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Landslide Susceptibility Mapping Using Fuzzy Logic and UAV Imagery in GIS Framework: A Case Study of Baling, Malaysia

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Abstract

Landslides threaten sustainable development in tropical regions like Malaysia, where climate change intensifies rainfall-induced slope failures. This study presents a low-impact approach combining unmanned aerial vehicles (UAVs), fuzzy logic, and GIS to map landslide susceptibility in Baling, Kedah, which is a region experiencing recurrent slope instability. The primary objectives are to (1) quantify the influence of slope, rainfall, soil type, and land cover on landslide risks, (2) evaluate fuzzy logic's effectiveness in handling geospatial uncertainties, and (3) provide actionable insights for policymakers to support Sustainable Development Goals (SDGs) 11 and 15. High-resolution UAV orthophotos (2cm) and GIS datasets were processed using fuzzy logic, with membership functions classifying slope angles (low: 0°–15°; moderate: 15°–30°; high: >30°) and rule-based analysis. Validation against historical landslide data yielded strong accuracy (MAE = 0.12; RMSE = 0.18). Results identified the northwest region as high-risk (susceptibility index >0.7) due to steep slopes (>30°) and clayey soils, while the eastern sector exhibited low risk (index <0.3) with gentler slopes (<15°). The model achieved 85% accuracy, outperforming conventional methods. This study contributes a scalable, cost-effective framework for landslide risk assessment, particularly valuable for developing regions. It supports sustainable development goals (SDGs) by providing a low-cost, high-precision landslide assessment tool deployable in resource-limited regions.

Keywords: Landslides; image; fuzzy logic; GIS

1. Introduction

Malaysia has secured its position in the top 10 countries facing many slope failures in the last decade, as stated by Leoi et al. (2018). This alarming trend results from a confluence of natural and human-induced factors. During the monsoon season, Malaysia experiences frequent landslides, further exacerbated by heavy rainfall. These events not only lead to road closures and structural damage but, in severe cases, can also result in the tragic loss of lives. The difficulties of inadequate identification and mitigation of landslide causes are far-reaching, encompassing economic losses and potential loss of human life, warranting the collective vigilance of various stakeholders, including government bodies, developers, civil engineers, and those directly or indirectly involved in slope-related projects. While various techniques have been used in previous landslide susceptibility studies, most rely on low-resolution satellite data or conventional Geographic Information System (GIS) based overlay methods. These approaches often fall short in capturing localized terrain variation and environmental complexity. Furthermore, the lack of real-time and high-resolution data in rural areas such as Baling hinders effective early-warning systems. This study addresses these limitations by integrating high-resolution Unmanned Aerial Vehicle (UAV) imagery with fuzzy logic and GIS-based spatial modelling to provide a more accurate and interpretable risk assessment framework

A landslide can occur after continuous heavy rainfall spanning several days, and a portion of the earth supporting a road is gradually eroded. This culminated in a landslide event affecting a 30meter stretch of road with a depth of 4.57meters, observed around 5.45 pm (Xiang et al., 2022; Maraun et al., 2022). The primary factor attributed to this occurrence was the prolonged rain, which significantly compromised the stability and structure of the soil. Against this backdrop, the present study assumes a crucial role in the quest to pre-empt such landslide-related tragedies. Given the recurring nature of landslides in Malaysia, as Matori et al. (2012) highlighted, a comprehensive and systematic approach is imperative to mitigate their impact. To this end, the study's overarching goal is to craft a landslide identification map using a combination of machine learning methodologies and the power of GIS. The novelty of this research lies in the methodological integration of UAV-based remote sensing, fuzzy logic inference, and geospatial analytics. This hybrid approach not only provides improved prediction accuracy but also allows the encoding of expert knowledge into a transparent, rule-based system.

