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Erosion Assessment of Slope Failure: A Case Study of UniMAP Pauh Campus

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Abstract

Erosional slope failures pose significant risks to infrastructure, ecosystems, and human safety, particularly in humid tropical regions where steep terrain and intense rainfall coincide. This study investigates erosion and its influence on slope stability at the UniMAP Pauh Campus through an integrated geotechnical and hydrological approach. Field surveys, soil sampling, and laboratory analyses were conducted to characterise soil profiles and evaluate erosion susceptibility using two established indicators, the ROM Scale for soil erodibility and the ROSE Index for rainfall erosivity. Key parameters, including slope gradient, soil texture, vegetation cover, drainage, rainfall intensity, and land-use patterns, were systematically examined across three representative slopes. Results indicate that Slope 1 exhibits very high erodibility (ROM = 10.1) due to its sandy texture and minimal clay content, while Slopes 2 and 3 show high erodibility (ROM = 4.4 and 7.9) under comparable rainfall conditions. The recorded ROSE values from 2021 to 2023 (6842.40, 5469.92, and 6475.05 tonne·m^2 ha^{-1} hr^{-1}) reflect a persistently moderate erosive climate. These findings suggest that variations in soil composition and compaction, rather than rainfall intensity alone, are the primary drivers of erosion across the study area. Targeted mitigation measures are recommended, including vegetation reinforcement on Slope 1, enhanced drainage and contour realignment on Slope 2, and bio-geotextile stabilization on Slope 3. The study provides a site-specific framework for managing campus slope erosion and contributes to broader efforts toward sustainable, climate-resilient slope management in tropical institutional landscape.

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1. Introduction

In Malaysia, slope erosion remains a pressing environmental issue intensified by heavy monsoonal rainfall, deforestation, and expanding urbanisation. These factors weaken soil structures and increase surface runoff, heightening the likelihood of landslides, as witnessed in events such as those in Bukit Antarabangsa and Genting Highlands. Government agencies, including JMG and JKR, advocate for proactive measures such as early warning systems and regular slope assessments.

At the institutional level, tools such as the ROM Scale and the ROSE Index enable localised evaluations of soil and rainfall characteristics, supporting evidence-based erosion risk management. Integrating academic research into these frameworks allows campuses to serve as practical models for sustainable slope practices and disaster resilience. The UniMAP Pauh Campus, situated within undulating terrain, experiences recurring erosion that threatens slope stability and campus infrastructure. Variations in gradient, soil composition, and vegetation cover complicate erosion, particularly as construction and development alter the natural landscape. Therefore, this study aims to investigate the physical and geotechnical properties of the campus slopes using the ROM Scale and the ROSE Index to establish correlations between soil characteristics and erosion potential. The resulting insights will inform targeted preventive strategies for safer, more sustainable slope management on campus and comparable settings.

2. Literature Review

2.1 Slope Erosion

Slope erosion in Malaysia is a critical environmental concern, intensified by high monsoonal rainfall and rapid urbanisation. Heavy rain saturates weak tropical soils, while deforestation and development reduce vegetation cover, increasing runoff and landslide risks, especially in hilly regions like the Cameron Highlands and the Klang Valley. These events threaten ecosystems, infrastructure, and lives. Recent slope failures in Bukit Antarabangsa and Genting Highlands highlight the consequences of poor drainage and slope management. Agencies such as the Department of Minerals and Geoscience Malaysia (JMG) and the Public Works Department (JKR) emphasise the need for early warning systems and regular assessments. Within institutions such as UniMAP, tools like the ROM scale and ROSE index offer site-specific assessments of erosion risk. These contribute to national slope hazard mitigation efforts by providing localised data and practical solutions. Integrating academic research with policy frameworks ensures that campuses can act as testbeds for sustainable slope management practices, helping to safeguard vulnerable landscapes across the country.

The complexity of assessing slope erosion lies in the interplay among multiple contributing factors, including rainfall intensity, slope gradient, soil composition, vegetation cover, land-use changes, and drainage conditions. In Malaysia, the high annual rainfall, particularly during the monsoon seasons, exacerbates erosion, while deforestation and construction activities further destabilise slopes by stripping protective vegetation and altering natural drainage patterns. Prominent historical incidents, such as the 1993 Highland Towers collapse in Selangor, which tragically claimed 48 lives due to soil saturation and poor slope management and the more recent events like the 2022 Batang Kali landslide, underscore the devastating consequences of uncontrolled erosion and slope instability.

