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Experimental investigation on slope runoff, sediment, and hydraulic parameters under different underlying surface

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Abstract

This study utilizes a rainfall simulator to conduct an experimental investigation of slope and rainfall on various underlying surfaces. This study aimed to determine the relationship between various hydraulic factors and sediment concentration by estimating runoff, sediment concentration generation, and hydraulic parameters on various underlying surfaces. The flow velocity, flow depth, shear stress, and unit stream power are the hydraulic parameters in this experiment. The soil sample will be set up appropriately in the rainfall simulator with a slope of 20^{o} and subjected to a rainfall event for two hours on four trays with various underlying surface types. The rainfall intensity of 10 $Lmin^{-1}$ was designated for the rainfall simulator. Throughout a two-hour period, the runoff flow was collected at intervals of 30, 60, 90, and 120 minutes. The measured sediment concentration using Total Suspended Solid (TSS). Then measurements were conducted of the sediment concentration, runoff discharge, and hydraulic parameters. According to the results, the stream power of the four covers is higher for the dried leaves (0.004606 ms^{-3}), grass cover (0.003274 ms^{-3}), gravel (0.00232 ms^{-3}), and bare soil cover (0.00081 ms^{-3}). But bare soil produces the maximum concentration of sediment and surface runoff, which is then followed by grass, gravel, and leaves. In general, the generation of sediment began with the bare surface, gravel, dry leaves, and grass in descending sequence. Research has shown that rain-induced plant cover can be used as a low-cost strategy to reduce soil erosion on construction slope sites.

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INTRODUCTION

Erosion is the process where soil and rock are removed from the Earth's surface by wind or water flow and then transported and deposited in other locations. Sedimentation is the accumulation of these eroded materials in new locations, such as riverbeds, lakes, or reservoirs. Erosion and sedimentation have significant economic and environmental impacts [1]. Addressing these issues requires sustainable land management practices, such as crop rotation, contour plowing, and maintaining vegetation cover to protect the soil.

Research on erosion and sediment started long ago to improve erosion commonly occurring on a development site [1]. This phenomenon typically occurs in the preliminary stage, which comes before the earthwork phase's structural work starts. Once the ground has been filled and excavated during an earthwork phase, disturbing soil cover will be the main issue if the soil has no top cover [2]. Mitigating erosion early in the construction phase is essential for economic efficiency, environmental protection, regulatory compliance, and long-term sustainability.

Rainfall causes erosion to begin on the upper bank, where it begins to flow at a certain speed and carries the surface-eroding silt down with it. Generally, when excessive sediment flows through a drainage system, the silt settles and reduces the volume of the drainage [3]. In addition, in other circumstances, gets certain point will be reached when rain and silt flowing through the drainage channel at a high velocity get bundled together. Several forms of soil cover, such as bare, grass, leaf, and gravel are effective in solving this problem. Vegetation is regarded as a significant element influencing the rate of soil erosion in most soil erosion models. The relationship between soil erosion rate and coverage under various environmental conditions has been the subject of numerous research, that soil erosion rate decreases either linearly or exponentially with coverage.

The hydraulic factors that are normally employed in simulating detachment rates such as shear stress [4], stream power [5][6], and unit stream power [7][8]. Moreover, it was thought that the sediment would be transported by the flow using the available energy; stream power, or the energy expended per unit of time, may be a significant factor in determining the sediment transport capacity. According to the erosion model's basic runoff transport capacity equation, the shear stress was appropriate for calculating the transport capacity of overland flows. Furthermore, the roles of shear stress and stream power have a greater association with rill detachment rates [4]. Numerous studies found that stream power is a more accurate method for predicting sediment than shear stress [10, 11, 12]. When it comes to soil detachment brought on by shallow flows, shear stress, and flow energy show less association [9]. Additionally, the slope gradient, effective stream power, unit stream power, and discharge are frequently used to depict the flow hydraulics to compute transport capacity.

The transport capacity of overland flows has been predicted to be using a variety of hydraulic variables in soil erosion models. However, the parameter values used to quantify this relationship also vary, primarily due to the usage of different soils and sediments, variations in experiment design, specifically in the range of flow rate and slope steepness, and other poorly controlled conditions like surface roughness and soil properties [12]. Additionally, in order to explain the modes, methods, and processes of slope failure, the majority of studies on texture-contrast soil slopes concentrated mostly on variations in hydraulic and hydrological parameters. Only a small number of studies have examined the differences in runoff and sediment generation processes and mechanisms on the silty sand-covered loess slopes, which need more investigation.