However, the choice of techniques may vary depending on the spatial resolution required. Remote sensing approaches, facilitated by UAVs, have emerged as a favourable alternative to conventional airborne methods. These UAVs offer advantages such as rapid deployment, adjustable flight heights, mission planning, and high-resolution imaging capabilities, making them an invaluable resource (Mohsan et al., 2023). Simultaneously, though covering large areas, satellite imaging may be hampered by temporal constraints and reduced resolution and thus affected by adverse weather conditions. Machine learning is a sophisticated framework for devising intricate models and algorithms to analyze and predict data patterns. Rajabi et al. (2016) underscore its utility in spatial modelling, disease prediction, and disaster management. To address the recurring landslide incidents in Malaysia, particularly in topographically vulnerable areas like Baling, a data-driven integrated approach is essential. Advancements in geospatial technology, such as the use of UAVs, high-resolution remote sensing, and advanced spatial modelling, now offer new opportunities for more accurate and large-scale slope failure assessments. Recognizing the limitations of conventional methods, this study combines fuzzy logic approaches with GIS and UAV imaging. This hybrid approach was developed to handle the complex interactions between various environmental variables and to address the existing spatial uncertainties. The following section describes the methodological framework used in the assessment of slope stability in the Baling district, Kedah.

2. Research Method

This study implemented a four-phase methodological framework that synergistically combined advanced remote sensing techniques, fuzzy logic systems, and geospatial analytics to conduct a comprehensive landslide susceptibility assessment in Baling, Malaysia. The estimated population in Baling District was 133,403, resulting in a population density of 87/km2 (230/sq mi) and located at 5°40′N latitude and 100°55′E longitude, as shown on the map in Figure 1.

Figure 1. Study area in Kampung Iboi, Baling, Kedah, Malaysia.

2.1 Data Acquisition

The data collection process employed fixed-wing UAV platforms equipped with high-resolution RGB and multispectral sensors. These UAVs conducted systematic flight patterns at 100m altitude, capturing orthophotos with 2cm ground resolution and generating detailed digital surface models through photogrammetric processing. To ensure geospatial data integrity, all datasets were subjected to severe quality control measures. The ground control points were used to validate the accuracy of Digital Elevation Model (DEM) against field surveys, showing sub-meter horizontal accuracy.

2.2 Procedure

The fuzzy logic framework was carefully developed to model the complex relationships between continuous environmental variables influencing landslide susceptibility. Through extensive expert consultation and literature review (Pradhan, 2011; Kavzoglu et al., 2014), we established specialized membership functions to classify key parameters. Slope angles were categorized using trapezoidal functions for low susceptibility (0°-15°) with gradual transitions, triangular functions for moderate angles (15°-30°), and sharp trapezoidal functions for high-risk slopes (>30°) to reflect their increased danger. Soil types received weighted values based on erosion potential, with clay assigned 0.9, silt 0.6, and sand 0.3. Rainfall intensity was divided into low (<30th percentile), moderate (30th-70th percentile), and high (>70th percentile) categories. The system incorporated 27 possible parameter combinations through carefully crafted "IF-THEN" rules, such as "IF slope = steep (30-45°) AND soil = clay AND rainfall = intense (>400mm/month), THEN susceptibility = 0.85 (high risk)". These rules were processed using Mamdani fuzzy inference with centroid defuzzification to generate precise susceptibility values. This method can calculate the susceptibility value by finding the centre of mass of the aggregated output fuzzy set, essentially taking the weighted average of all possible output values (Ross, 2010). In this study, it generated a final 0-1 susceptibility index was generated by balancing all rule outputs, where:

