Modeling of Sediment Transport Capacity by Overland Flow Using Multifactorial Analysis: Flume Experiment

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Abstract. Sediment transport capacity (STC) is critical in predicting soil erosion under overland flow, especially on sloped and vegetated terrains. This study aims to assess the influence of hydraulic parameters (flow velocity, depth, shear stress, unit stream power) and root mass density on STC and to develop an empirical model through controlled flume experiments. Experiments were conducted under bare and vegetated surface conditions with varying slopes. STC was calculated from sediment mass collected at the flume outlet. Flow properties were derived using standard hydraulic equations, while root mass density was obtained from soil volume and dried root mass. Multiple linear regression was used to analyze variable contributions to STC. Unit stream power showed the strongest positive influence on STC ($\beta = 0.689$), while root mass density had a negative effect ($\beta = -0.235$), suggesting a stabilizing role. However, none of the predictors were statistically significant ($p > 0.05$). Visual trends indicated lower sediment transport in vegetated conditions, especially at higher velocities and slopes. The findings support integrating both hydraulic energy and vegetation factors into erosion prediction models and offer a base for improving land management in erosion-prone areas.

1 Introduction

Soil erosion driven by overland flow is a global issue with far-reaching environmental consequences, including degradation of land productivity, water pollution, and increased sedimentation in rivers and reservoirs. Climate change and unsustainable land use practices exacerbate these processes, particularly in vulnerable regions. Sediment transport capacity (STC), defined as the maximum amount of sediment that overland flow can carry, serves as a vital indicator in understanding and modeling erosion processes. Despite the existence of numerous models, many fall short in accounting for the combined effects of hydraulic and biophysical variables. Traditional models often focus on individual parameters such as slope gradient or flow velocity, while the interaction between multiple factors, including soil structure, root density, and stream power, remains underexplored.

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To address this gap, this study investigates sediment transport under simulated overland flow using flume experiments. It focuses on quantifying the influence of slope, flow velocity, hydraulic energy, and root mass density on sediment transport capacity.

Flow velocity directly influences sediment entrainment through increased shear forces. [1] demonstrated a positive linear relationship between velocity and STC across various soil types. Slope gradient similarly accelerates overland flow, enhancing sediment transport, although some studies [2] found that discharge often has a stronger effect than slope alone. Hydraulic parameters like shear stress and unit stream power are also critical. [3] reported strong correlations between these parameters and sediment transport, suggesting they be used as key predictors in modeling efforts. Meanwhile, soil properties, including particle size, cohesion, and structure, influence how easily sediment detaches and moves. [4] highlighted that aggregate stability and texture play pivotal roles in modulating STC. Vegetation, particularly root mass density, contributes by increasing surface roughness and anchoring soil, which reduces erosion. [5, 6] found that higher root densities significantly decreased STC, mainly through increased flow resistance and reduced detachment.

Understanding sediment transport capacity (STC) under overland flow is crucial for accurate soil erosion modeling and sustainable land management. Several studies have identified the major influencing factors on STC, including flow velocity, slope gradient, soil properties, hydraulic parameters, and vegetation structure. These factors affect sediment detachment, entrainment, and transport mechanisms either independently or interactively. More recent research has emphasized the interaction between these variables. For instance, studies by [7, 8] explored how slope and vegetation together modify hydraulic dynamics, while others (e.g., [9]) included sediment properties to improve model accuracy. Despite advances, many models still lack integration of these combined effects, underscoring the need for empirical studies like this one.

This literature provides the foundation for evaluating STC in controlled flume settings. It supports the study's methodological choices and underpins the regression modeling approach used to predict sediment transport under variable hydraulic and surface conditions. The objectives of this research are: (1) to examine the relationship between slope, flow conditions, and sediment transport; (2) to evaluate the role of soil and vegetation properties on STC; and (3) to develop a multiple linear regression model for predicting STC based on hydraulic and biophysical inputs. This study provides insights into sediment transport dynamics and supports the refinement of erosion prediction tools for better land and water resource management.

