

Experimental Study of Sediment Detachment Capacity by Overland Flow Using Hydrodynamic Parameters

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Manuscript received January 5, 2026; revised February 23, 2026; accepted May 13, 2026; published October 23, 2026.

Abstract—Sediment detachment by overland flow is a critical process in soil erosion, influencing land degradation, sediment transport, and water quality. This study aims to evaluate the relationship between flow rate, slope gradient, and hydrodynamic parameters on the sediment detachment capacity and to develop an empirical model to estimate sediment detachment capacity based on a multifactor effect. An experiment was conducted using a flume channel to test soil samples with various flow rates ($6 \text{ L} \cdot \text{min}^{-1}$, $10 \text{ L} \cdot \text{min}^{-1}$, and $14 \text{ L} \cdot \text{min}^{-1}$), slope gradients (4° , 8° , and 12°), and soil cover (bare and vegetative). The results indicated that bare soil exhibits a significantly higher sediment detachment capacity than vegetative soil across all tested hydrodynamic parameters, including flow velocity, shear stress, unit stream power, and root parameters. A multifactorial mathematical model was developed to estimate soil detachment capacity based on hydrodynamic parameters for both bare and vegetative soil. The model showed varying degrees of predictive accuracy, with the vegetative samples ($R^2 = 0.4173$; $\text{RMSE} = 0.0041$) performing better than the bare soil samples ($R^2 = 0.1138$; $\text{RMSE} = 0.0133$), where the low R^2 reflects the high stochasticity of detachment on unprotected surfaces. Based on correlation analysis and regression, shear stress, unit stream power, and root density were identified as the most significant predictors of soil detachment capacity in the study area. Overall, the study findings provide insight into better soil conservation practices that minimize soil erosion, leading to improved water sources.

Keywords—sediment detachment capacity, hydrodynamic parameters, overland flow, multifactor analysis, soil erosion

I. INTRODUCTION

Soil erosion remains a significant environmental challenge, impacting agricultural productivity, water quality, and ecosystem stability. A critical phase of this process is sediment detachment, where soil particles are mobilized from the surface matrix by the hydraulic forces of overland flow. Previous studies have demonstrated that steeper slopes and higher flow velocities generally enhance soil detachment capacity by increasing the kinetic energy available to overcome cohesive forces [1]. Under these conditions, hydrodynamic characteristics, specifically mean flow depth and velocity, are decisive factors, as higher values represent a greater potential for detachment. Furthermore, disturbed soils typically exhibit significantly higher detachment rates than undisturbed silt; the degradation of soil structure reduces critical shear stress, thereby increasing the susceptibility of loose particles to mobilization [2]. The ability of overland flow to detach sediment is influenced by several hydrodynamic factors, including flow velocity, shear stress, stream power, and unit stream power [3]. These parameters play a dual role: they serve both as the forces driving particle

detachment and as variables that determine transport capacity. Hydrodynamic processes further affect soil water dynamics and the rate of soil erosion on slopes. Therefore, when modeling soil erosion across hilly agricultural landscapes, it is essential to incorporate specific hydrodynamic parameters, namely flow velocity, shear stress, and unit stream power, to accurately capture the detachment and transport processes [4].

II. LITERATURE REVIEW

Hydrodynamic parameters are fundamental components in the investigation of water systems, and the analysis of hydraulic systems is perhaps fundamental in fluid mechanics and hydraulic engineering. A recent literature review suggested that the sediment detachment capacity, known as D_c , depends mainly on the hydraulic properties of the overland flow [5]. These include the type of predictions that employ both hydraulic and topographical features to calculate sediment detachment capacity containing slope gradient and flow rate. However, some research pointed out that sediment detachment capacity will be more related to shear stress rather than other hydraulic variables for certain soil types [6]. Flow velocity is an essential hydrodynamic characteristic defining sediment removal in overland flow. Research has shown that with an increase in flow velocity, the detachment capacity of the soil also increases and as such, this aspect plays a very crucial role in erosion [7]. Root parameters such as root biomass, also one of the hydrodynamic parameters, clearly lead to a reduction in soil detachment capacity [8].

