Assessing the Impact of Topography on Soil Erosion in Agricultural Areas Using UAV and GIS-Based Analysis

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Abstract
Soil erosion is a critical environmental issue in mountainous agricultural areas such as the Lojing Highlands, where intensive agricultural activities accelerate soil degradation. Topographical factors such as slope, elevation, and aspect play a significant role in determining the rate of soil erosion, which in turn affects soil stability and agricultural productivity. This study investigated the influence of topographical factors (slope, aspect, and elevation) on soil erosion by integrating UAV photogrammetry and GIS analysis. High-resolution UAV images are processed in Agisoft Metashape to produce orthophoto and Digital Elevation Models (DEMs), while topographic parameters are extracted using ArcGIS Pro. Results showed that slopes greater than 15° (15-25%) had a high risk of erosion, with slopes exceeding 45% recording the most critical soil loss due to rapid surface flow. The south-facing slope has a 30% higher erosion rate than the north-facing slope due to its lower vegetation cover. The integration analysis of topographic parameters using GIS identified the risk zone with 85% accuracy, as validated by Ground Control Points (GCPs) and RMSE analysis. The study suggests focused management strategies, such as bioengineering (utilizing vetiver) for slopes exceeding 25° and agroforestry in southern regions, as well as enhancements to Sustainable Development Goals 2 (Zero Hunger) and 15 (Life on Land). This study is the first to integrate UAV-derived slope analysis in the Lojing Highlands by offering a scalable model for tropical upland erosion monitoring. This approach proves to be an efficient method for soil erosion monitoring in tropical upland agricultural landscapes.

Keywords: Agricultural, Elevation, Slopes, Soil Erosion

1. Introduction

An understanding of slope stability and cohesive soil erosion at the slope scale is essential primarily because human activities themselves, such as mining, road construction, airport construction, and land development, occur at this scale, an area traditionally built on top of a slope, where significant economic and social impacts can occur if slope failure of this cohesive soil slope disaster occurs [1]. While erosion studies exist in Southeast Asia, few have applied UAV-GIS integration to the unique agro-topographic conditions of the Lojing Highlands. Notably, [2] highlights that agroforestry systems in Sarawak's highlands reduced erosion rates by 40–60%, suggesting potential applicability to Lojing's agricultural slopes. Soil erosion is a growing environmental issue, especially in high-altitude areas such as the Lojing Highland, where intensive agricultural activities are on the rise. A major influence on soil stability and agricultural production is the rate of soil erosion, which is mostly determined by topographic parameters such as slope inclination, elevation, and aspect [1]. Soil erosion can reduce soil fertility, increase surface runoff, and worsen ecosystems if not properly controlled. Therefore, to ensure that more sustainable land management techniques may be implemented, an extensive knowledge of the relationship between topography and soil erosion is required.

2. Study Area and Methodology

The study was conducted in Malaysia's high-altitude agricultural region of Lojing Highland, renowned for its steep terrain and growing agricultural activities. The area was chosen because it has steep slopes

(Figure 1), and receives heavy rainfall, making it more vulnerable to soil erosion. This study area is situated in the Lojing Highlands of Kelantan, Malaysia, near the borders with Pahang and Perak. The study area chosen is shown in Figure 2 below.

2.1 Data Acquisition

To achieve the study's goal, data collection and analysis techniques are used to gather precise, thorough information on the relationship between topography and soil erosion. Thus, high-resolution photos are captured with UAVs. Drone flights are carefully planned to ensure a comprehensive evaluation of the selected agricultural areas within the study area. Ground Control Points (GCPs) are gathered using high-precision GNSS technology, which supports the data collected by these drones. By improving the georeferencing accuracy of drone photos, GCPs ensure that the resulting spatial data has high resolution and can be utilized for more in-depth research. The data capture process involves several steps, including drone flight planning, the collection of ground control points (GCPs), and image processing to produce orthophotos and digital elevation models (DEMs). Topographic maps and satellite images were used to assess the study region prior to the flight to identify the coverage area. This planning includes establishing the flight path, altitude, and overlap rate to ensure adequate data coverage.