A comprehensive literature review has been conducted to establish the theoretical and empirical foundation for the study. It explores the causes of slope erosion and failure, geotechnical and hydrological influences, and key assessment tools like RUSLE, the ROM scale, and the ROSE index. The review emphasises the impact of climate change on erosion risks and identifies research gaps, particularly in localised institutional contexts. These gaps justify the focus on UniMAP Pauh Campus, where site-specific erosion analysis using established indices and soil properties will inform effective slope management and mitigation strategies tailored to the campus environment.

2.2 Factors Influencing Slope Stability

Slope stability is governed by a complex interplay of natural and anthropogenic factors, particularly in tropical regions like Malaysia. One of the primary natural factors is rainfall intensity and duration, which significantly influences slope hydrology. In tropical climates, prolonged and intense rainfall can increase pore-water pressure in the soil, reduce matric suction, and consequently lower shear strength, making slopes more prone to failure [1]. Saturated soil conditions also promote seepage forces that destabilise slopes, particularly in residual soils common in hilly Malaysian terrains.

Soil properties play a crucial role in determining the strength and erodibility of a slope. Parameters such as grain size distribution, plasticity, cohesion, permeability, and unit weight affect the soil's ability to resist shear stress. Cohesive soils like clay may appear stable when dry but can become highly unstable when saturated, whereas sandy soils, though well-drained, are susceptible to rapid erosion in the absence of vegetation cover [2]. Poorly graded soils with low cohesion and high permeability tend to have lower resistance to surface runoff and

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internal erosion. The slope gradient or inclination angle directly influences the gravitational forces acting on the slope material. Steeper slopes exert greater downslope stress, reducing the safety factor and increasing the likelihood of failure [3]. Even small increases in slope angle can significantly affect stability, especially in the absence of counteracting stabilising forces such as vegetation or engineered structures. Vegetation cover is another critical factor contributing to slope stability through mechanical and hydrological mechanisms. Plant roots reinforce the soil matrix and improve shear strength, while foliage reduces the velocity of surface runoff and limits raindrop impact, thereby reducing erosion [4]. The removal of vegetation due to deforestation or construction disrupts this natural reinforcement, leaving slopes vulnerable to erosion and failure.

Land uses and human activities such as urban development, road construction, and agricultural expansion further exacerbate slope instability. These activities often involve the removal of topsoil, regrading of land, and alteration of natural drainage paths, which can trigger or accelerate slope failures [5]. Poorly managed development practices in steep terrain have been widely recognised as contributing factors to many slope failures across Malaysia, including urbanised areas such as Penang and Selangor. Lastly, drainage conditions significantly influence the hydro-mechanical behaviour of slopes. Inadequate or blocked drainage systems lead to water accumulation, increasing soil weight and reducing its shear strength. Efficient surface and subsurface drainage systems are therefore essential in preventing water build-up and maintaining slope stability [6]. Understanding these factors is essential for assessing slope stability and designing effective erosion and landslide mitigation strategies, especially in environments subjected to extreme weather events and rapid land-use changes.

2.3 The ROM Scale and ROSE Index

The ROM scale and the ROSE index are widely used to assess soil erosion. The ROM Scale classifies soil susceptibility to erosion through compositional analysis, distinguishing levels of erodibility based on the relative proportions of sand, silt, and clay. The ROSE index measures rainfall erosivity, which reflects the kinetic energy of rainfall in detaching soil particles. When applied jointly, both indices provide an integrated framework for evaluating and interpreting the erosion potential of slope systems. In Malaysia, where soil erosion is a significant concern due to heavy rainfall and rapid urbanisation, the ROM scale and the ROSE index have been increasingly used to assess soil erodibility and rainfall erosivity across regions, particularly in areas with sloped topography. The ROM scale categorises soil erodibility into distinct levels based on empirical data, and the ROSE index assesses the erosive potential of rainfall, with categories defined as shown in Table 1.