Despite extensive research on erosion mechanics, the complex interactions between hydraulic forces and tropical soil reinforcement remain under-explored. This gap is particularly evident in high-risk residential areas in Malaysia, such as Kemensah Heights, where the specific characteristics of tropical silty sand (42% sand, 28% silt) are not fully accounted for in existing frameworks. Consequently, the present study investigates sediment detachment capacity under overland flow, with a specific focus on quantifying the relationship between hydrodynamic parameters, including flow velocity, shear stress, and unit discharge, and the stabilizing effects of root density. By developing a localized empirical model that integrates biological factors with key hydrodynamic drivers, such as unit stream power and shear stress, this research provides a calibrated tool for regional disaster mitigation. These findings offer a more robust understanding of how hydrodynamic conditions govern sediment detachment, ultimately informing improved soil

conservation measures that minimize erosion and protect critical water resources.

III. MATERIALS AND METHODS

A. Study Area

The soil samples were taken and collected in Bukit Gemilang, National Defence University of Malaysia (NDUM), and a residential area in Hulu Kelang at Kemensah Heights. The soil characteristics around Bukit Gemilang and the residential area in Kemensah Heights are ideal for this study as it has the same properties. Both soil samples from these two places have similar characteristics of soil type, which are silty sand with 42% sand and 28% silt. The foundational rock in the region consists of phyllite, granite, and schist formations [9]. The reason why Kemensah Heights was chosen in the first place is that there was a landslide occurring in the area in September 2018 [10].

B. Soil Samples

The soil sample was collected using a rectangular steel mold with dimensions of 30 cm × 15 cm × 10.5 cm. The process of taking soil samples from the places stated earlier is to hold the mold into the soil until the soil fills about three-quarters of the mold, and pull out the mold while maintaining the condition of the soil that is held without losing its shape. For this research, two types of soil cover that will be used are bare and vegetative. Bare and vegetative soil covers are appropriately incorporated in the research on sediment detachment by overland flow because they assist in identifying the effects of the soil cover on the process. The samples should be tested within 3 days to make sure their moisture content and soil parameters match the soil on the site [11].

C. Flume Channel Setup

A rectangular flume channel with dimensions of 146 cm × 14 cm × 12 cm is used to run the soil samples. The setup allowed for precise adjustments of slope gradients (4°, 8°, and 12°) and volumetric flow rates (6, 10, and 14 L·min⁻¹). In case there is any outlier data, the experiment will be run three times for each sample to find the average data.

D. Experimental Design

For this experiment, the uniform flow rates used are 6 L·min⁻¹, 10 L·min⁻¹ and 14 L·min⁻¹ and the slope gradients used are 4°, 8°, and 12°. The soil samples with a soil bed height of 10 cm, a length of 30 cm, and a width of 15 cm were placed 30 cm from the end of the flume channel [11], and it will run until the sediment mass loss decrement reaches 50% or until 2 h of maximum time to run the sample if it does not decrease in half. The remaining sediment will be dried in the oven for 24 h to dry out the extra water in the sample, since it is the weight of the sediment that is important. The weight of the sediment will be measured before and after running the experiment. This experiment must be repeated three times to find the average data which makes each experiment need eighteen soil samples to run for both bare and vegetative soil cover. Tables 1 and 2 shows the relationship between the flow rates and slope gradients with soil cover for both bare and vegetative cover.