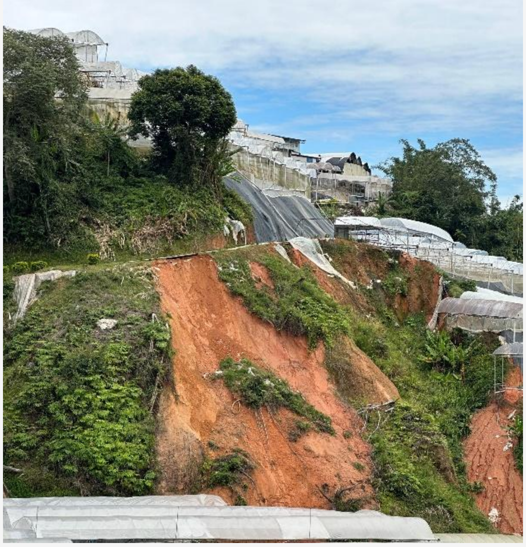

Figure 1: Steep slope in Lojing, Kelantan, Malaysia

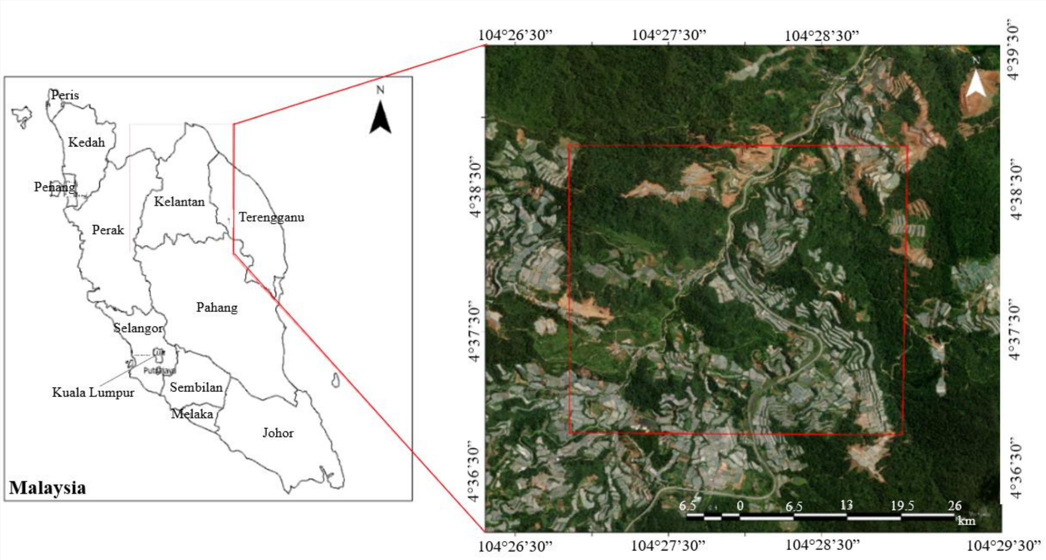

Figure 2: Location of the study area in Lojing Highlands, Kelantan, Malaysia

Figure 3: Data observation of a GCP and UAV drone

Drones equipped with high-resolution cameras were flown over the study area at a predetermined altitude. A good flight altitude typically ranges from 80 to 120 meters, depending on the required image resolution [3][4][5] and [6]. For optimal DEM accuracy, Ground Control Points (GCPs) were established, and drone flights were conducted at an altitude of 110 meters with a 75% overlap. The GCPs are placed at several strategic locations within the study area, and their coordinates are recorded with high precision, as shown in Figure 3. This information is used in image processing to improve the spatial accuracy of the orthophoto and the resulting DEM.