Table 1 *ROM scale and ROSE index categories*

ROM scale	ROSE index
Low: ROM < 1.5	Low: ROSE index < 5,000 MJ·mm/(ha·h)
Moderate: 1.5 ≤ ROM < 4.0	Moderate: 5,000 ≤ ROSE index< 10,000 MJ·mm/(ha·h)
High: 4.0 ≤ ROM < 8.0	High: 10,000 ≤ ROSE index < 15,000 MJ·mm/(ha·h)
Very High: 8.0 ≤ ROM < 12.0	Very High: 15,000 ≤ ROSE index < 20,000 MJ·mm/(ha·h)
Critical: ROM ≥ 12.0	Critical: ROSE index ≥ 20,000 MJ·mm/(ha·h)

Erosion risk assessments using the ROM scale and the ROSE index are vital in hilly regions such as Fraser's Hill, Genting Highlands, and Cameron Highlands. In Crocker Range Park, Sabah, ROSE values of 15,282.2–35,401.6 MJ·mm/(ha·h) indicate "very high" to "critical" risk levels. Clay-rich soils and intense rainfall heighten the risks of erosion and landslides, affecting agriculture and infrastructure. These indices guide effective land management for sustainable development in vulnerable areas. The primary objective of this study is to evaluate erosion risk on campus slopes using two established indices: the ROM Scale and the ROSE Index. The ROM Scale assesses soil erodibility based on particle composition (sand, silt, and clay), while the ROSE Index measures rainfall erosivity, reflecting the kinetic energy of rainfall to dislodge soil. Together, they provide a comprehensive framework for understanding erosion potential by integrating both soil vulnerability and rainfall impact. By applying these tools alongside field and laboratory data, the study not only quantifies erosion risk but also aims to inform best practices for slope stabilisation and campus safety.

3. Research Methods

This section presents a field- and laboratory-based methodology for assessing slope erosion and stability at the UniMAP Pauh Campus using the ROM and ROSE indices. The methodological approach integrates comprehensive site surveys, detailed soil sampling, and systematic slope profiling to capture critical data reflecting the physical and environmental conditions of the study area. Soil samples were analysed for texture, moisture, density, permeability, and organic content to understand their influence on erosion susceptibility. Additionally, rainfall data spanning multiple years was collected to compute the ROSE index and evaluate erosive forces. Considering

geotechnical properties with climatic variables, this methodology ensures a holistic understanding of erosion dynamics and provides a sound basis for proposing targeted and effective slope stabilisation and soil conservation strategies.

3.1 Site Selection

Three slope locations (Slopes 1, 2, and 3) within the UniMAP Pauh Campus were selected based on preliminary site reconnaissance and the presence of visible erosion features. Each site exhibits distinct geomorphological characteristics, vegetation cover, and evidence of surface runoff, as visually documented in Fig. 1.

