However, smaller slope failures often go unreported, suggesting that the actual numbers may be higher. In Cameron Highlands, 21 landslide incidents were reported between 2011 and 2025, underscoring the area's vulnerability to rainfall-induced slope failures (Bernama, 2025).

Advancements in Geographic Information Systems (GIS), combined with Multi-Criteria Decision Analysis (MCDA) methods such as the Analytic Hierarchy Process (AHP), have enhanced the accuracy of landslide hazard mapping. GIS provides a robust framework for integrating spatial datasets such as Digital Elevation Models (DEM), slope, aspect, rainfall, and land use/land cover (LULC). AHP improves the objectivity of hazard assessment by systematically weighting these factors. For example, Rahim et al. (2021) employed GIS-AHP integration to map slope failure vulnerability in Hulu Kelang, while Tan et al. (2022) combined rainfall and soil data to refine hazard maps in Peninsular Malaysia. Similar approaches in Southeast Asia, including Thailand and Indonesia, have also demonstrated the value of integrating GIS with AHP and remote sensing indices (Phanuwong & Kittiphong, 2021; Arifin et al., 2023).

Recent studies focusing on Cameron Highlands further highlight the importance of updated hazard assessments. Tarmizi and Billa (2023) found that annual rainfall exceeding 2,687 mm, intensive agricultural activities, and high-elevation zones above 1,800 meters are strongly associated with landslide occurrences. Meanwhile, Yusoff et al. (2024) integrated the Normalized Difference Moisture Index (NDMI) with slope data, introducing a new perspective on plant-water stress as a contributing factor to slope instability. At the national level, Zakaria et al. (2023) reviewed GIS-based landslide vulnerability studies in Malaysia from 2000 to 2022, identifying Pahang (including Cameron Highlands) as one of the most studied states, while emphasizing the diversity of models and parameters applied.

Despite these advancements, notable research gaps remain. Few studies have integrated vegetation indices such as NDVI and NDMI with the latest high-resolution rainfall datasets within the GIS-AHP framework in highland areas. Addressing this gap could significantly improve the accuracy of vulnerability mapping in ecologically sensitive and rapidly changing landscapes such as Cameron Highlands.

Cameron Highlands was selected as the case study not only because of its agricultural and tourism importance but also due to its ecological fragility, rapid land-use changes, and climate sensitivity. Intensive slope development, deforestation, and fragile ecosystems heighten its susceptibility to rainfall-induced landslides. By integrating NDVI, rainfall, and topographic variables (DEM, slope, aspect, and LULC) within the GIS-AHP framework, this study aims to generate landslide hazard maps categorized into low, moderate, and high vulnerability zones. The results will provide valuable guidance to local authorities and disaster management agencies for land-use planning, risk reduction, and hazard mitigation strategies.

2.0 Study Area

Cameron Highlands is a district in the state of Pahang, Peninsular Malaysia (Figure 1), covering an area of approximately 712 km². Its topography consists of steep hills, narrow valleys, and elevations ranging from 800 to over 2,000 meters above sea level. The area is well known for highland tourism, with agricultural activities such as vegetable, fruit, and tea cultivation serving as major attractions for visitors. Cameron Highlands receives high annual rainfall exceeding 2,500 mm, with peak rainfall typically occurring during the monsoon season. Rapid land-use changes, slope cutting, and deforestation have further increased the district's vulnerability to landslides.

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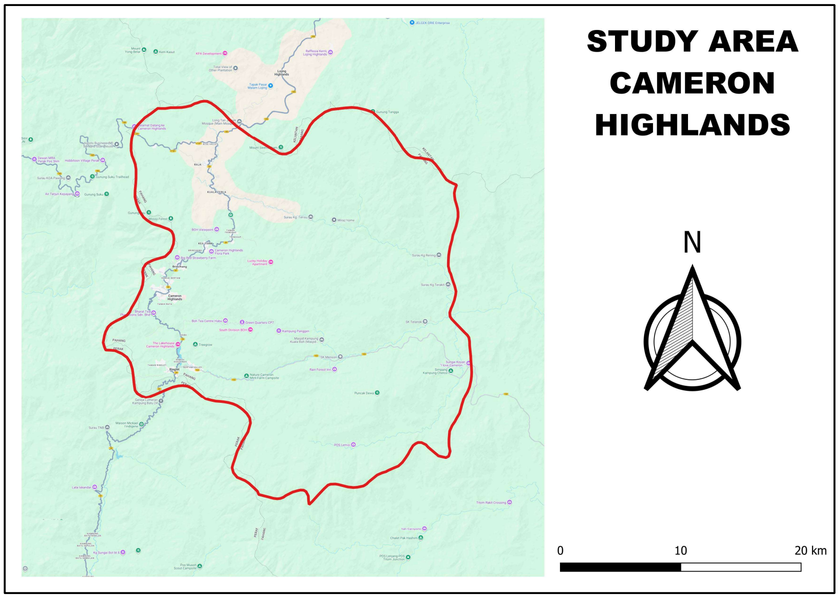