2 Methodology

This study was conducted in three main stages to investigate the factors influencing sediment transport capacity under overland flow. The first stage involved soil sampling from selected slope areas, followed by laboratory preparation, where root parameters such as root mass density and root length density were extracted from oven-dried soil samples. The second stage comprised flume experiments carried out under controlled conditions with varying slope gradients and flow discharges to simulate overland flow. Sediment transport capacity was measured, and key hydraulic parameters including shear stress and stream power were calculated. The final stage involved statistical analysis to determine the relationships between sediment transport capacity, hydraulic forces, and root parameters, and to develop a predictive model for sediment transport across varying conditions.

2.1 Soil sampling

Undisturbed topsoil samples will be collected from Kemensah Heights, Hulu Kelang, Selangor, a residential area. Main reason why this soil was taken is for them to be tested and checked for its the safety and durability of the soil. According to [10], Hulu Kelang has recorded 28 large landslides between 1990 and 2011, making it extremely prone to landslides in Malaysia. According to [11], the findings of the laboratory tests, the residual soil was classified as silty sand with minimal flexibility with sand makes about 42% of its composition, followed by silt (28%), clay (16%), and gravel (14%). Supporting the flume experiments and root analysis carried out in the lab, soil samples were taken from certain slopes with discernible overland flow and different root densities. Because to its steep slope and soil saturation from regular rainfall occurrences, Kemensah Heights has also been classified as a landslide-prone location [12].

A standardized soil corer (30.5 cm diameter × 14.2 cm × 11 cm depth) was used to extract undisturbed soil cores, ensuring consistent volume for comparison across sites. Each core was immediately sealed in airtight plastic bags and labelled according to location, vegetation condition, and slope angle. In total, 36 samples were collected. Samples were transported to the laboratory for further analysis.

2.2 Experimental design

A flume channel experiment involves conducting controlled studies using a specialized channel known as a flume, designed to simulate and analyze the behavior of flowing water in a controlled environment. These experiments are pivotal in fields like hydrology, civil engineering, environmental science, and fluid mechanics. Flumes are constructed with precise dimensions and adjustable slopes to replicate real-world hydraulic conditions. The soil sample was tested in the flume with dimension 146 cm × 14 cm × 12 cm. For each type of sample, the experiment will be run twice to make comparison, in case there will be any outliers data.

2.3 Experimental setup

Experiments were conducted using a laboratory-scale flume with a length of 2 meters and a width of 0.149 meters. A known quantity of soil was applied to the flume surface at varying slope gradients and water flow rates. The flume was subjected to overland flow conditions, simulating both bare and vegetative surfaces. The flow was maintained for a fixed duration (typically 7200 seconds) and the sediment transported by the flow was collected at the outlet for analysis. The experimental setup aimed to replicate surface runoff and sediment detachment under controlled conditions.

2.4 Experimental measurements

2.4.1 Sediment transport capacity (STC)

Sediment Transport Capacity was determined by measuring the mass of eroded soil collected at the flume outlet over a fixed time. The STC (in kg/s·m) was calculated using:

$$D_c = \frac{M}{t \times w} \quad (1)$$

where *M* is the mass of sediment transported (kg), *t* as flow duration (s) and *w* is the width of the flume (m). Flow velocity was estimated based on volumetric discharge and cross-sectional area:

$$v = \frac{Q}{A} = \frac{Q}{h \times w} \quad (2)$$

where Q is the discharge (m^3/s) and h are the flow depth (m). Flow depth was measured manually using a point gauge during steady-state flow. It was averaged across three cross-sectional points for each slope setting. Flow depth serves as a key parameter for hydraulic calculations such as velocity and shear stress [9].