Table 1. Relationship between flow rates and slope gradients

Bare Soil Cover			
Slope (θ)	Flow rate, Q (L·min ⁻¹)		
	6	10	14
θ ₁	Sample 1	Sample 2	Sample 3
θ ₂	Sample 4	Sample 5	Sample 6
θ ₃	Sample 7	Sample 8	Sample 9

Table 2. Relationship between flow rates and slope gradients

Vegetative Soil Cover			
Slope (θ)	Flow rate, Q (L·min ⁻¹)		
	6	10	14
θ ₁	Sample 10	Sample 11	Sample 12
θ ₂	Sample 13	Sample 14	Sample 15
θ ₃	Sample 16	Sample 17	Sample 18

E. Hydrodynamic Parameters

The data collected from the experiment can be processed to calculate the hydrodynamic parameters with sediment detachment capacity. The hydrodynamic parameters used in this research will be flow velocity, flow depth, shear stress, unit stream power, and the root parameter. The flow depth, h (m), was taken while the experiment is running. The reading will be taken three times to find the average flow depth for hydrodynamic parameters. The flow velocity can be calculated using Eq. (1).

$$v = Q/A \quad (1)$$

where v is flow velocity (m s⁻¹), Q is volumetric flow rate (m³·s⁻¹) and A is cross-sectional area of flume (m²). The shear stress was calculated using Eq. (2).

$$\tau = \rho ghS \quad (2)$$

where τ is the shear stress (Pa), ρ is the density of water (kg·m⁻³), g is the acceleration due to gravity (m·s⁻²), h is the flow depth (m), and S represents the sine of the slope angle ($\sin\theta$) or the hydraulic gradient, which is dimensionless. Another hydrodynamic parameter that can be measured is the unit stream power using the formula stated in Eq. (3).

$$\omega = \tau v = \rho ghS \frac{Q}{A} \quad (3)$$

where ω is unit stream power (Watt·m⁻²), τ is the shear stress (Pa), v is flow velocity (m·s⁻¹), ρ is density of water (kg·m⁻³), g is acceleration due to gravity (m·s⁻²), h is flow depth (m), S is the sine of the slope angle ($\sin\theta$) (dimensionless), Q is volumetric flow rate (m³·s⁻¹), and A is cross-sectional area of flume (m²). The root parameter can be determined using the following Eq. (4).

$$RD = M_D/V \quad (4)$$

where RD is root density (g cm⁻³), M_D is dry living root mass (g), and V is the volume of the sample (cm³).

F. Sediment Detachment Capacity

A total of 54 samples were considered, and the sediment transport rate was computed for each one using Eq. (5) [11].

$$D_c = \frac{W_o - W_a}{A \times t} \quad (5)$$

where D_c is the sediment detachment capacity ($\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), W_o is the dry weight of the sample before (kg), W_a is the dry weight of the sample after scouring (kg), A is the scouring area (m^2), and t is the scouring time (s).

G. Statistical Analysis and Multifactor Mathematical Model Development

A statistical analysis was performed to determine how much sediment transport capacity correlates with different hydrodynamic parameters. Relationships between sediment detachment capacity and hydrodynamic parameters were found using a fitted polynomial curve. The polynomial functions were used to capture non-linear trends; further research with more complex non-linear or machine-learning models may be required to better characterize these interactions. The mathematical model was developed with multifactor based on the coefficient of determination (R^2) of the relationship between each of the hydrodynamic parameters and sediment detachment capacity. The equations were validated using R^2 and the Root Mean Square Error (RMSE) value to evaluate the performance of the developed multifactor mathematical models.

IV. RESULT AND DISCUSSION

A. Effects of Different Flow Rates and Slopes on Sediment Detachment Capacity

As illustrated in Fig. 1, the sediment detachment capacity across slopes of 4° , 8° , and 12° varied significantly between the two soil cover types, confirming that slope steepness is a primary driver in erosion measurement [12]. Fig. 2 presents the detachment capacity across varying flow rates (6, 10, and $14 \text{ L} \cdot \text{min}^{-1}$), showing that bare soil consistently yielded higher sediment detachment rates compared to vegetative samples. These results indicate that both sediment detachment and transport capacity increase proportionally with slope gradient and flow velocity [13]. The higher sediment yield from bare soil is attributed to direct surface exposure to hydraulic shear forces. In contrast, vegetative cover, such as grass, provides a complex root system that enhances soil structural integrity and increases infiltration rates [14]. This biological reinforcement reduces overland flow energy and facilitates subsurface drainage, thereby mitigating the detachment and subsequent transport of soil particles.