Figure 1: Study area

3.0 Data and Materials

To conduct landslide hazard mapping in Cameron Highlands, several conditioning factors were selected based on their relevance to slope stability analysis. These include slope steepness, aspect, rainfall, vegetation index (NDVI), and land use/land cover (LULC). Such variables are widely applied in landslide susceptibility studies as they directly influence soil erosion, infiltration, and slope failure potential. While other factors such as soil type, geology, and proximity to roads or streams may also be relevant, the selected datasets were prioritized for their high spatial resolution, compatibility with the Multi-Criteria Decision Analysis (MCDA) framework, and demonstrated significance in similar studies.

The rainfall dataset covers the period from October 2023 to March 2024, coinciding with the northeast monsoon season in Malaysia, which typically records the heaviest rainfall and is strongly associated with landslide occurrences in highland areas (Funk et al., 2015). Although long-term rainfall records provide valuable insights into susceptibility, this short-term dataset was chosen to capture recent extreme rainfall variability, which is critical for understanding current triggering conditions in Cameron Highlands.

The Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) was used to derive slope and aspect (NASA JPL, 2013). Land use/land cover data were obtained from ESA's WorldCover product, which provides global coverage at 10 m resolution (European Space Agency, 2021). Sentinel-2 satellite imagery (Bands 04 and 08) from the Copernicus Open Access Hub was used to calculate NDVI (European Commission, 2023). Administrative boundary shapefiles were sourced from the GADM database for overlay and map reference (GADM, 2024).

All datasets were projected to a common coordinate reference system (CRS: UTM Zone 47N, EPSG:32647) and resampled to a uniform spatial resolution of 30 m to ensure consistency in spatial analysis. Table 1 summarizes the datasets used.

Table 1: Summarizes of data collection

No.	Data	Format	Resolution	CRS	Source	Note
1	Digital Elevation Model (DEM) SRTM 30 m	GeoTIFF	30 m	EPSG:4326 (WGS 84)	USGS Earth Explorer (NASA JPL, 2013)	Used to derive slope and aspect
2	Rainfall (Oct 2023 – Mar 2024)	GeoTIFF	10 m	EPSG:4326 (WGS 84)	CHIRPS Data Portal (Funk et al., 2015)	Represents extreme rainfall season
3	Sentinel-2 Imagery (Bands 04 & 08)	GeoTIFF	25 m	UTM 47N (EPSG:32647)	Copernicus Open Access Hub (European Commission, 2023)	Used to compute NDVI
4	Land Use and Land Cover (LULC)	GeoTIFF	10 m	EPSG:4326 (WGS 84)	ESA WorldCover (European Space Agency, 2021)	Reclassified into major land cover categories
5	Administrative Boundaries	Shapefile	–	EPSG:4326 (WGS 84)	GADM Database (GADM, 2024)	For map overlay and boundary reference

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4.0 Methodology

The methodology of this study is structured around four main components: data preparation, factor derivation, AHP weighting, and hazard zone generation. Figure 2 presents the workflow, illustrating these components and the processes carried out within each.