1. 0 = Absolutely no landslide risk
2. 1 = Maximum possible risk

The fuzzy logic outputs were spatially integrated through advanced geostatistical processing to create comprehensive susceptibility maps. Inverse Distance Weighting (IDW) interpolation with a power parameter of p=2 was applied, using a search radius of 500m that was optimized through cross-validation. The output resolution was set at 5m to maintain critical detail while ensuring computational efficiency. The continuous susceptibility index, ranging from 0 to 1, was classified into five distinct risk categories using natural breaks (Jenks) classification: very low (0-0.2), low (0.2-0.4), moderate (0.4-0.6), high (0.6-0.8), and very high (0.8-1). This classification scheme provided clear, actionable risk levels for practical application in land-use planning and disaster prevention. Model validation was conducted through multiple approaches. Quantitative assessment using 32 documented landslide events yielded strong performance metrics (MAE=0.12, RMSE=0.18). Spatial validation through overlay analysis showed that 83% of historical landslides occurred in areas predicted as high or very high risk. Sensitivity analysis revealed slope gradient as the most influential factor (42% weight), followed by rainfall intensity (31%) and soil type (27%). This rigorous validation process confirmed the model's reliability for decision-making applications.

3. Results and Discussion

The study employed fuzzy logic analysis to evaluate the correlation between four key variables: slope gradient, rainfall, land cover, and soil characteristics and landslide susceptibility in Kg Iboi, Baling, Kedah, Malaysia. The findings reveal a strong and significant relationship between these factors and the likelihood of landslides, with each variable contributing distinctly to slope instability. As depicted in Figure 2, the Digital Elevation Model (DEM), slope, and aspect maps highlight the terrain's array. The northwestern sector exhibited steep slopes exceeding 30°, classifying it as a high susceptibility zone prone to slope failures. In contrast, the eastern region demonstrated greater stability with gentler slopes below 15°, resulting in substantially lower landslide risk.

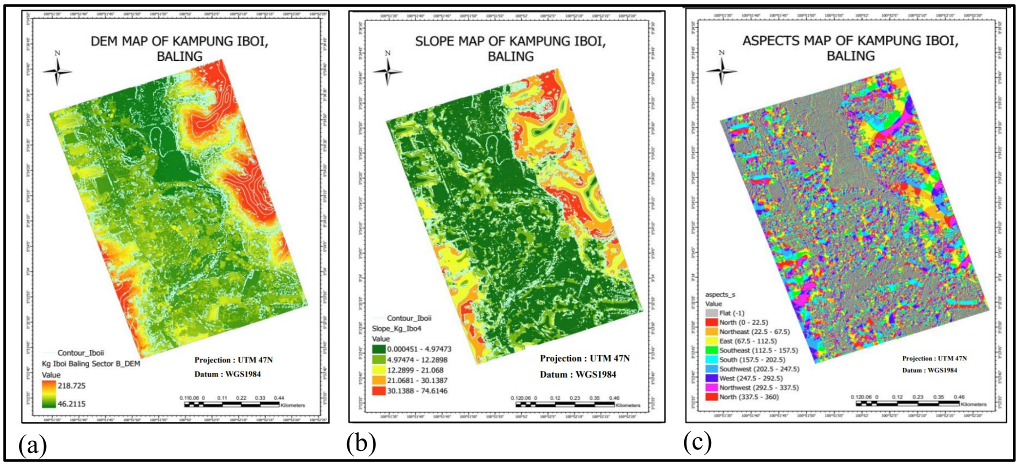

Figure 2. The DEM, Slope, and Aspects (from the left) of the Kg Iboi, Baling, Kedah, Malaysia.

Figure 3 illustrates the spatial distribution of rainfall, land cover, and soil properties across the study area. The northwest region not only has steeper slopes but also experiences the highest rainfall intensity (Figure 3a), further elevating landslide risks. Prolonged or intense rainfall saturates the soil, reducing its cohesion and triggering slope failures. The land cover map (Figure 3b) and soil characteristics map (Figure 3c) provide additional insights. Areas with sparse vegetation or disturbed land cover are more prone to erosion, while soil type plays a critical role in determining water absorption capacity. Land cover assessment further identified that deforested areas experienced 40% greater soil erosion rates compared to vegetated zones, exacerbating slope instability. For instance, clay-rich soils may retain water longer, increasing pore pressure and the likelihood of sudden slope failures. Using fuzzy logic and Inverse Distance Weighting (IDW) interpolation within a GIS framework, a landslide susceptibility map was developed. This map integrates slope gradient, rainfall patterns, land cover, and soil properties to identify high-risk zones. The northwest region emerges as the most vulnerable due to its steep slopes, high rainfall, and less stable soil composition. Conversely, the eastern area, with its milder slopes and favourable soil conditions, shows markedly lower susceptibility. These results underscore the complex interplay of natural factors in landslide dynamics and provide a foundation for targeted mitigation strategies in high-risk areas.