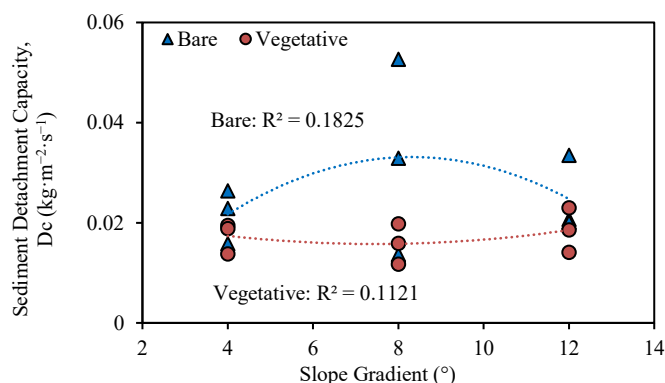


Fig. 1. Sediment detachment capacity as polynomial functions of different slope gradient.

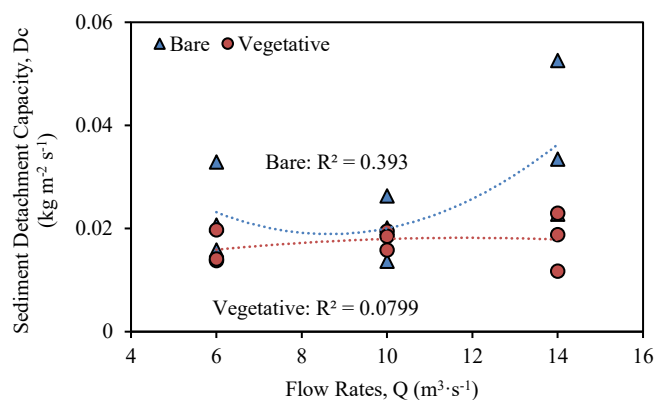


Fig. 2. Sediment detachment capacity as polynomial functions of different flow rates.

B. Response of Sediment Detachment Capacity to Hydrodynamic Parameters

1) Flow velocity

Fig. 3 illustrates the relationship between sediment detachment capacity and flow velocity for both bare and vegetative soil samples. While bare soil followed a predictable quadratic increase in detachment relative to velocity, a polynomial regression analysis indicates a significantly stronger correlation for bare soil ($R^2 = 0.393$) compared to vegetative cover ($R^2 = 0.0799$). This low correlation and the nearly constant detachment rate observed in vegetative samples, marked by a negative quadratic coefficient, suggest that root reinforcement and surface roughness successfully decoupled the direct impact of flow velocity from soil detachment. This statistical trend likely reflects the chaotic nature of turbulent flow around stems and the potential for vegetation to shield the soil surface at specific velocity thresholds. While increased flow velocities typically enhance the dragging force on soil particles, vegetation moderates this erosive energy by acting as a physical shield [1]. By intercepting raindrop impact and increasing surface hydraulic resistance, plants effectively dissipate kinetic energy and improve soil structural integrity through root-binding mechanisms [15].

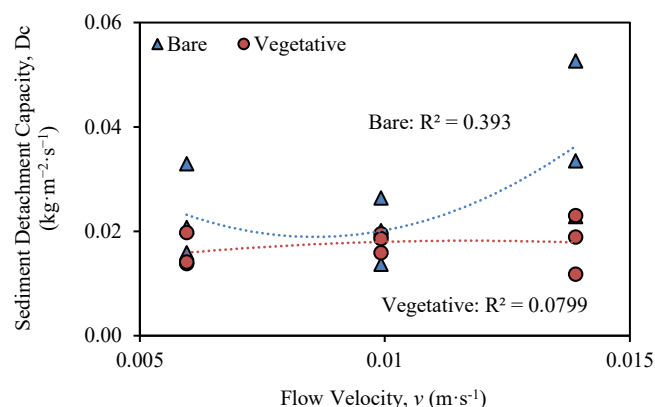


Fig. 3. Sediment detachment capacity as polynomial functions of flow velocity.