$$h = \frac{y_1 + y_2 + y_3}{3} \quad (3)$$

Shear stress was computed using the standard hydraulic formula:

$$\tau = \rho g R S \quad (4)$$

where ρ = water density (1000 kg/m^3), g = acceleration due to gravity (9.81 m/s^2), R = hydraulic radius ≈ flow depth (m) and S = slope. Meanwhile, Unit stream power (ω) was derived as the product of shear stress and flow velocity:

$$\omega = \tau v \quad (5)$$

All measurements were repeated under varying slope gradients and flow rates. Soil moisture was controlled to maintain consistency, and sediment samples were dried before weighing to ensure accurate mass readings. Data collection and computation followed standardized fluvial geomorphology procedures [1–2]. Root Mass Density (RMD) quantifies the root biomass per unit volume of soil, used to assess vegetation reinforcement effects. It was calculated as:

$$RMD = \frac{W_0 + W_a}{V_S} \quad (6)$$

Where, W_0 = dry weight of sample (g), Wa = dry weight of sample after scouring (g), Vs = soil volume sampled (cm^3). RMD was measured following soil washing and drying procedures outlined by Mu and Fu [4], and it played a critical role in evaluating the vegetative surface's resistance to erosion.

2.4.2 Regression analysis

For data analysis, Statistical Package for the Social Sciences (SPSS) software was employed to provide descriptive analysis and data screening before testing the hypothesis. The software that will be used is SPSS version 30.0 and it is chosen because of its user friendliness features. It was used to analyse the numerical and quantitative data from the flume experiment with the factors being independent A simple linear regression to investigate the relationship between a single independent variable and a dependent variable, simple linear regression is appropriate. Meanwhile, multiple linear regression to examine how multiple factors (e.g., slope, flow discharge, soil properties) collectively influence sediment transport capacity. This analysis will show the relationship between one dependent variable and two or more independent variables, providing an equation to predict the dependent variable.

3 Result and discussion

3.1 Statistical findings

Table 1 shows the result of the multiple regression analysis. Based on the regression analysis using, none of the tested independent variables were statistically significant predictors (all p-values > 0.05). Although none of the variables achieved $p < 0.05$, unit stream power had the highest positive beta value (0.689), suggesting it is the most influential predictor in practical terms.

Several variables exhibited notable directional trends in their influence on sediment transport capacity (STC), despite the lack of statistical significance in most cases. Unit Stream Power had the strongest positive effect ($\beta = +0.689$), indicating that the energy of overland flow remains a key factor in sediment movement, although this relationship was not statistically significant ($p = 0.564$). Shear stress showed a moderate negative effect ($\beta = –0.536$, $p = 0.642$), which may be partly due to its overlapping role with stream power. Root Mass Density demonstrated a moderate negative influence ($\beta = –0.235$) and had the lowest p-value among the predictors ($p = 0.196$), aligning with the expectation that vegetation helps reduce erosion potential. Flow velocity also had a moderate negative coefficient ($\beta = –0.304$), which contrasts with typical physical models and is likely a result of multicollinearity with other variables [13]. Additionally, both slope and flow depth showed weak to moderate negative effects, but these too were statistically non-significant. Despite the lack of statistical significance, the model offers practical insights: variables like stream power and root density show directionally consistent trends with sediment transport theory. The findings suggest that a refined model or larger sample size may better capture these influences. Overall, these trends suggest complex interactions among variables influencing sediment transport.

Table 1. Summary of regression coefficients and interpretations for sediment transport model variables

No.	Variable	B (Unstd.)	Beta (Std.)	p-value	Interpretation
1	Shear Stress (Pa)	–0.001	–0.536	0.642	Moderate negative influence : not statistically significant
2	Unit Stream Power (W/m²)	+0.002	+0.689	0.564	Strongest positive effect; not significant due to high p-value
3	Flow Depth (m)	–0.165	–0.239	0.515	Weak negative effect; not significant
4	Flow Velocity (m/s)	–1.380	–0.304	0.501	Moderate negative effect; opposite to expected direction, not significant
5	Root Mass Density (g/cm³)	–5.46E-5	–0.235	0.196	Moderate negative effect; aligns with theory, lowest p-value (still > 0.05)

3.2 Influence of slope gradient on sediment transport capacity

Figure 1 shows that an increase in slope gradient generally results in a slight increase in sediment transport capacity, but this pattern is inconsistent across different flow rates. At

lower flow rates, the change in sediment transport capacity with increasing slope is nearly flat. This suggests that slope alone does not significantly influence sediment transport capacity unless combined with other dominant factors such as flow velocity. This agrees with the regression result showing a very small and statistically insignificant effect of slope (B = -4.779E-5, p = 0.539).