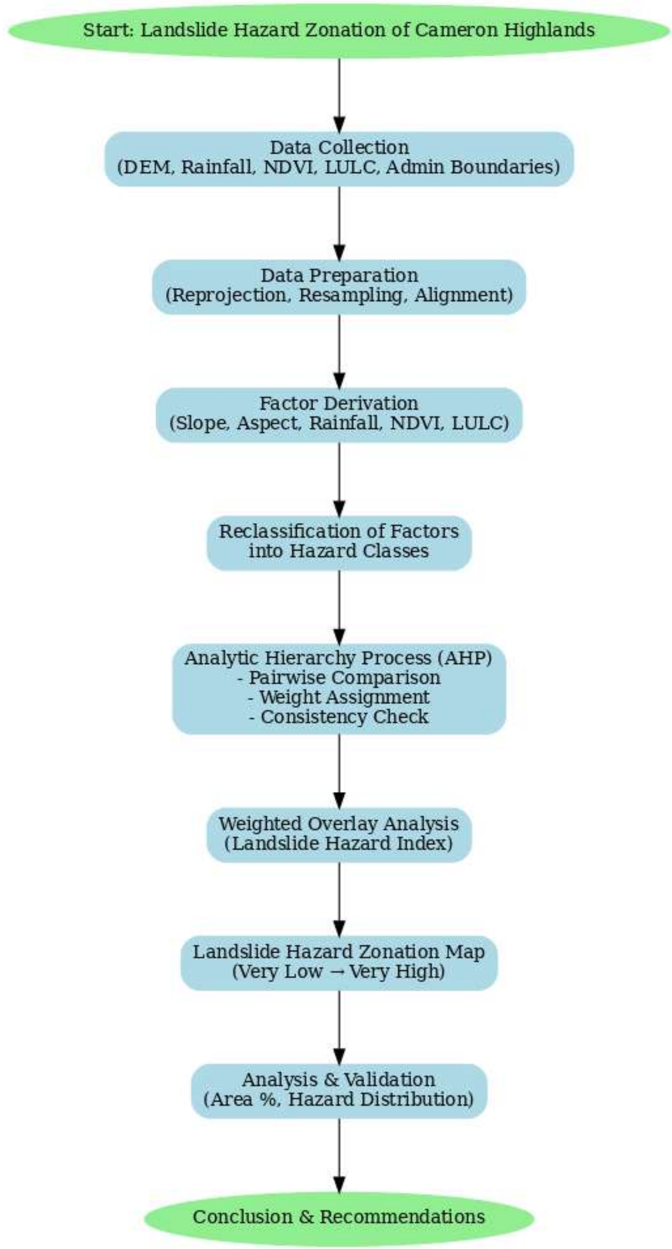

Figure 2: Workflow of Study.

4.1 Data Preparation and Factor Derivation

Data were collected from global sources, including the 30 m SRTM Digital Elevation Model (DEM) from USGS Earth Explorer, rainfall data from the CHIRPS Data Portal, Sentinel-2 imagery (Bands 04 and 08) from the Copernicus Browser, land use/land cover (LULC) data from ESA WorldCover, and administrative boundaries from GADM. All datasets were standardized to a 30 m resolution and harmonized to UTM Zone 47N (EPSG:32647) (Hijmans et al., 2005; Funk et al., 2015).

From the DEM, slope and aspect maps were derived and classified according to national guidelines and GIS terrain analysis standards (Malaysia Public Works Department, 2009; Silva et al., 2013). Rainfall data were aggregated for October 2023–March 2024 using QGIS raster tools, while NDVI was calculated from Sentinel-2 imagery to represent vegetation cover (Sentinel Hub, 2017). LULC classes were reclassified following ESA WorldCover categories, with hazard weights assigned according to their relative susceptibility to landslides (Esri, 2025).

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4.2 AHP Weighting

The Analytic Hierarchy Process (AHP) was applied to assign relative importance to the factors of slope, aspect, rainfall, NDVI, and LULC. Weighting was determined primarily through expert judgment, supported by literature, to ensure a balance between empirical evidence and professional experience (Saaty, 1990; Malczewski, 2006).

The final weights obtained were:

- Slope = 0.497
- Rainfall = 0.235
- NDVI = 0.100
- LULC = 0.100
- Aspect = 0.067

4.3 Consistency Check

The AHP consistency ratio (CR) was calculated as 0.027, which is below the acceptable threshold of 0.1. This indicates that the pairwise comparisons are consistent, and the resulting weights are reliable. Specifically, CR = 0.027 < 0.1, confirming its acceptability (Saaty, 1990).

4.4 Landslide Hazard Zonation

The weighted overlay analysis was performed in QGIS to generate the Landslide Hazard Index (LHI), which was then reclassified into five hazard classes: very low, low, moderate, high, and very high. The resulting Landslide Hazard Zonation (LHZ) map of Cameron Highlands represents the main output of this study.

5.0 Result and Discussion

The results produced Landslide Hazard Zonation (LHZ) maps of Cameron Highlands, as shown in Figure 3. Overall, 56% of the district is classified as high to very high hazard (365 km²), while the low-hazard zone accounts for only 7% (46 km²), and the moderate-hazard zone covers approximately 246 km² (37%), warranting monitoring due to potential escalation. These proportions are consistent with earlier hazard zonation efforts in the region. For example, Talib and Napiah (2000) identified concentrated very high-risk areas along road slopes and agricultural zones in Bertam Valley and Tanah Rata, highlighting the influence of land use and infrastructure on hazard patterns. Likewise, Jasmi Ab. Talib (1997) noted roads and land use as dominant causative factors in hazard mapping.