2) Flow depth

Fig. 4 illustrates the relationship between sediment detachment capacity and flow depth for both bare and vegetative soil samples using polynomial regression. The results yielded low coefficients of determination for both bare

soil ($R^2 = 0.1615$) and vegetative cover ($R^2 = 0.1168$), indicating that flow depth alone explains a minimal proportion of the variance in detachment capacity. While the trendline for vegetative soil shows a marginal upward trajectory, the bare soil exhibits a nearly stationary pattern, suggesting that detachment rates may be limited by other factors such as soil consolidation or sediment supply. Although increased flow depths typically correlate with higher hydraulic pressure, the presence of vegetation introduces surface roughness that effectively dissipates the energy of the moving water column [1]. The high degree of unexplained variance (low R^2) suggests that in these tropical silty sand samples, detachment is likely governed by more complex interactions between localized turbulence and the root-soil matrix rather than uniform flow depth alone.

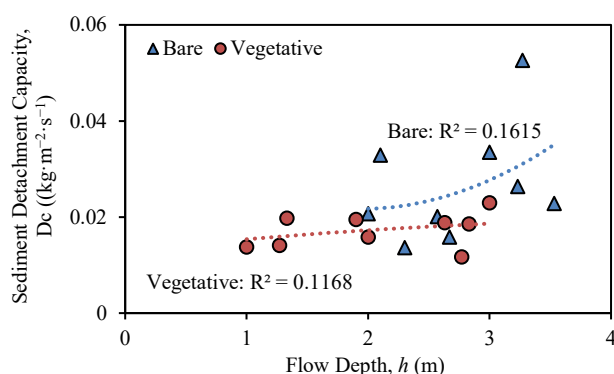


Fig. 4. Sediment detachment capacity as polynomial functions of flow depth.

3) Shear stress

The relationship between sediment detachment capacity and shear stress for both bare and vegetative soil covers is illustrated in Fig. 5. The regression analysis shows that bare soil samples consistently exhibit higher detachment rates compared to vegetative samples, with coefficients of determination (R^2) of 0.1211 and 0.3079, respectively. These results confirm a positive correlation where increased shear stress leads to a higher sediment detachment capacity. In bare soil, the absence of protective elements like plant roots and surface litter leaves soil particles directly exposed to the hydraulic entrainment forces of flowing water. The intensity of this shear stress is a function of flow velocity, depth, and the friction factor [1]. Conversely, vegetation acts as a protective mechanism that mitigates detachment by intercepting hydraulic energy. The root systems provide structural reinforcement by converting a portion of the applied shear stress into tensile resistance within the soil-root matrix. Furthermore, the presence of plant litter increases surface roughness, which effectively reduces the net shear stress reaching the soil surface, thereby enhancing erosion resistance [16].

4) Unit stream power

Fig. 6 illustrates the relationship between sediment detachment capacity and unit stream power for both bare and vegetative soil samples. The regression analysis shows that bare soil consistently exhibits higher detachment rates than vegetative samples, with R^2 values of 0.2591 and 0.2955, respectively. These results indicate that unit stream power, representing the rate of energy dissipation against the soil

surface, is a significant driver of sediment detachment [1]. In bare soil, the lack of surface protection allows for the rapid breakdown of soil aggregates as the hydraulic energy increases. Conversely, the presence of roots and plant litter in the vegetative samples significantly reduces detachment capacity. This mitigation is attributed to the combined effects of increased soil shear strength, enhanced structural stability, and higher infiltration rates, which collectively reduce the net energy available for particle entrainment [17].