Across all flow rates, showed minimal variation with slope. At lower flows, slope had negligible impact on sediment transport capacity, while at higher flows, slight increases in slope corresponded with marginally higher sediment transport capacity. This suggests slope alone is not a dominant factor unless coupled with high discharge. These results indicate that slope gradient, within the tested range, may have a limited direct effect on sediment transport capacity. This contradicts traditional assumptions where slope steepness is expected to enhance transport due to increased flow energy. The slightly positive relationship between flow velocity and sediment transport capacity aligns more closely with literature, which generally supports velocity as a key driver of sediment movement [14]. However, the non-significant p-values suggest that either experimental variability or underlying multicollinearity may be masking true effects. Future studies should include a broader range of slope values and flow rates to capture more representative overland flow conditions. Additionally, modeling interactions between slope and velocity could clarify their joint impact on sediment transport.

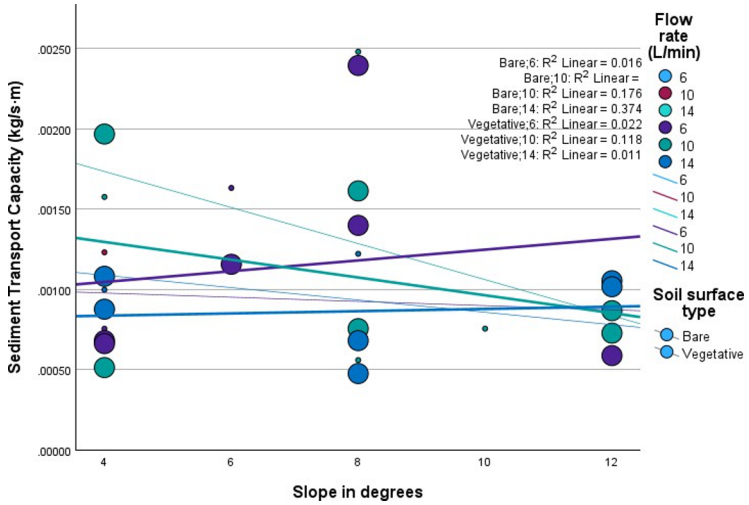

Fig. 1. Relationship between sediment transport capacity (Dc) and slope gradient under different flow rates.

3.3 Influence of soil and hydraulic properties

3.3.1 Flow depth

From Table 1, the flow depth yielded a positive but weak standardized effect (β = 0.313) and a very high p- value (0.720). This suggests that depth may contribute to sediment transport in a supportive role, amplifying the energy of flow when combined with velocity, but it is not a key driver by itself in the tested range. Deeper flows are generally more capable of carrying suspended particles [15]. However, under shallow overland conditions as simulated here, depth variations are limited, and the influence of depth may only be significant when velocity and turbulence thresholds are crossed [15].

Figure 2 shows a clear difference in STC between bare soil and vegetative soil as flow depth increases. Bare soil exhibits higher STC values compared to vegetative soil, particularly at greater flow depths. STC increased with flow depth in both soil types, but bare soil had consistently higher STC. This indicates that vegetation reduced sediment detachment even at deeper flow conditions. This reflects that the presence of vegetation (roots) helps reduce sediment transport capacity by improving soil stability and increasing hydraulic resistance. The regression supports a mild negative effect of flow depth (B = -0.165), although it was not statistically significant (p = 0.515).

3.3.2 Flow velocity

Table 1 shows that, flow velocity had a relatively strong positive standardized coefficient (β = 0.653), with a large unstandardized B value (2354.499). However, its p-value was 0.488, indicating a lack of statistical significance. The correlation was nearly flat (r = –0.030), possibly due to noise in the velocity data or inconsistent energy transfer across trials. Nevertheless, Figure 3 visually showed STC increasing with velocity, especially in bare plots, highlighting its practical importance even if not statistically validated [2, 3].