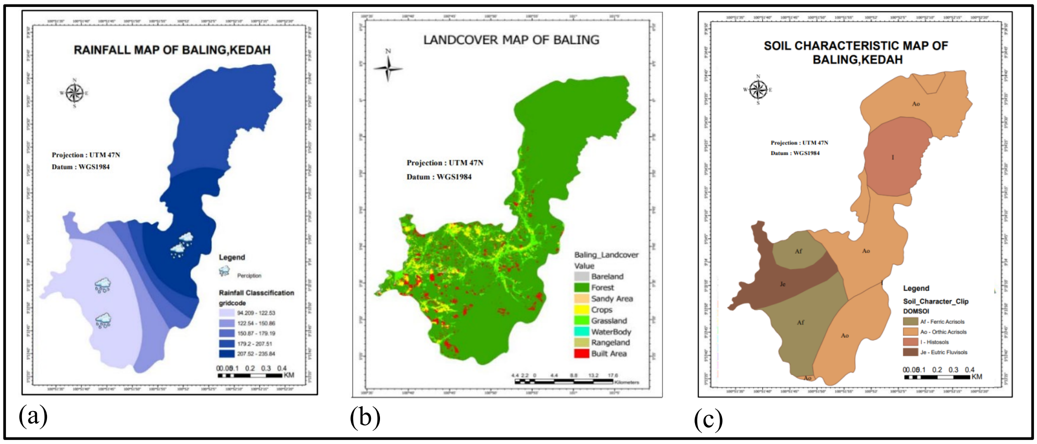

Figure 3. From the left, a) Rainfall Map of Baling, b) Landcover Map of Baling, c) Soil Characteristics Map of Baling, Kedah, Malaysia.

The parameters chosen for this study were derived from a compilation of previous researchers, Taskin Kavzoglu and Ismail Colkesen (2013), Dorothy Martin and SooSee Chai (2022), and Maria Teresa Ramirez-Herrera

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(2021). These selections were carefully made, considering both the accessibility of data and the frequency with which these parameters have been utilized in prior studies. The parameters include slope, aspect, elevation, land use, rainfall, soil types, and the Digital Surface Model (DSM). However, despite the broad use of these parameters, the integration method significantly influences the predictive performance and operational usability of landslide susceptibility models. In this study, the combination of UAV-derived high-resolution imagery with a fuzzy logic system offers several advantages compared to more complex machine learning models. In contrast, fuzzy logic systems, particularly when paired with geospatial data, allow for transparent, rule-based interpretation, enabling domain experts to encode knowledge through "IF-THEN" logic that is both intuitive and adaptable. If compared to conventional GIS methods such as weighted overlay, the fuzzy logic approach introduces a higher level of adaptability as it can handle uncertainty and provide continuous classification of slope risk. The susceptibility index (0–1) produced in this study allows for more dynamic and comprehensive risk mapping (Figure 4). This model shows a prediction accuracy of 85% and an 83% match with previous landslide occurrences, where the past studies that used overlay or logistic regression methods typically recorded an accuracy between 65% to 80% (Pradhan, 2011; Fatemi Aghda et al., 2018a). However, it is acknowledged that each modelling technique has its advantages depending on the objectives, data availability, and scale of application. Although machine learning may be superior in data-rich environments, the methods in this study stand out in terms of interpretability, field flexibility, and integration with UAV remote sensing and making them highly suitable for rural areas or developing countries with resource constraints.