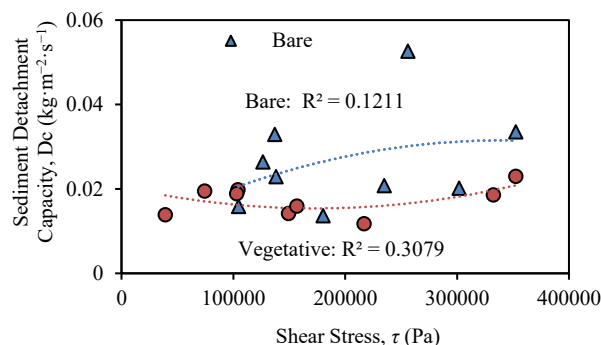


Fig. 5. Sediment detachment capacity as polynomial functions of shear stress.

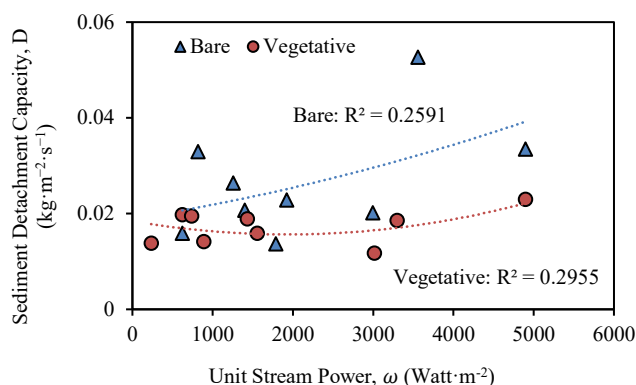


Fig. 6. Sediment detachment capacity as polynomial functions of unit stream power.

5) Root parameter

Fig. 7 illustrates the correlation between sediment detachment capacity and the root mass density parameter.

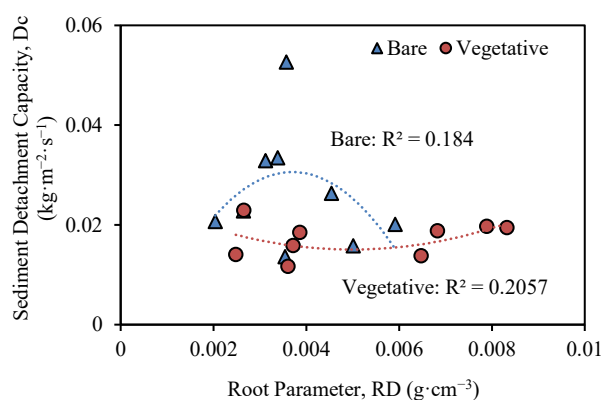


Fig. 7. Sediment detachment capacity as polynomial functions of root parameter.

The regression analysis shows that bare soil samples consistently exhibit higher detachment rates than vegetative samples, with R^2 values of 0.184 and 0.2057, respectively. These results indicate that the presence of a developed root

system provides significant resistance to hydraulic detachment. Specifically, fine roots enhance soil cohesion and structural stability, thereby reducing susceptibility to entrainment by overland flow [18]. In contrast, bare soil lacks this biological reinforcement, making the soil matrix more vulnerable to the kinetic energy of runoff. The stabilization effect is further augmented by root exudates and organic matter, which act as binding agents for soil aggregates [19]. Furthermore, because fine roots possess a high surface-area-to-volume ratio, they maximize contact with soil particles, creating a dense network that anchors the soil and minimizes particle displacement.

C. Regression Results between Sediment Detachment Capacity with Hydrodynamic Parameters

Table 3 summarizes the performance of the polynomial correlations between sediment Detachment capacity (D_c) and various hydrodynamic parameters. The derived equations and their corresponding coefficients of determination (R^2) are presented for both bare and vegetative soil covers. The R^2 values serve as a metric for evaluating the explanatory power of each empirical equation, where values approaching unity indicate a highly dependable relationship.