Flow velocity plays a fundamental role in entraining and transporting sediment, as higher velocities increase the energy of the system. The visual increase in STC with velocity aligns with physical expectations, though the flat correlation suggests velocity must interact with depth and slope to manifest stronger influence statistically [15]. Sediment transport capacity increases with increasing flow velocity, and the increase is more significant in bare soil compared to vegetative soil as shown in the Figure 3. This indicates that bare soil is more susceptible to erosion when the flow velocity increases [15]. Vegetative cover slows down the flow and reduces the kinetic energy involved in sediment transport. Interestingly, the regression result showed a negative coefficient for velocity (B = -1.380), which may be attributed to multicollinearity with stream power and shear stress.

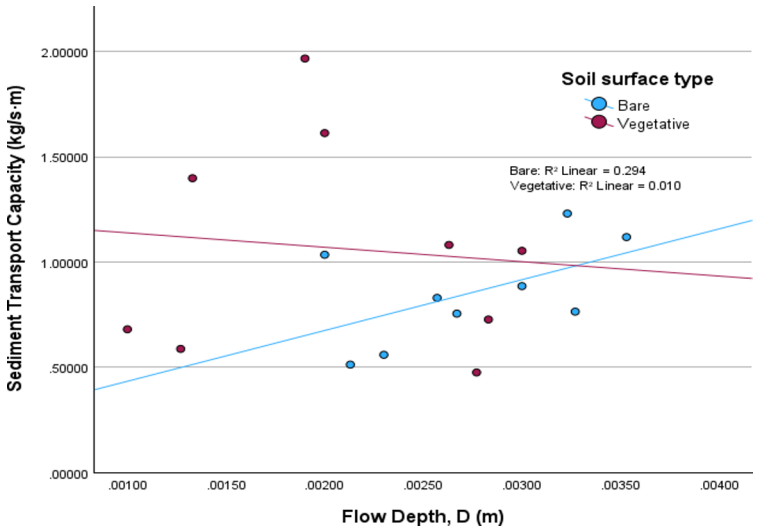

Fig. 2. Comparison of STC and flow depth for bare and vegetative soil conditions.

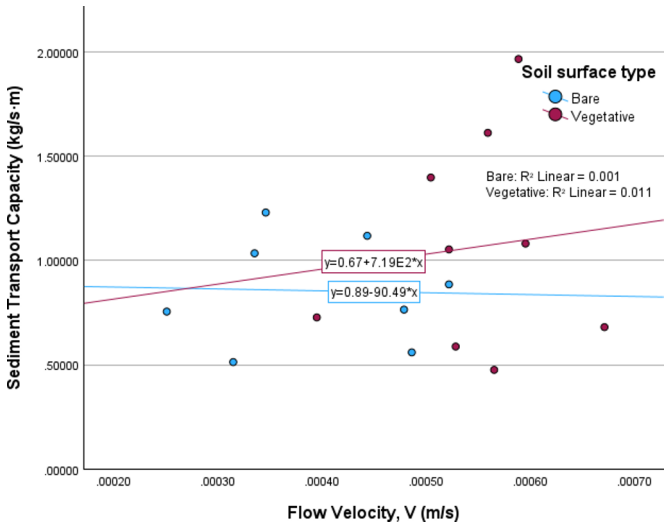

Fig. 3. Effect of flow velocity on sediment transport capacity (STC) for bare and vegetative soils.

3.3.3 Shear stress

Shear stress had a moderately strong standardized coefficient (β = 0.691) and a low unstandardized B (0.650), yet the p-value remained high at 0.763 as stated in Table 1. The correlation was weakly negative (r = –0.191), showing that τ alone does not consistently predict STC in this setting. Visual trends in Figure 4 showed some increase in STC under bare conditions, but it was less apparent with vegetation, suggesting that plant resistance disrupts shear-driven erosion. Although shear stress is a critical force in initiating sediment movement, the inconsistent trend here suggests that in vegetated environments, resistance from roots dampens shear forces [14]. Moreover, overlapping influence with flow velocity and stream power may obscure its standalone impact.