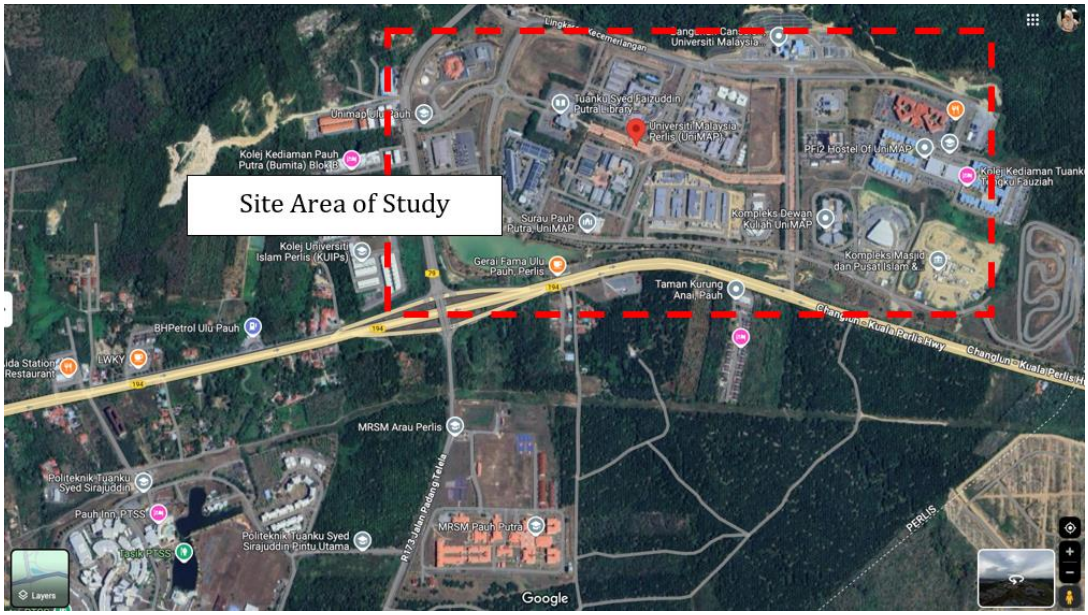


Fig. 1 *Site location*

Three slopes within UniMAP Pauh Campus were examined for erosion characteristics. As shown in Fig. 2 and Fig. 3, Slope 1, near the Jabatan Pembangunan office, shows severe surface erosion, sparse vegetation, and rill formations. Slope 2, by the Chancellery Building parking lot, has moderate vegetation with visible soil displacement and steep gradients. Slope 3, along the main road to student housing, exhibits sheet erosion, minimal ground cover, and sediment buildup, indicating poor soil structure and a high risk of erosion. These observations highlight varying degrees of slope vulnerability requiring targeted management interventions.

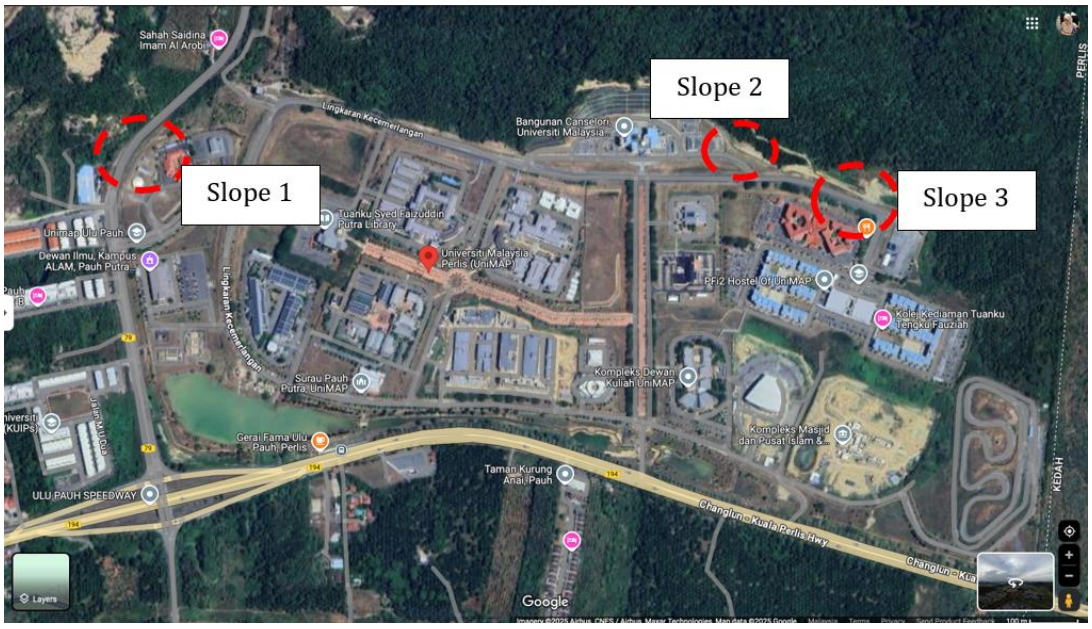


Fig. 2 *Slope locations in UniMAP Pauh Campus*

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Fig. 3(a) illustrates Slope 1, characterised by a gentle 40° gradient and homogeneous soil composition, serving as the baseline for stability comparisons. Fig. 3(b) presents Slope 2, featuring an intermediate steepness of 50° with vegetation cover. In contrast, Fig. 3(c) showcases Slope 3, a near-vertical profile incorporating critical features, e.g., no retaining walls or simulated rainfall channels to assess failure mechanisms under extreme conditions. Collectively, these figures highlight progressive variation in slope parameters, enabling systematic analysis of the study in terms of shear strength, hydrological impact, or mitigation efficacy. These photographic observations provide qualitative evidence that complements the quantitative analysis conducted through soil sampling and erosion index evaluation. The variation in erosion severity and site conditions across the three locations supports a comprehensive understanding of slope behaviour within the campus.