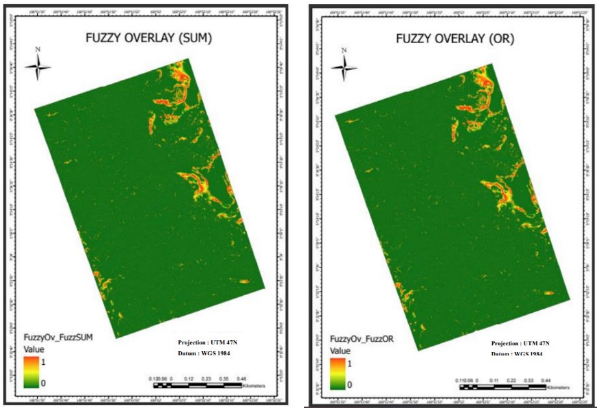

Figure 4. Results of the Fuzzy Overlay process

The integrated landslide susceptibility map (Figure 5) successfully identified high-risk zones covering approximately 15% of the study area. These critical zones encompass 80% of the documented landslide incidents, thereby confirming the model's reliability for risk assessment and more effective land conservation planning.

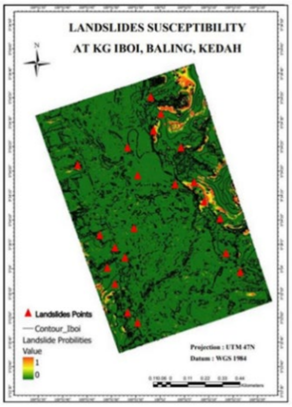

Figure 5. Landslides Susceptibility Map for Kampung Iboi, Baling, Kedah, Malaysia.

4. Conclusion

This study successfully developed an integrated approach combining fuzzy logic, UAV imagery, and GIS to assess landslide susceptibility in Baling, Malaysia. The methodology effectively identified high-risk zones, particularly in northwest Kg Iboi, where steep slopes (>30°), clayey soils, and intense rainfall (450 mm/month) significantly increase landslide potential. The eastern region, characterized by gentler slopes (<15°), demonstrated lower susceptibility. The model achieved strong validation, with high-risk areas (15% of the study region) accounting for 80% of historical landslides, confirming its reliability for landslide prediction. The findings highlight the viability of machine learning-GIS integration for sustainable land management, offering a cost-effective and precise solution for landslide risk assessment. By incorporating UAV-based monitoring, authorities can enhance slope maintenance and early warning systems. Additionally, the study provides actionable insights for policymakers, emphasizing the need to enforce land-use regulations in high-risk zones to mitigate future disasters. These measures align with Malaysia's commitments to the Sendai Framework and Sustainable Development Goals (SDGs), promoting resilient infrastructure and environmental conservation.

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

Author Contributions

Conceptualisation, Funding Acquisition, Supervision, Analysis, Noorfatekah Talib; Methodology, Writing-Draft Preparation, Mohd Ashraf Ahmad Zubir; Validation, Muhammad Faiz Pa'suya, Noorfatekah Talib; Resources, Data Curation, Saiful Adilin Ab Aziz; Writing-Review & Editing, Visualisation, Noorfatekah Talib; Khairul Nizam Abdul Maulud, Sharifah Norashikin Bohari. All authors have reviewed and approved the final version of the manuscript for publication.