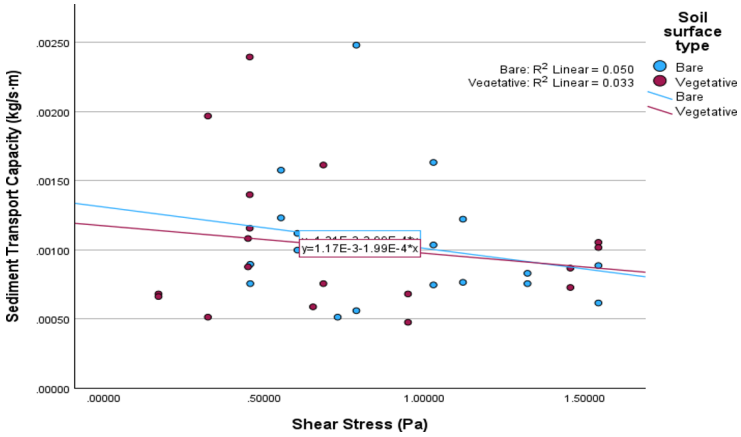

Fig. 4. Relation between shear stress and sediment transport capacity (STC) for bare and vegetative soils.

3.3.4 Unit stream power

Sediment transport capacity increases with increasing flow velocity, and the increase is more significant in bare soil compared to vegetative soil as shown in the Figure 5. This indicates that bare soil is more susceptible to erosion when the flow velocity increases. Vegetative cover slows down the flow and reduces the kinetic energy involved in sediment transport. Interestingly, the regression result showed a negative coefficient for velocity (B = - 1.380), which may be attributed to multicollinearity with stream power and shear stress.

3.4 Root mass density (RMD)

Root mass density (RMD) yielded a moderate negative influence on STC (β = –0.303, B = –0.054) with a p- value of 0.423. The correlation was negative as well (r = –0.229). This supports the hypothesis that vegetation helps stabilize the soil and reduce sediment yield [4,5]. Figure 6 visually confirmed a steady decline in STC with increasing RMD in vegetated plots, reinforcing its role as an erosion buffer.

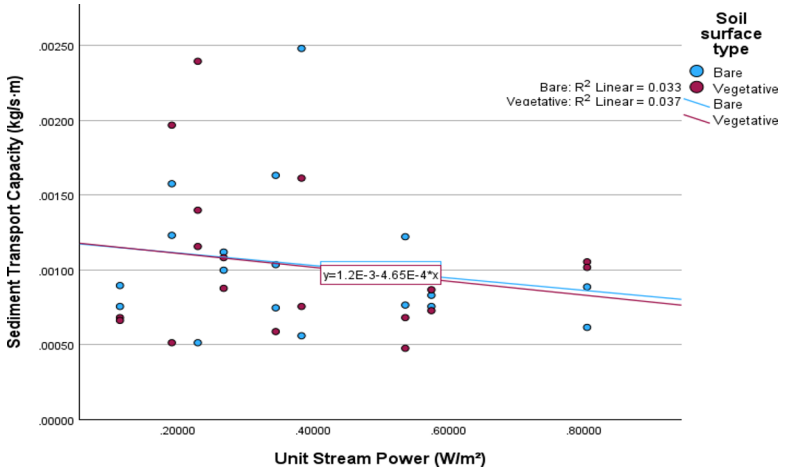

Fig. 5. Comparison of STC and unit stream power between bare and vegetative soil conditions.

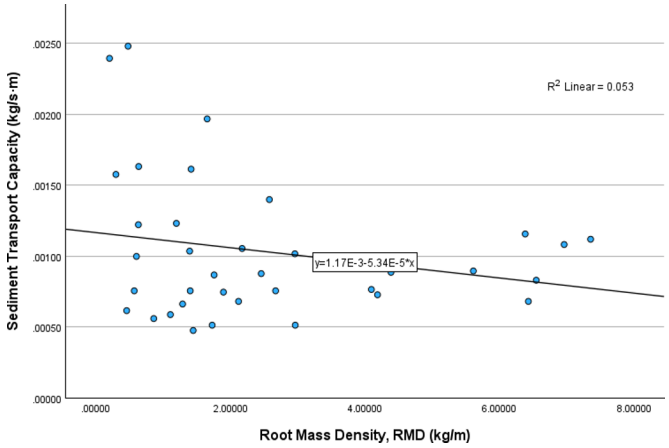

Fig. 6. Influence of root mass density on sediment transport capacity in vegetative soil.