(a) **(b)**



(c)

Fig. 3 *Illustration of the three slope variations analysed in this study (a) Slope 1; (b) Slope 2; and (c) Slope 3*

3.2 In-situ Mackintosh Probe

Field investigations were conducted across three eroded slope sites within UniMAP Pauh Campus to evaluate subsurface soil strength and compaction variability. The selection of sampling locations was based on visible signs of erosion, including surface rills, exposed roots, and sediment accumulation zones, ensuring representative data collection from high-risk areas. Disturbed and undisturbed soil samples were extracted using a hand auger at depths of 0–50 cm, capturing variations in soil strata influenced by erosion. These samples were subsequently transported to the laboratory for further analysis of particle-size distribution, moisture content, organic matter composition, and bulk density, a key parameter governing slope stability.

To complement the laboratory data, an in-situ strength assessment was performed using the Mackintosh Probe Test**,** a cost-effective and rapid method for evaluating subsurface soil resistance. The test involved driving a conical-tipped probe (30° apex angle, 20 mm diameter) into the ground using a standardised 4.5 kg hammer dropped from a fixed height of 300 mm. The penetration resistance was recorded as the number of blows required to achieve successive 30 cm increments, providing a semi-quantitative index of soil density and firmness. Higher blow counts indicated denser, more compacted layers, while lower values correlated with weaker, erosion-prone strata. Spatial variability was accounted for by conducting tests at 2 m intervals along transects parallel to the slope contours.

To contextualise soil strength data, historical rainfall records (2021–2023) from the nearest meteorological station were analysed. Parameters such as cumulative precipitation, storm duration, and intensity were integrated to compute the Rainfall Erosivity (ROSE) Index**,** which quantifies rainfall's erosive potential. This dual approach, which combines Mackintosh Probe data with rainfall erosivity, enabled a holistic assessment of slope vulnerability to hydraulic forces.

3.3 Laboratory Testing

Laboratory analyses focused on quantifying soil properties that directly influence erodibility and slope failure mechanisms**.** Sieve analysis (performed in accordance with ASTM D6913) was employed to determine the grain size distribution of coarse particles (>75 μm), while the hydrometer method (ASTM D7928) characterised clay (<2 μm) and silt (2–75 μm) fractions. These tests revealed critical trends where slopes with higher clay content exhibited greater cohesion, while moisture content (oven-drying method, ASTM D2216) and organic matter (loss on ignition, ASTM D2974) were measured to assess their roles in binding soil particles and mitigating erosion. Bulk density (core method, ASTM D2937) further indicated compaction levels, with lower values (<1.4 g/cm^3) suggesting porous, easily transportable soils. Rainfall data processing emphasised event-specific erosivity**.** Using the Modified Fourier Index, ROSE values were derived from metrics such as the total kinetic energy of storms and peak 30-minute intensity, both of which are critical drivers of splash erosion and overland flow. For instance, a ROSE value exceeding 500 MJ·mm/(ha·hr·year) signalled high erosion risk, necessitating correlation with soil test results.

3.4 Data Processing and Evaluation

The ROM scale was applied to classify site-specific erosion potential based on laboratory-derived soil properties. Soils were ranked from Class I (low erodibility: high clay, low silt) to Class V (very high erodibility: sandy loam, low cohesion), with results cross-referenced against Mackintosh Probe blow counts. For example, slopes with ROM Class IV–V and blow counts <10 blows/30 cm were flagged as critical.

Concurrently, ROSE Index values categorised rainfall aggressiveness, with thresholds aligned to FAO (Food and Agriculture Organisation of the United Nations) guidelines, which are widely recognised international standards for evaluating rainfall erosivity and its impact on soil loss**.** By superimposing ROM and ROSE datasets, erosion risk matrices were generated for each slope (e.g., high ROSE + high ROM = imminent instability). Statistical tools (e.g., Pearson correlation) identified significant relationships, such as between blow counts and clay content ($r = 0.82$, $p < 0.05$). Interpretation prioritised actionable insights: Slope 1 has a low-risk designation (ROM II, ROSE 300), justifying minimal intervention, whereas Slope 3 has extreme scores (ROM V, ROSE 700), demanding urgent mitigation (e.g., terracing or vegetation). This integrative methodology not only clarified current stability but also projected long-term vulnerability under climate-driven rainfall intensification.