2.2 Data Processing

Data processing in this study began with Agisoft Metashape to generate orthophotos and digital elevation models (DEMs) from UAV drone imagery. The first step in Agisoft Metashape is to import and organize images that contain metadata, such as GPS coordinates and flight altitude. Next, the image alignment process identifies tie points between overlapping images, which then form sparse point clouds. This early model depicts the ground surface in three dimensions. To improve image georeferencing accuracy, Ground Control Points (GCPs) collected with high-precision GNSS were registered in Agisoft Metashape. These GCPs are used to correct image position and improve the spatial accuracy of the orthophoto and the resulting DEM. Subsequently, dense point clouds were developed to obtain more detailed ground surface images before the digital elevation model (DEM) was constructed. This DEM is important for extracting topographical information, such as slope inclination, elevation, and slope aspect, which are crucial for soil erosion analysis. Additionally, high-resolution orthophotos are produced by correcting perspective and topographic distortion. The orthophoto and DEM data, processed in Agisoft Metashape, are then exported as GeoTIFFs for analysis in ArcGIS Pro. DEM is used to extract topographic information, such as slope, elevation, and aspect, to examine the relationship between topography and soil erosion. Both the orthophoto and the processed DEM are imported into the ArcGIS Pro software for more in-depth geospatial analysis.

2.3 Geospatial Tools and Data Analysis

A geospatial analysis is performed once the data is imported into ArcGIS Pro to detect patterns of soil erosion and analyze the connection between topographical characteristics and the extent of erosion. First, topographic mapping is done using the DEM. The region's slope is then calculated using the Slope tool, the aspect is determined using Aspect Analysis, and the height is examined using Height Analysis. This study aims to investigate the effects of elevation, slope, and slope direction on soil erosion rates. The eroded areas are then identified by differences in colour and texture in the orthophoto. Areas with vegetation exposed to soil are classified using classification techniques enabled by ArcGIS Pro's features. Zonal statistics are also used to connect topographical characteristics to identified soil erosion spots. The collected data is then analyzed using correlation and regression methods to determine the relationship between topographical factors and soil erosion rates. Statistical analyses such as correlation and regression are used to determine the relationship between topographical factors and the observed degree of soil erosion. The results of this analysis are used to produce a soil erosion map that shows areas with high erosion and related topographical factors. In addition, statistical findings will help in understanding the relationship between topographical factors and soil erosion in more depth. Based on the study's results, recommendations for land conservation and sustainable agricultural practices have been developed to assist farmers and local authorities in mitigating land erosion in the area. Overall, the study's methodology incorporates the latest geospatial technologies to provide a more detailed understanding of soil erosion patterns and the factors that affect them, thereby contributing to more sustainable soil management in upland agricultural areas.

3. Results and Analysis

Once data processing was complete, key results revealed the relationship between topographical factors and soil erosion in the Lojing Highland agricultural area. The output is high-resolution orthophotos that provide a detailed picture of the land surface and land use in the study area. Additionally, statistical analyses, such as correlation and regression, demonstrate the extent to which topographical factors influence soil erosion rates. Statistical analyses across several studies have shown that slope gradient is a dominant factor influencing soil erosion, with erosion risk increasing substantially on slopes steeper than approximately 15° in Southeast Asia [7][8][9] and [10]. Slopes are a major factor in influencing the extent of soil erosion in the region, as indicated by a high correlation between steep slopes and erosion rates. Additionally, regression can help develop predictive models that, based on evaluated topographical characteristics, identify other potential erosion sites.

3.1 Slope Calculation

Slope calculation is essential to this study's analysis of the soil surface's slope, which determines its influence on soil erosion. The ArcGIS Pro software is used to process a digital elevation model (DEM) for slope calculations. In ArcGIS Pro, the Slope tool can be used to determine the slope of each pixel in a DEM by calculating the change in elevation within each pixel's area. The slope in percentage form is calculated as the ratio of the vertical change to the horizontal distance, expressed as a percentage by multiplying by 100 [11] and [12]. Recent regional studies by [13] and [14] demonstrate the application of this method to Southeast Asian highlands. The mathematical expression is given in Equation (1):

$$Slope = \frac{\Delta h}{d} \times 100$$

Equation 1

Where Δh is the vertical elevation change (m), and d is the horizontal distance between two points (m). Slope is often used in civil engineering and road planning because they are easier to understand in practical terms [15]. Meanwhile, the slope, measured in degrees, is the angle of inclination between the ground surface and the plane [16] and [17]. This is calculated using the inverse tangent function, as shown in Equation (2):

$$\theta = tan^{-1}\left(\frac{\Delta h}{d}\right)$$

Equation 2

Where θ is the slope angle (°)

For instance, if the rise/run ratio is 0.2 (20%), then the slope in degrees is approximately 11.31°. The unit is more commonly used in geomorphological analysis and environmental modelling because of its strong mathematical basis [18] and [19]. The resulting slope maps are classified into five classes to facilitate the analysis and mapping of areas at high risk of soil erosion (Table 1).