The main aims of this study are to calculate runoff and sediment production, as well as to calculate hydraulic parameters and examine the relationship between these variables on various types of soil covers. Furthermore, other researchers will benefit from the experimental results by receiving the kind value of data of the sediment concentration and hydraulic parameters for modeling work. Moreover, this work provides a complete experimental reference data set that might be used to assess and improve the forecast accuracy of soil erosion models.

MATERIAL AND METHODS

Several components will be included in this chapter such as the experimental setup and material used that had been determined in this study. The Universiti Pertahanan Nasional Malaysia (UPNM) is the location where the study has been done. An investigation using various types of underlying surface runoff, hydraulic parameters, and sediment concentration. This investigation is being conducted in three laboratories. Initially, once the sieve examination is finished, the geotechnical laboratory allows a start of completely distinct aggregate sizes that surpass the sieve's metric linear unit by 1.18 mm and 0.6 mm. The hydrology laboratory is the second. A precipitation apparatus will be used in this laboratory experiment, and general data regarding the production of sediment was gathered and examined using the total suspended solids (TSS) test.

Experimental Soil and Flume Layout

The soil sample that was utilized in this study was collected from a slope area close to a UPNM new development site. Each of the four trays, each measuring 67 cm by 23 cm by 18 cm, has a unique underlying surface. In the centre of the tray shown in Figure 1, a pipe with a diameter of 2.5 cm is cut in half and serves as drainage to collect the surface discharge. On the bottom of the tray, there is another pipe that serves as drainage to collect the infiltration flow.

In order to gather the water flow from the land stream, the outlet is connected to the pipeline [13]. The sample of soil was compacted to replicate the field actual soil conditions. To make sure the sample is saturated before being exposed to rainfall using the rain simulator, it will be allowed to dry in the sun. The soil sample is first weighted for preliminary data and then put through a sieve to obtain the soil profile for further analysis.

Experimental Framework

This study has multiple experiments. The sieve analysis is the first experiment for attaining the soil profile. In addition, the sample must be tested using a rainfall simulator to determine the surface runoff. Furthermore, the rainfall simulator was used to measure the hydraulic parameters. The soil sample was compacted and arranged correctly in the tray in the rainfall simulator. The rainfall event lasts for two hours, and every thirty minutes, surface runoff is collected in separate containers. The TSS involves collecting surface runoff and purifying it using a filtering apparatus. Next, the sample was dried in an oven at 105ºC for an hour. The aim of this test is to remove the water and silt. Thus, the sediment content, Qs (gm³), and runoff discharge, Q (m³s⁻¹) ascertained once the experiment is complete.

Rainfall Simulator

In order to analyze the various rainfall intensities, the Hydrology Laboratory is equipped with a rainfall simulator. This rainfall simulator's dimensions are approximately 2.4 m long by 1.0 m broad by 1.8 m high, and the electric pump. The sieved soil is compacted inside the tray and placed below the rain simulator. In order to collect water that runs off the surface and through the soil, each rectangular tray in the test has a single hole at the top connected to a PVC pipe. This allows the channeled soil to flow into a bucket near the outlet of the tray. After allowing sediment to settle for half an hour following the highest rainfall event, the total runoff was calculated.

The bucket was weighed after being removed from the tray. Subsequently, the sediments gathered at the bottom of every container will be dried until completely dry, at which point they will be weighed once more. For every aggregate size, the data were gathered three times following the highest rainfall event. Measurements and records were made of the sediment production's physical characteristics. During data collection, the slope angle will be changed from 0º to 20º, correspondingly. Figure 2 shows how the sample is set up for a flat surface. A brick is set beneath the tray as a basement to control the incline steepness like in Figure 3. When the incline steepness of θ = 20º, the height of the tray from the brick must be 11.4 cm height.

Figure 1. Arrangement of pipe as drainage

Figure 2. Sample at θ = 0º

Sampling for Runoff and Sediment Concentration

For a duration of two hours, the infiltration and overland flows are recorded every thirty minutes. Water is collected in buckets and changed every 30 minutes. The TSS experiment will be conducted after the collection of samples since sediment contains unfilterable contaminants. The sediment that has been filtered will be dried in an oven at 105ºC for an hour. The sediment concentration, Qs (gm^{-3}), and runoff flow discharge, Q (m^3s^{-1}), can be calculated from the weight of the dried sediment and the water that separates from the sediment.