4. Results & Discussion

4.1 Mackintosh Probe Test Results

Results from the Mackintosh Probe Test demonstrated notable differences in subsurface strength among the three slopes, which directly affect their resistance to erosion. Slope 1 exhibited high blow counts (>25 blows/30 cm), indicative of dense compaction and high load-bearing capacity. While such compaction typically indicates stability, the low infiltration capacity of these soils exacerbates surface runoff during rainfall events. This aligns with previous research findings [7], which noted that compacted soils with poor permeability amplify hydraulic erosion, particularly on steep gradients. The paradox of high strength but high erosion risk in Slope 1 underscores the importance of balancing compaction with drainage efficiency in slope management.

In contrast, Slope 2 demonstrated moderate blow counts (15–20 blows/30 cm), reflecting a transitional soil structure with partial compaction. This intermediate state allows better infiltration than Slope 1 but remains susceptible to particle detachment under high-intensity rainfall due to insufficient cohesion. The correlation between moderate blow counts (15–20 blows/30 cm) and observed rill erosion aligns with previous research findings [8], which noted that semi-compacted soils exhibit transitional erosion modes due to insufficient cohesive strength. Similarly, previous studies [9], [10] highlighted that partial compaction can lead to selective particle detachment during high-intensity rainfall. Slope 3, with alarmingly low blow counts (<10 blows/30 cm), confirmed the presence of soft, weakly bonded soils. These conditions, often associated with high silt or organic content, facilitate rapid soil detachment and shallow landslides, as documented in tropical regions with similar hydrogeological settings. The probe data correlated with visual observations of slumping and sediment accumulation at the slope toe, validating the need for immediate stabilisation measures such as bioengineering or geotextile reinforcement.

4.2 Soil Classification and Erodibility (ROM Scale)

The analysis using the ROM scale provided further clarity on soil erodibility at each slope. A summary of the soil composition and corresponding erodibility classifications is presented in Table 2. The evaluation classified Slope 1 as having a very high erodibility index, despite its well-compacted nature. This paradox can be explained by the soil's texture and composition, which are predominantly sandy and have low clay content. Sandy soils have large

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particles with minimal cohesion, which facilitates rapid detachment and transport under runoff, especially when combined with compacted surfaces that limit infiltration.

In contrast, Slope 2, with its moderately compacted and more balanced texture, demonstrated high but comparatively lower erodibility. Its intermediate structure offers marginal resistance, but without cohesive clay content or protective vegetation, it remains at risk during intense rain events. Slope 3, despite being the least compacted, recorded a high-to-moderate ROM value. Its low density contributes to easy erosion, but the presence of finer particles such as silt or clay may provide a minimal degree of cohesion that tempers the overall erosion rate, though still insufficient for long-term slope stability.

Table 2 *Summary of soil compositions and erodibility classifications*

Slope	Sand (%)	Silt (%)	Clay (%)	ROM Scale	Erodibility Category
1	14.8	2.4	0.85	10.1	Very High
2	28.1	8.5	4.1	4.4	High
3	7.3	2.8	0.6	7.9	High

These results underscore the complexity of slope erosion dynamics, where compaction, particle size distribution, and hydrological behaviour interact in multifaceted ways. The findings confirm that soil composition significantly influences ROM outcomes and must be carefully considered in erosion risk assessments. In summary, slopes with high compaction but low cohesion soils (like Slope 1) require improved drainage and surface protection to reduce runoff-induced erosion. Loosely compacted slopes (like Slope 3), on the other hand, demand structural and vegetative reinforcement to prevent collapse under rainfall impact. These insights form a critical foundation for designing targeted, slope-specific erosion mitigation strategies.

4.3 Rainfall Erosivity (ROSE Index)

The analysis of the ROSE index highlights the considerable impact of rainfall characteristics on slope erosion across the UniMAP Pauh Campus. As shown in Table 3, rainfall events over the three-year period (2021–2023) consistently fell within the moderate erosivity category. Despite variations in rainfall intensity, energy, and peak 30-minute intensity (I_{30}), all three years exhibited ROSE index values ranging between 5,400 and 6,800 tonne·m^2/ha·hr, indicating persistent and noteworthy erosive forces.