Table 3. Regression results of sediment detachment capacity and hydrodynamic parameters

Hydrodynamic Parameter	Soil Cover	Equation	R^2
Flow velocity, v ($\text{m} \cdot \text{s}^{-1}$)	Bare	$D_c = 615.33v^2 - 10.551v + 0.0642$	0.3930
	Vegetative	$D_c = -69.512v^2 + 1.6263v + 0.0087$	0.0799
Flow depth, h (m)	Bare	$D_c = 0.0052h^2 - 0.02h + 0.041$	0.1615
	Vegetative	$D_c = -0.0003h^2 + 0.0027h + 0.013$	0.1168
Shear stress, τ (Pa)	Bare	$D_c = -2 \times 10^{-13}\tau^2 + 1 \times 10^{-07}\tau + 0.0087$	0.1211
	Vegetative	$D_c = 2 \times 10^{-13}\tau^2 - 6 \times 10^{-08}\tau + 0.0205$	0.3079
Unit stream power, ω ($\text{Watt} \cdot \text{m}^{-2}$)	Bare	$D_c = 3 \times 10^{-10}\omega^2 + 3 \times 10^{-6}\omega + 0.0189$	0.2591
	Vegetative	$D_c = 7 \times 10^{-10}\omega^2 - 3 \times 10^{-6}\omega + 0.0184$	0.2955
Root Parameter, RD ($\text{g} \cdot \text{cm}^{-3}$)	Bare	$D_c = -3148.1\text{RD}^2 + 23.305\text{RD} - 0.0125$	0.1840
	Vegetative	$D_c = 472.25\text{RD}^2 + 4.7105\text{RD} + 0.0268$	0.2057

In this study, bare soil served as the control treatment where Root Density (RD) is zero. The regression was performed across all treatments to establish a baseline. The resulting equation for bare soil is included in the table for mathematical completeness and to show the intercept of detachment capacity when root influence is absent. Nothing that for bare soil applications, RD is assumed to be zero, effectively reducing the equation to its constant term (0.0125).

However, the relatively low R^2 measurements observed across several parameters, particularly for vegetative samples, reflect the inherent complexity and stochastic nature of the sediment detachment process. These results suggest that while the polynomial functions capture the general trend, the variance is likely influenced by unmeasured variables in the flume environment, such as localized turbulence, soil-root

matrix heterogeneity, and fluctuating infiltration rates [20]. Consequently, these models should be interpreted as localized indicators of detachment trends rather than absolute predictive frameworks.

D. Sediment Detachment Capacity Estimation

1) Predicted soil detachment capacity

Using multivariate regression analysis, a mathematical model was developed to predict sediment detachment capacity based on the interaction of multiple hydrodynamic and biological parameters. Three key variables shear stress, unit stream power, and root density were selected for the model due to their consistently higher coefficients of determination (R^2) and their physical significance in the detachment process. The resulting multifactorial empirical models for bare (baseline of zero, $\text{RD} = 0$) and vegetative soil surfaces are expressed in Eqs. (6) and (7), respectively:

For bare soil cover:

$$D_c = -7.7231 \times 10^{-8}\tau + 8.5908 \times 10^{-6}\omega - 1.9942\text{RD} + 0.0313 \quad (6)$$

For vegetative soil cover:

$$D_c = 3.0332 \times 10^{-8}\tau + 1.4340 \times 10^{-7}\omega + 1.4690\text{RD} + 0.0044 \quad (7)$$

where ω is unit stream power ($\text{Watt} \cdot \text{m}^{-2}$), τ is the shear stress (Pa), and RD is root density ($\text{g} \cdot \text{cm}^{-3}$).