The spatial distribution of high-risk zones strongly coincides with land-use changes. Activities such as forest clearing, slope excavation for crops and roads, and unplanned agricultural practices compromise slope stability. This is supported by anti-erosion modeling in Cameron Highlands, which showed that over 79% of landslides occurred on agricultural land, particularly on slopes steeper than 15° (Rahim et al., 2021). Similarly, increasing pressures from mass tourism and agriculture have driven extensive land clearance, significantly elevating erosion and landslide susceptibility (Razali et al., 2018). Aik et al. (2021) documented the loss of nearly 36 km² of primary forest between 2009 and 2019, with agricultural and urban expansion onto slopes exceeding 35°, reinforcing the link between land-use change and hazard escalation.

This study, however, has notable limitations. The omission of soil and detailed geological data constrains slope stability assessment. The inclusion of multi-temporal proxies such as NDVI, soil wetness, and land surface temperature, as demonstrated by Basith (2011), could improve model accuracy, particularly where rainfall data are limited. Moreover, reliance on short-term rainfall records and relatively coarse spatial resolution may underestimate localized hazard potential.

Despite these constraints, the hazard map is a pivotal resource for policy, planning, and community resilience. It can inform land-use zoning by steering development away from high and very high hazard zones and enforcing stricter controls on slope agriculture. Rahim et al. (2021) similarly advocated improving agricultural practices and limiting tourism development in vulnerable zones. The map also has practical applications for disaster preparedness initiatives, community awareness programs, and early warning systems, contributing to resilience among populations living near unstable slopes.

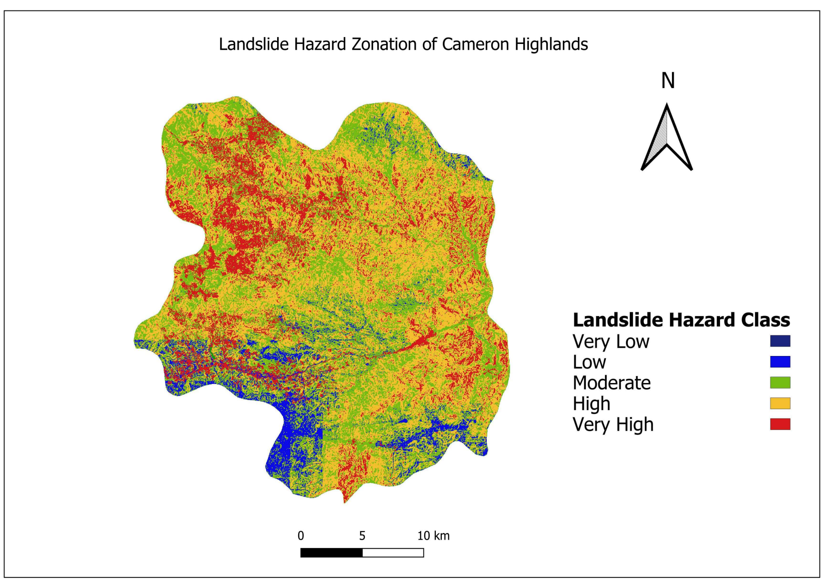

Figure 3: Landslide Hazard Zonation Maps of Cameron Highlands

6.0 Conclusion

This study contributes new insights by integrating NDVI, rainfall, and topographic factors within a GIS–AHP framework to produce an updated landslide hazard zonation map of Cameron Highlands. The approach demonstrates novelty by incorporating vegetation indices alongside traditional conditioning factors, offering a more nuanced understanding of slope stability in ecologically sensitive highland regions. The methodological framework developed here is replicable and adaptable to other highland or mountainous areas in Malaysia and Southeast Asia. By adjusting factor weightings or incorporating additional datasets such as soil and geology, future applications can further refine hazard assessments and provide localized risk profiles for diverse terrains.

The findings hold strong practical relevance for policymakers, planners, and local communities. The hazard map serves as an evidence-based tool for land-use zoning, guiding restrictions on development in High and Very High hazard zones while promoting sustainable agricultural practices. For disaster management, the results can inform the design of targeted preparedness programs, slope monitoring, and community-based early warning systems. Furthermore, by balancing ecological protection with development needs, this study contributes to sustainable tourism planning in Cameron Highlands, ensuring long-term resilience of both the environment and the livelihoods that depend on it.

Acknowledgement: Thanks to the editor and reviewers for their constructive comments.

Conflicts of Interest: The authors declare that there are no conflicts of interest.

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