Table 3 *Results on erosivity index rainfall events over the three-year period (2021–2023)*

Year	Rainfall Intensity (cm/hr)	Rainfall Energy (tonne.m/ha.cm)	I_{30} (cm/hr)	ROSE Index (tonne.m^2/ha/hr)	Category
2021	208.1	416.33	16.4	6842.4	Moderate
2022	214.8	417.55	13.1	5469.9	Moderate
2023	175.8	409.80	15.8	6475.0	Moderate

These findings affirm that rainfall patterns in the study area exert a sustained erosive influence on the slopes, even in the absence of extreme weather events. The relatively stable classification across three consecutive years suggests that erosion risks are not solely episodic but rather chronic, driven by a combination of intense, short-duration storms and cumulative rainfall energy. The consistency of moderate ROSE index values underscores the need for proactive erosion management, particularly on slopes that are already classified as highly erodible by the ROM scale, such as Slope 1. Although the rainfall intensity slightly decreased in 2023, the erosivity index remained comparable to previous years due to high I_{30} values, indicating that short bursts of heavy rain contribute significantly to erosion.

By identifying Slope 1 as both highly erodible and exposed to moderate erosive rainfall, the study reinforces the importance of integrating geotechnical and climatic data in erosion risk assessments. This data-driven approach provides a strategic framework for prioritising interventions, enabling campus planners to focus resources where they will have the greatest impact. Recommended strategies may include installing surface runoff control systems, implementing revegetation programs, and using erosion-resistant soil treatments. In essence, the ROSE index not only quantifies erosivity but also strengthens the argument for climate-resilient slope management, ensuring that both natural and engineered solutions are tailored to the site's long-term environmental dynamics.

4.4 Correlation Between Soil Erodibility and Rainfall Erosivity

The integrated results presented in Table 4 indicate that slope erosion at UniMAP Pauh Campus is predominantly controlled by soil composition and compaction**,** while rainfall serves as a consistent yet secondary influencing factor**.** Slope 1**,** though mechanically strong (> 25 blows / 30 cm), recorded the highest erodibility (ROM = 10.1) because its sandy matrix (14.8 %) contains almost no clay (0.85 %), leaving grains unbound. Under moderate rainfall erosivity (ROSE ≈ 5400–6800 tonne·m^2 / ha·hr) and high short-burst intensities (I_{30} ≈ 16 cm hr^{-1}), runoff scours the surface, illustrating that compaction without permeability control accelerates erosion rather than prevents it. The absence of binding agents allows runoff to easily transport loose particles, particularly during high-intensity rainfall events. This aligns with established erosion models [10], [11], which emphasise that sandy, low-clay soils exhibit minimal resistance to shear forces from runoff.

Table 4 *Integrated analysis of soil strength, erodibility and rainfall erosivity at UniMAP Pauh Campus*

Slope	Mackintosh Probe (blows/ 30 cm)	ROM Value	Erodibility Class	ROSE Index from 2021-2023 (tonne·m^2/ha·hr)	Erosivity Category	Remarks
1	>25	10.1	Very High	5469.9 – 6842.4	Moderate	High compaction with poor infiltration; severe surface runoff, particle detachment
2	15–20	4.4	High		Moderate	Transitional soil; partial infiltration but selective erosion under high rainfall
3	<10	7.9	High		Moderate	Loose structure, very low cohesion; prone to slumping and sediment transport

In contrast, Slope 2 demonstrates a transitional behaviour. Its more balanced texture (28.1% sand, 4.1% clay) and moderate compaction result in a lower ROM (4.4) compared to Slope 1, reflecting marginally better cohesion. However, the moderate ROSE index values still pose a significant risk, as the intermediate structure permits partial infiltration while remaining vulnerable to particle selectivity during heavy rain [8]. The 2023 data (I30 = 15.8 cm/hr) illustrate how even soils with modest clay content can experience erosion when compaction is insufficient to stabilise aggregates. Slope 3 exhibits the weakest structure (<10 blows/30 cm) and a low clay content (0.6%), resulting in high erodibility (ROM = 7.9) despite similar rainfall energy. Its silty-sand texture cannot withstand even moderate erosive forces, producing visible slumping and sediment accumulation downslope. The steady ROSE index trends observed from 2021 to 2023 indicate that intrinsic soil characteristics exert greater control on erosion intensity than year-to-year rainfall variation. This underscores the need for targeted mitigation; for instance, Slope 1 requires surface protection to reduce runoff velocity, while Slope 3 demands structural reinforcement to compensate for its low density. Together, these findings highlight the non-linear relationship between soil composition, compaction, and hydrological forces, reinforcing the importance of site-specific erosion management strategies.