3.2 Slope Analysis

Areas with slopes exceeding 45° are categorized as high risk for soil erosion, especially if slope stability is disturbed (Figure 4). The higher slopes showed a greater potential for soil erosion because rainwater flows more rapidly over steep areas, thereby increasing the soil surface's susceptibility to erosion. On the other hand, sloping areas with a lower slope have a lower risk of erosion because the flow rate is slower, allowing more time for water infiltration into the soil.Analysis of the aspect and slope data obtained provides a deep understanding of the topographical characteristics of the study area in Lojing, Gua Musang. Aspect also helps to understand microclimate variation based on elevation and slope direction [5] and [13]. Aspect values were classified into ten major categories as summarized in Table 2.

Table 1: Slope classification and erosion risk categories

Slope Angle (°)	Slope Category	Erosion Risk Level	Description
0 - 5	Flat	Very Low	Minimal surface runoff; stable terrain
> 5 - 15	Gentle	Low	Slow runoff; minimal erosion risk
>15 - 25	Moderate / Hilly	Moderate	Increased runoff velocity: erosion may occur if vegetation cover is disturbed
>25 - 35	Steep	High	High runoff potential; prone to soil loss during heavy rainfall
>35 - 45	Very Steep	Very High	Significant erosion susceptibility
>45	Extremely Steep	Extreme	Critical erosion and landslide risk

Table 2: Aspect classification

Aspect Category	Aspect Range (°)	Slope Orientation	Environmental Characteristics
Flat	-1.0	90° to the sky	Minimal influence on solar radiation and microclimate
North	0.0 – 22.5	North	Reduced solar exposure; higher moisture retention
Northeast	22.5 – 67.5	Northeast	Moderate solar exposure; relatively humid conditions
East	67.5 – 112.5	East	Receives morning sunlight; moderate moisture levels
Southeast	112.5 – 157.5	Southeast	Increased solar exposure; moderate drying effect
South	157.5 – 202.5	South	High solar exposure, drier conditions, and higher erosion potential
Southwest	202.5 – 247.5	Southwest	Strong afternoon sunlight; elevated erosion susceptibility
West	247.5 – 292.5	West	Receives intense afternoon sunlight; relatively dry
Northwest	292.5 – 337.5	Northwest	Reduced solar exposure; cooler and more humid
North	337.5 – 360.0	North	Lowest solar exposure; high moisture retention