2) Validation on Soil Detachment Capacity

From Fig. 8, the R^2 values for both bare and vegetative correlation between predicted and measured sediment detachment capacity are 0.1138 and 0.4173, respectively. The model performed significantly better for vegetative soil ($R^2 = 0.4173$) compared to bare soil, suggesting that the inclusion of the Root Parameter (RD) provides better explanatory power in vegetated conditions. The bare soil model ($R^2 = 0.1138$) shows a weak correlation, indicating that sediment detachment in bare silty sand is likely influenced by unmeasured variables such as soil cohesion or instantaneous turbulence. The R^2 values indicated high variability in the bare soil samples ($R^2 = 0.1138$). Additionally, the model's predictive accuracy was considered acceptable for localized application given the low error margins (Bare: RMSE = 0.0133; Vegetative: RMSE = 0.0041).

This shows that the mathematical model for predicted sediment detachment capacity was preliminary estimations that require further refinement because the values are small and near to zero.

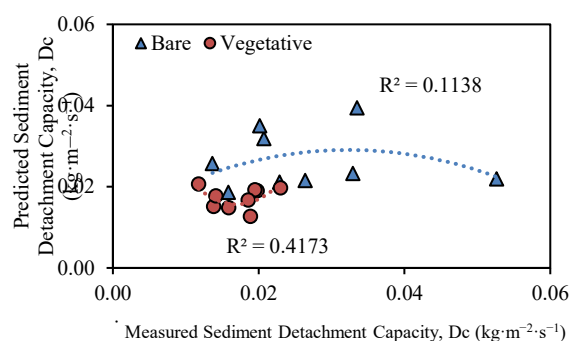


Fig. 8. Comparison between predicted and measured sediment detachment capacity in polynomial functions.

V. CONCLUSION

The study identifies a clear correlation between overland flow hydrodynamic parameters and sediment detachment capacity. Experimental results indicate that bare surfaces experience significantly higher sediment detachment compared to vegetated surfaces, provides hydraulic resistance and root reinforcement. This confirms that vegetative cover is far more effective than exposed soil at mitigating erosion, even over short durations.

While new multifactor mathematical models were developed from the data, the calculated R^2 values were consistently near zero. This indicates that the selected independent variables explain only a minimal proportion of the variance in the dependent variable, suggesting that other factors may be influencing the detachment process. Specifically, the model performed significantly better for vegetative soil ($R^2 = 0.4173$) than for bare soil ($R^2 = 0.1138$). This suggests that the inclusion of the root density (RD) parameter provides superior explanatory power compared to hydrodynamic forces alone.

Ideally, as R^2 approaches 1.0, the model's predictive power increases. However, in this experiment, the calculated R^2 values were lower than anticipated, likely due to the inherent complexity of predicting sediment detachment in disturbed silt soils. This suggests that while the model has a low absolute error, indicating high precision in its predictions, the independent variables still fail to account for the overall variance in the detachment process.

Interestingly, despite the low R^2 , the Root Mean Square Error (RMSE) remained low (Bare: 0.0133; Vegetative: 0.0041). This suggests that while the model has a low absolute error, indicating high precision in its specific predictions, the independent variables still fail to account for the overall variance in the detachment process. Consequently, these models should be viewed as localized indicators of detachment trends in tropical regions like Kemensah Heights rather than absolute predictive frameworks.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

A.Q.A.K. conducted the research and wrote the paper; Z.S. analyzed the data, wrote, reviewed and edited the paper; J.J. reviewed and edited the paper; N.A. reviewed and edited the paper; L.S.S. reviewed and edited the paper; all authors had approved the final version.

FUNDING

This research was funded by the National Defence University of Malaysia under the scheme of Short Term Grant with project code J0437-UPNM/GPJP/2025/TK/18. The authors also gratefully acknowledge the support of the National Defence University of Malaysia under the scheme of Self Fund with project code UPNM/2024/SF/TK/5.

ACKNOWLEDGMENT

The authors acknowledge the National Defence University of Malaysia for the approved fund which makes this important research viable and effective.

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