In practice, each slope at UniMAP Pauh Campus requires a carefully tailored mitigation approach based on its soil behaviour and erosion characteristics. Slope 1**,** which exhibits high compaction and very high erodibility, should be reinforced by installing surface armouring and interceptor drains to reduce runoff velocity and prevent direct particle detachment during rainfall. For Slope 2, a more balanced but moderately cohesive profile, the focus should be on enhancing vegetative cover and improving contour alignment to increase surface roughness and promote infiltration while minimising rill formation. Meanwhile, Slope 3**,** characterised by loose, silty sand with minimal clay content, requires the use of bio-geotextiles or light-retaining systems to strengthen its weak structure and prevent sedimentation at the slope toe. Implementing such site-adapted measures can mitigate immediate erosion threats while promoting a durable and sustainable slope management system that integrates engineering measures with ecological stabilisation practices. Collectively, the results reinforce the need for site-specific**,** climate-resilient erosion-control strategies that integrate geotechnical measures with ecological rehabilitation to safeguard the UniMAP campus landscape.

5. Conclusion and Recommendations

The assessment of slope erosion dynamics at UniMAP Pauh Campus highlights the critical interplay between soil composition, compaction, and rainfall erosivity in determining erosion vulnerability. Among the three slopes analysed, Slope 1 emerges as the most susceptible due to its very high erodibility (ROM = 10.1), driven by its sand-

dominated texture (14.8%) and negligible clay content (0.85%). This composition results in minimal cohesive strength, rendering the slope highly prone to particle detachment even under moderate rainfall erosivity (ROSE index: 5,400–6,800 tonne·m^2/ha·hr). The absence of binding agents allows runoff to easily dislodge and transport loose particles, particularly during high-intensity rainfall events, such as the 2021 peak 30-minute intensity (I30I30 = 16.4 cm/hr). These observations are consistent with classical erosion models [10], [11], which show that sandy soils with low clay content offer weak resistance to runoff-induced shear stresses.

Slope 2, while less erodible (ROM = 4.4) due to its balanced texture (28.1% sand, 4.1% clay), remains at risk during intense rainfall. Its transitional structure permits partial infiltration but fails to fully stabilise aggregates, leaving it vulnerable to selective particle removal [8]. Slope 3, though loosely compacted, exhibits high erodibility (ROM = 7.9) due to its extremely low clay content (0.6%), which undermines slope stability despite moderate rainfall conditions. Collectively, these results underscore that soil properties rather than rainfall variability are the primary determinants of erosion severity across the campus.

To address these risks, the study proposes a multifaceted erosion management strategy tailored to the specific needs of each slope, including vegetative stabilisation for high-risk slopes, enhanced drainage systems, structural interventions for critical areas, and long-term monitoring and adaptive management. The study's recommendations align with global best practices for sustainable slope management, such as the UN Sustainable Development Goals (SDG 15: Life on Land) and Malaysia's National Slope Master Plan (NSMP). By integrating nature-based solutions (e.g., vegetation) with engineered systems (e.g., drainage), the campus can achieve cost-effective, environmentally friendly erosion control. Moreover, these measures will safeguard infrastructure, including buildings, roads, and utilities, from erosion-related damage, ensuring long-term operational resilience.

The UniMAP Pauh Campus slopes exemplify how soil texture-driven erodibility can amplify erosion risks even under moderate rainfall. Slope 1's extreme vulnerability demands immediate action, while Slopes 2 and 3 require targeted stabilisation to prevent future degradation. By adopting a hybrid approach that combines vegetation, drainage improvements, and structural reinforcements, the campus can mitigate erosion while promoting ecological sustainability. This strategy not only addresses current risks but also provides a scalable model for other hilly regions facing similar challenges. Future research could explore the role of microbial biofilms in enhancing soil cohesion or conduct a cost-benefit analysis of different mitigation techniques to further refine these recommendations.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Nor Faizah Bawadi;* ***Data collection:*** *Ahmad Ilham Mat Zakri, Nurul Syazana, Ahmad Faizal Mansor;* ***Analysis and interpretation of results:*** *Nor Faizah Bawadi, Ahmad Ilham Mat Zakri, Nurul Syazana Zaidi, Agil Fitri Handayani;* ***Draft manuscript preparation:*** *Nor Faizah Bawadi, Nurliza Rahim, Masyitah Md Nujid. All authors reviewed the results and approved the final version of the manuscript.*

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