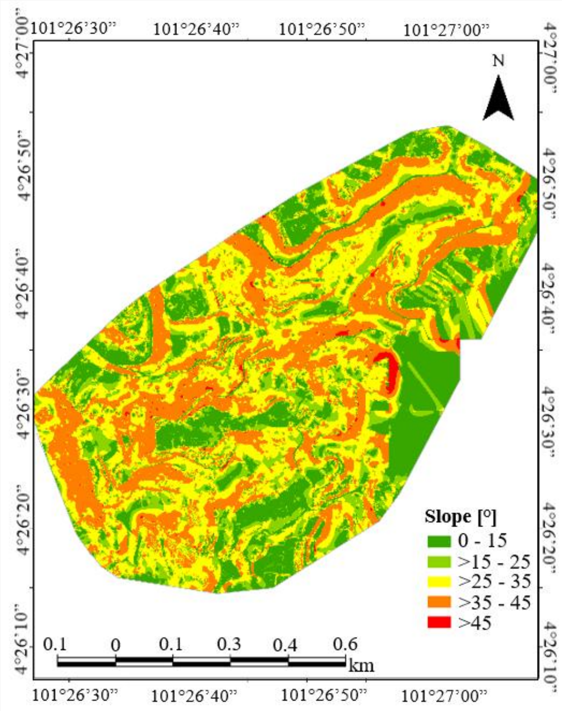

Figure 4: Slope map of Lojing Highland, Kelantan, Malaysia

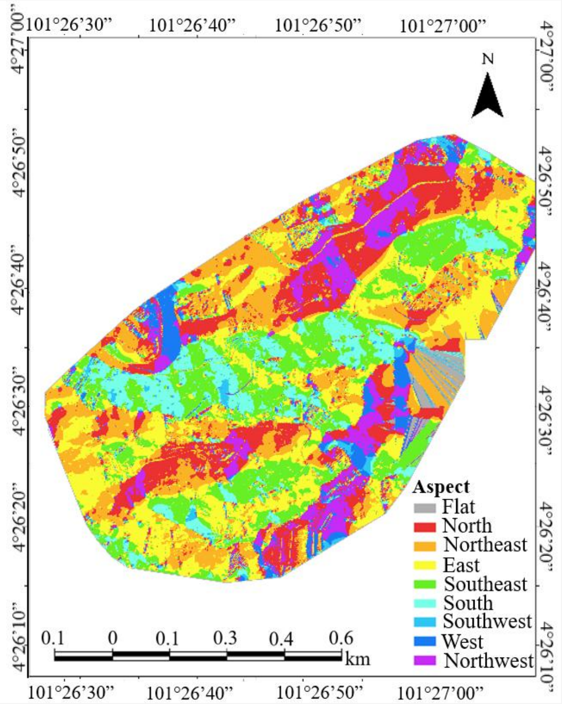

Figure 5: Aspect map of Lojing Highland, Kelantan, Malaysia

Areas with north-facing slopes tend to be more humid due to reduced exposure to direct sunlight, while southern slopes are drier and are more prone to erosion if vegetation cover is insufficient. The spatial distribution of aspect classes is illustrated in Figure 5. The combination of slope-aspect analysis through the Combine tool in ArcGIS Pro enables a more comprehensive assessment of risk zones. As a result, areas with a slope exceeding 45° and facing south or southwest show a higher potential for erosion and slope instability than other areas. The results of this analysis are beneficial for land-use planning, environmental conservation, and disaster mitigation. Meanwhile, the elevation determines the slope's magnitude. Mountain areas with high elevations typically have steeper slopes than lowland areas. An accuracy assessment was conducted in this study to verify the accuracy of geospatial data derived from UAV image processing and digital elevation models (DEMs). This assessment of accuracy is important to ensure that the results of slope mapping and soil erosion analysis are accurate and reliable. Additionally, areas mapped for erosion using GIS analysis are compared with field observations to verify the analysis results. Spatial correlation techniques are used to measure the extent to which erosion locations identified on maps correspond to physically observed erosion areas. Visualization through maps and statistical charts can clarify the spatial distribution of topographical features, aiding in informed decision-making. Figure 6 shows the elevation map, which was classified into five categories ranging from very low to very high elevation to maintain consistency with the slope classification used in the analysis. A weighted overlay technique was applied to integrate slope, land use, aspect, and elevation factors. All input rasters were standardized to a common integer scale prior to overlay analysis. The erosion susceptibility map is shown in Figure 7 below.

4. Discussion

The integration of UAV-based photogrammetry and GIS analysis in this study has yielded a comprehensive understanding of how topographical features, particularly slope, aspect, and elevation, influence soil erosion in the Lojing Highland. These findings align with prior research, affirming that topography is a dominant factor in erosion processes in upland agricultural areas. The high-resolution outputs from UAV imagery and DEM processing have not only enhanced spatial accuracy but also enabled the detailed recognition of erosion patterns, which is often difficult to achieve through conventional field-based surveys.