Figure 3. Sample at $\theta = 20^{\circ}$

Hydraulic Parameters

The flow velocity, v (ms^{-1}), depth flow, D (m), shear stress, τ (Pa), and unit stream power, U (ms^{-1}) are the hydraulic parameters that will be used in this study. The runoff discharge, Q (m^3s^{-1}), might be calculated using (1).

$$v = Q/t \tag{1}$$

Equation (2) is used to determine the sediment concentration, Qs (gm^{-3}), as shown below. The sediment that passed through the TSS test and was dried in the oven is known as the mass of the sediment, m (g), whilst the amount of water collected, V (m^3) depends on the amount of water collected for each soil cover.

$$Q_s = m/V \tag{2}$$

The flow velocity, or v (ms^{-1}), is the most crucial parameter that is frequently used to determine other hydraulic parameters. It is dependent upon the flow discharge and slope gradient. The average flow depth, D (m), was calculated by (3) [14].

$$D = q/v \tag{3}$$

where q is average unit flow discharge per unit width (m^2s^{-1}) and v (ms^{-1}), measured the flow velocity. The shear stress was calculated using (4).

$$\tau = \rho g D S \tag{4}$$

where ρ is the density of water (kgm^{-3}) [4], gravitational acceleration, g is the constant of gravity (ms^{-2}) and S is the tangent value of bed slope in degree. Then, the unit stream power (U, ms^{-1}) was calculated using (5) [15], where D is the average flow depth (m), and S is the is tangent value of bed slope in degrees.

$$U = DS \tag{5}$$

RESULTS AND DISCUSSIONS

Runoff

The result of runoff is shown in Figure 4 and Figure 5 collected for slope 0° and slope 20° respectively. The two slopes indicate disparities in results since the steepness of the slope is influenced by runoff discharge [2][16].

The most surface runoff is collected by bare soil since there is no cover on the top for both slopes presented. Soil without any vegetation does not consist of any flow resistant on the surface. After that followed by a gravel cover also for both slopes. The water flow of the gravel surface from the top hill to the channel cannot be directly compared to bare soil because the gravel surface soil may disrupt rainfall that falls on the soil surface. Next, dry leaves are dispersed throughout the soil surface. Dry leaves could absorb rainwater until the leaves water storage was full. While compared to other surfaces, the root structure of the grass cover may provide an additional channel for water to travel in addition to the overland flow. In comparison to other surface covers, grass has the highest amount of infiltration flow.

Sediment Concentration

Based on the sediment concentration results, it can be inferred that in both slope situations shown in Figure 6 and Figure 7, respectively, bare soil generates a significant amount of sediment. This could occur because bare soil prevents overland flow, which makes rainfall water strike surface of soil and readily distort so that it flows directly to the drainage.

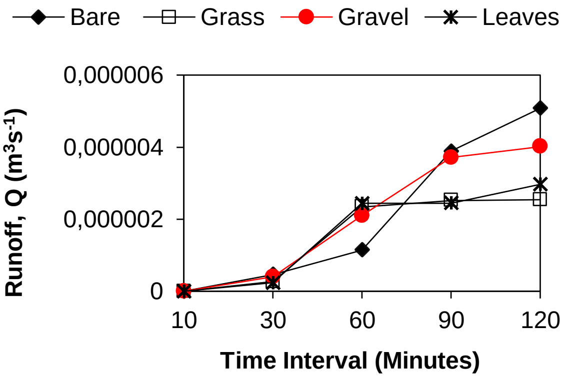

Figure 4. Runoff generation on different underlying surface for slope 0°

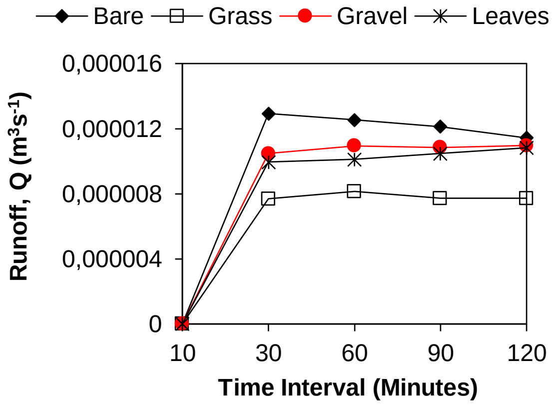

Figure 5. Runoff generation on different underlying surface for slope 20°

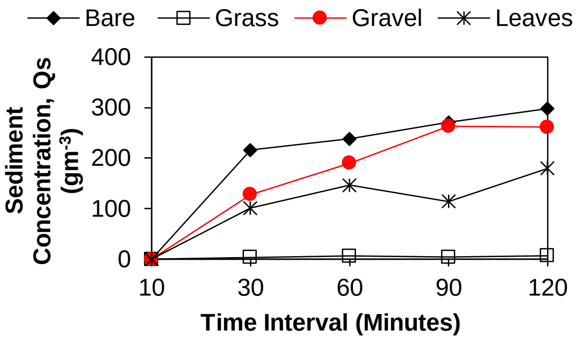

Figure 6. Sediment concentration generation on different underlying surfaces for slope 0°