Although not statistically strong, RMD showed a reliable qualitative trend worth incorporating into erosion control strategies. Root systems increase soil cohesion and disrupt flow paths, reducing both detachment and transport of sediment particles. Even with variability, the negative trend seen in both regression and visual data supports the ecological benefit of vegetative cover in reducing erosion [5].

3.5 Regression model summary

Despite its statistical limitations, this equation captures the physical relationships of interest and may serve as a basis for refinement in future studies involving field-scale data or non-linear modeling. The regression model explains multiple interrelated influences on sediment transport capacity. Although none of the predictors reached statistical significance ($p > 0.05$), the standardized coefficients reveal practical insights. Unit Stream Power ($\beta = 0.689$) emerged as the strongest predictor, reinforcing the importance of hydraulic energy as a key driver of erosion. Root Mass Density ($\beta = -0.235$) also showed a consistent and theoretically expected stabilizing effect. The unexpected negative coefficient for flow velocity may be attributed to multicollinearity with stream power and shear stress, which are all derived from velocity and slope [14]. This overlap could obscure the unique contribution of each predictor. The model's intercept and magnitude of coefficients are small, suggesting low overall variance in STC across treatments. These findings contribute to ongoing efforts in quantifying overland flow erosion and provide direction for enhanced process-based modeling as shown in equation below.

$$STC = -0.135 + 0.650\tau - 1.891\omega + 172.541h + 2354.499V - 0.054RMD - 0.010S \quad (7)$$

Equation (7) represents a multiple linear regression model developed to estimate STC, expressed in kilograms per second per meter (kg/s·m). The model incorporates several hydraulic and biophysical variables that influence sediment transport in overland flow conditions. Specifically, STC is a function of shear stress, τ (Pa), unit stream power, ω (W/m^2), flow depth (h), flow velocity, V (m/s), root mass density (RMD) in unit g/cm^3, and slope, S (degrees). Each coefficient in the equation reflects the strength and direction of the variable's effect on STC.

As an initial empirical framework, the regression model is usable for estimating relative trends in controlled environments. It can guide parameter prioritization in future experiments and may be improved with additional data or by incorporating non-linear terms and interaction effects [13]. For field application, recalibration and validation using broader datasets with natural variability would enhance its reliability. Overall, the model is accomplishable, informative, and provides a springboard for more robust sediment transport modeling in hydrological studies.

4 Conclusion

The results demonstrated that vegetated surfaces consistently reduced sediment transport capacity, as evidenced by lower STC values across all parameters compared to bare soil. It was supported with regression models for vegetative soil outperformed those for bare soil, suggesting that vegetation moderates flow behavior more consistently, leading to more predictable sediment transport patterns. These findings are in line with theoretical expectations and reinforce the role of vegetation as a natural erosion control mechanism. Furthermore, unit stream power and flow velocity were the most influential parameters,

especially under vegetated cover, with the highest R^2 values (0.6472 and 0.6471, respectively), indicating strong predictive power.
Despite some non-linear trends and moderate R^2 values, the models developed in this study offer useful empirical tools for erosion prediction and support the integration of vegetation in erosion control strategies.

The multiple regression model developed offers a practical tool for predicting sediment transport based on measurable hydraulic and surface parameters. The figure-based regression analysis further strengthens the model's interpretability by confirming consistent trends across six comparative plots. Despite promising results, this study is limited by its laboratory scale, controlled flow rates, and simplified vegetation structure. Field validation and the inclusion of additional variables such as rainfall intensity, soil cohesion, and root tensile strength are recommended for future studies. Integration with geographic information systems (GIS) and erosion risk mapping may also enhance the model's practical application in environmental planning.

Overall, the findings highlight the importance of robust empirical evidence supporting the inclusion of vegetation and hydraulic energy parameters in erosion prediction models. The regression models developed can serve as a foundation for improving sediment transport predictions in soil conservation and land management planning in erosion-prone landscapes.

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