4.1 The Role of Slope in Erosion Dynamics

Slope inclination is among the most significant topographic factors influencing soil erosion. The results indicate that areas with slopes greater than 15° are particularly vulnerable, consistent with studies by [20], which reported similar thresholds in Southeast Asian contexts. The steeper the slope, the greater the gravitational pull acting on soil particles, which leads to higher runoff velocity and reduced water infiltration. The categorization of slopes into five classes (ranging from 0% to 8% and from 45% to 100%) enables effective identification of areas prone to erosion. Areas with slopes exceeding 45% were observed to be the most critical, often exhibiting exposed soils and signs of sediment displacement. This finding is consistent with research by [14] and [21]. This reinforces the need for physical interventions such as terracing or slope reinforcement in high-risk zones. The slope risk maps (Figure 6) guide targeted bioengineering, such as vetiver grass hedgerows on slopes of 25–45%, as successfully implemented in Thailand's Chiang Mai [22].

4.2 Aspect Orientation and Microclimate Influence

Aspect, or the directional orientation of slopes, also plays a crucial role in modulating erosion processes. In the Lojing Highland, south-facing slopes showed greater erosion than north-facing slopes, as reported by [23] and [13]. This can be attributed to increased solar radiation on southern aspects, leading to higher evapotranspiration rates, reduced soil moisture, and, consequently, weaker vegetation cover. Vegetation is a key barrier against erosion, as it enhances soil cohesion and reduces the direct impact of raindrops on the soil.

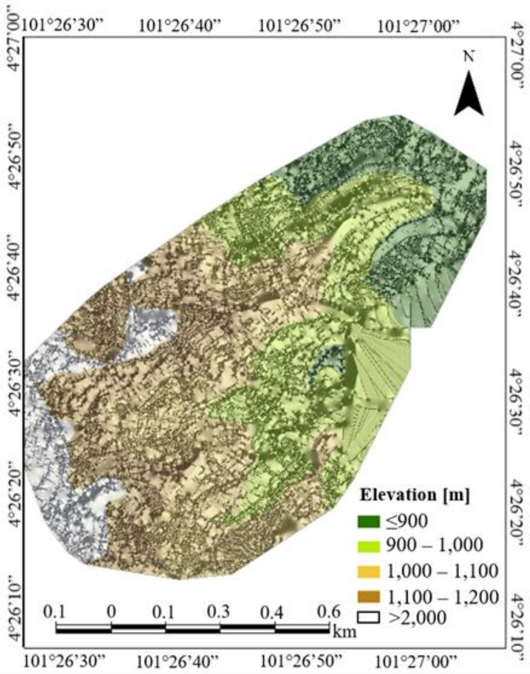

Figure 6: Elevation map of Lojing, Kelantan, Malaysia

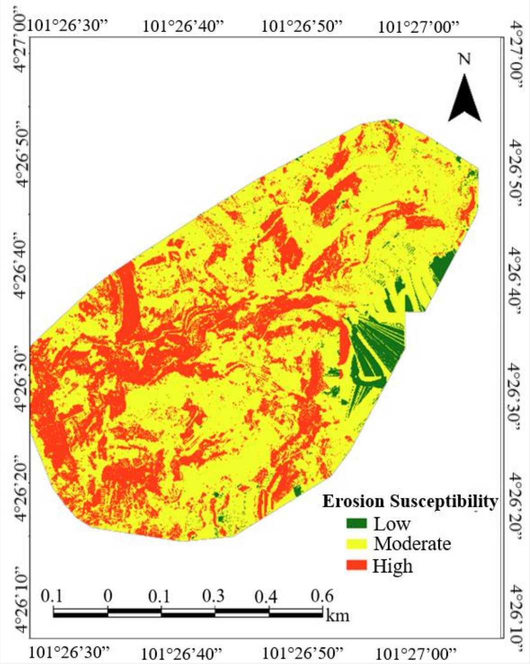

Figure 7: Slope erosion susceptibility of Lojing, Kelantan, Malaysia

The aspect map derived in this study enabled the classification of the terrain into ten directional categories, which, when combined with slope analysis, pinpointed high-risk erosion zones, particularly those that are both steep and south-facing. These findings can inform targeted conservation efforts, such as vegetation replanting or mulching on slopes prone to erosion [24].