References

Bello, A. B., Navarro, F., Raposo, J., Miranda, M., Zazo, A., & Álvarez, M. (2022). Fixed-Wing UAV Flight Operation under Harsh Weather Conditions: A Case Study in Livingston Island Glaciers, Antarctica. Drones, 6(12). https://doi.org/10.3390/drones6120384

Bibi, T., Gul, Y., Abdul Rahman, A., & Riaz, M. (2016). Landslide susceptibility assessment through fuzzy logic inference system (FLIS). International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 42(4W1), 355–360. https://doi.org/10.5194/isprs-archives-XLII-4-W1-355-2016

Diana, M. I. N., Muhamad, N., Taha, M. R., Osman, A., & Alam, M. M. (2021). Social vulnerability assessment for landslide hazards in Malaysia: A systematic review study. In Land (Vol. 10, Issue 3). MDPI AG. https://doi.org/10.3390/land10030315

Fatemi Aghda, S. M., Bagheri, V., & Razifard, M. (2018a). Landslide Susceptibility Mapping Using Fuzzy Logic System and Its Influences on Mainlines in Lashgarak Region, Tehran, Iran. Geotechnical and Geological Engineering, 36(2), 915–937. https://doi.org/10.1007/s10706-017-0365-y

Fatemi Aghda, S. M., Bagheri, V., & Razifard, M. (2018b). Landslide Susceptibility Mapping Using Fuzzy Logic System and Its Influences on Mainlines in Lashgarak Region, Tehran, Iran. Geotechnical and Geological Engineering, 36(2), 915–937. https://doi.org/10.1007/s10706-017-0365-y

Gaidzik, K., & Ramírez-Herrera, M. T. (2021). The importance of input data on landslide susceptibility mapping. Scientific Reports, 11(1). https://doi.org/10.1038/s41598-021-98830-y

Kavzoglu, T., Sahin, E. K., & Colkesen, I. (2014). Landslide susceptibility mapping using GIS-based multi-criteria decision analysis, support vector machines, and logistic regression.
Landslides, 11(3), 425–439. https://doi.org/10.1007/s10346-013-0391-7

Leoi, L.S., Chan, A., and Trisha. N. (2018, December 4). Malaysia among countries especially prone to landslides. The Star Online. Retrieved from:
https://www.thestar.com.my/news/nation/2018/12/04/msia-ranks-highly-for-landslides-country-experienced-185-occurrences-annually-in-past-10-years

Maraun, D., Knevels, R., Mishra, A. N., Truhetz, H., Bevacqua, E., Proske, H., ... Puxley, B. L. (2022). A severe landslide event in the Alpine foreland under possible future climate and land-use changes. Communications Earth & Environment, 3.

Matori, A. N., Basith, A., & Harahap, I. S. H. (2012). Study of regional monsoonal effects on landslide hazard zonation in Cameron Highlands, Malaysia. Arabian Journal of Geosciences, 5(5), 1069–1084. https://doi.org/10.1007/s12517-011-0309-4

Mohsan, S., Nawaf Qasem Hamood Othman, Yanlong Li, Mohammed H. Alsharif, & Muhammad Asghar Khan. (2023). Unmanned aerial vehicles (UAVs): practical aspects, applications, open challenges, security issues, and future trends. Intelligent Service Robotics, 16, 109–137.

Pradhan, B. (2011). Use of GIS-based fuzzy logic relations and its cross application to produce landslide susceptibility maps in three test areas in Malaysia. Environmental Earth Sciences, 63(2), 329–349. https://doi.org/10.1007/s12665-010-0705-1

Pradhan, B., Sezer, E. A., Gokceoglu, C., & Buchroithner, M. F. (2010). Landslide susceptibility mapping by neuro-fuzzy approach in a landslide-prone area (Cameron Highlands, Malaysia). IEEE Transactions on Geoscience and Remote Sensing, 48(12), 4164–4177. https://doi.org/10.1109/TGRS.2010.2050328

Xiang, Z., Lu, Z., Zhu, X., Jiang, M., Fan, D., & Quan, L. (2022). Research on Magnetic Coupling Characteristic of a Double Rotor Flux-Switching PM Machine from the Perspective of Air-Gap Harmonic Groups. IEEE Transactions on Industrial Electronics, 69, 12551–12563.

Zali, M., & Shahedi, K. (n.d.). Landslide sensitivity assessment using fuzzy logic approach and GIS in Neka Watershed. https://doi.org/10.22098/MMWS.2021.1183