4.3 Elevation Impact and Terrain Characteristics

Elevation affects the length and steepness of slopes, thereby increasing the risk of erosion. Longer and steeper slopes tend to occur at higher elevations, which increases the erosive force of water runoff. Elevation data in the Lojing research area revealed that areas above 900 meters exhibited more pronounced erosion indicators, particularly when combined with steep slope gradients [9]. This pattern is essential for comprehending the vertical distribution of erosion and indicates that elevation affects slope stability even though it is not a direct cause of erosion. Furthermore, different erosion patterns were also observed in lower-elevation regions that had undergone artificial alterations, such as terracing or deforestation, indicating that the topographic effect is further modulated by human land use [25].

4.4 Spatial Accuracy and Validation of Erosion Patterns

A robust accuracy assessment technique supports the methodological rigor of this study. As indicated by [21] and [26], the spatial accuracy of UAV-derived orthophotos and DEMs was validated using Ground Control Points (GCPs) and Root Mean Square Error (RMSE) analysis. The consistency between GIS, identified erosion sites, and field observations further confirmed the accuracy of the spatial results. This work quantitatively demonstrates how topographic characteristics influence erosion patterns using spatial correlation and zonal statistics. This methodological approach is especially useful in high-altitude agricultural landscapes where ground surveys are limited by rough terrain. These results support the robustness of geospatial validation in complicated environments, as demonstrated by [25], who reported a GIS-field correlation accuracy of over 85% in comparable erosion investigations in Selangor.

4.5 Implications for Sustainable Agricultural Management

The study's conclusions have significant implications for sustainable agriculture and land-use planning. Policymakers and local authorities can create mitigation plans suited to terrain conditions by locating erosion hotspots using topographic criteria. For example, reforestation can be prioritized in areas with steep, south-facing slopes, whereas contour farming or vegetative buffer strips may be more advantageous in regions with moderate slopes. The Cameron Highlands have implemented contour farming, which has been shown to enhance output by 35% [13][22] and [27]. To enable preventive actions, the GIS technologies employed in this study provide an efficient means of tracking changes in land stability over time. With this strategy, the long-term costs associated with infrastructure damage and land degradation from erosion can be significantly reduced.

4.6 Contribution to Geospatial and Environmental Research

By demonstrating an approach to erosion assessment in developing-country contexts that is affordable, scalable, and easily accessible, this study contributes to the growing field of geospatial applications in environmental monitoring. UAV and GIS technologies provide a feasible alternative in regions where conventional ground surveys are impractical due to resource constraints or large geographical areas. The combined slope-aspect-elevation analysis and statistical validation, which improves the interpretive capacity of geographical data, are innovative. Additionally, using open and commercial software, such as ArcGIS Pro and Agisoft Metashape, demonstrates a transferable approach that researchers and practitioners can utilize elsewhere.

5. Conclusion

In conclusion, this study offers a comprehensive understanding of the topographical impact on soil erosion in the agricultural areas of the Lojing Highland, using geospatial technologies such as UAVs and GIS. The study's results indicate that topographical factors, including slope, elevation, and aspect, significantly influence soil erosion, which in turn affects soil stability and agricultural productivity. Slopes greater than 15° (15-25%) are highly susceptible to erosion, while slopes greater than 45% are at high risk due to rapid surface flow and low water absorption. South-facing slopes experience a higher rate of erosion than north-facing slopes due to exposure to sunlight and loss of vegetation cover. In addition, altitude affects erosion indirectly by increasing slope, especially in areas above 900m, where monsoon rains accelerate soil loss. Additionally, using data processing software, detailed soil-erosion maps have been generated, enabling more accurate identification of high-risk areas. While UAV-GIS provided high-resolution data, the dynamics of the monsoon season and UAV battery constraints may affect long-term monitoring. Future studies could integrate multi-temporal datasets. The recommendations presented in this study can serve as a reference for designing mitigation measures to reduce soil erosion, including intercropping systems, cover cropping, and the installation of erosion control structures. Overall, the high-tech approach employed in this study highlights the potential for systematic and efficient soil erosion monitoring, thereby contributing to more sustainable soil resource management in highland regions, such as the Lojing Highland.

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