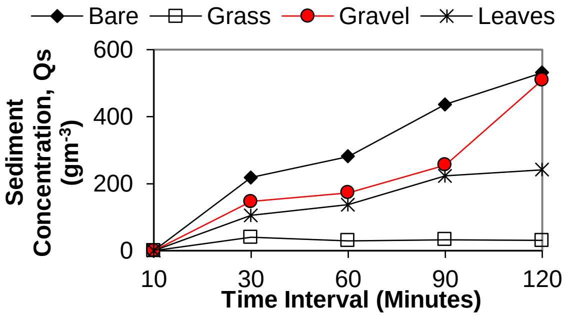

Figure 7. Sediment concentration generation on the different underlying surfaces for slope 20°

The surface covered by gravel generates the highest amount of sediment after bare soil. The only thing that will cause overland flow is the presence of gravel on the surface, which acts as a barrier to allow sediment to flow in addition to obstructing flow velocity. Cover mainly dry leaves produced the third most sediment. It makes sense that once the leaves absorb rainwater to fill their water storage and gain weight, the sediment beneath them may find it difficult to move beneath them. Finally, the cover that generates the least amount of sediment formation is grass. The production value is almost nothing. The most preferred cover to avoid sediment concentration and lower flow velocity is grass.

Relation between Sediment Concentration with Hydraulic Flow

The hydraulic parameters that were connected to sediment detachment were unit stream power, flow velocity, flow depth, and shear stress. These characteristics have been utilized to replicate the soil detachment process in process-based erosion models [17]. After analyzing the relation between Qs, and these four hydraulic parameters, it was discovered as shown in Table 1.

The measured Qs of all four tested overland surfaces increased with all four hydraulic parameters. The performance of flow velocity with $R^2 = 1$ as a predictor for Qs was satisfactory. Moreover, the flow depth (R^2 varied from 0.0123 to 0.9199 with a mean of 0.5131), shear stress (R^2 varied from 0.3764 to 0.9444 with a mean of 0.641), and unit stream power (R^2 varied from 0.0717 to 0.9552 with a mean of 0.3679) were all satisfactory as predictors for Qs. Furthermore, no significant difference was discovered among all these characteristics. This finding was in line with previous studies [18, 19, 20] that demonstrated that flow velocity, flow depth, and shear stress are useful hydraulics parameters for simulating soil detachment. Except for the grass surface, all underlying surfaces had low coefficients of determination (R^2), indicating rather weak predictor performance for unit stream power.

There is a good correlation between flow velocity and Qs generation, as indicated by the relationship for all covers in the two types of slopes (Figure 8). In comparison to a flat slope, the bare surface with the steepest slope produces a significant amount of sediment. The same remains for grass, gravel, and leaves. According to [21], grass has a small value of velocity flow and produces the lowest number of Qs. Steep slopes naturally result in high flow velocities and significant concentrations of sediment. In addition, soil cover is crucial for overland flow [22].

Table 1. Regression results between sediment concentrations and flow velocity, flow depth, shear stress, and unit stream power

Flow velocity, v (ms^{-1})		
Soil Cover	Eqn.	R^2
Bare	$Qs = 235.24e^{35.093v}$	1
Grass	$Qs = 5E\text{-}09e^{10193v}$	1
Gravel	$Qs = 193.01e^{37.779v}$	1
Leaves	$Qs = 119.43e^{61.572v}$	1
Flow depth, D (m)		
Soil Cover	Eqn.	R^2
Bare	$Qs = 368.93e^{-37.04D}$	0.8995
Grass	$Qs = 1.6214e^{158.84D}$	0.9199
Gravel	$Qs = 498.46e^{-130.4D}$	0.0123
Leaves	$Qs= 69.044e^{98.275D}$	0.2206
Shear stress, τ (Pa)		
Soil Cover	Eqn.	R^2
Bare	$Qs = 1849.9e^{-0.078\tau}$	0.9444
Grass	$Qs = 737.45e^{-0.046\tau}$	0.4013
Gravel	$Qs = 3E\text{-}05e^{0.6746\tau}$	0.3764
Leaves	$Qs = 0.0044e^{0.3278\tau}$	0.8419
Unit stream power, U (ms^{-1})		
Soil Cover	Eqn.	R^2
Bare	$Qs = 253.93e^{66.735U}$	0.2738
Grass	$Qs = 5.0409e^{2331.7U}$	0.9552
Gravel	$Qs = 202.24e^{51.788U}$	0.0717
Leaves	$Qs = 132e^{101.65U}$	0.1710

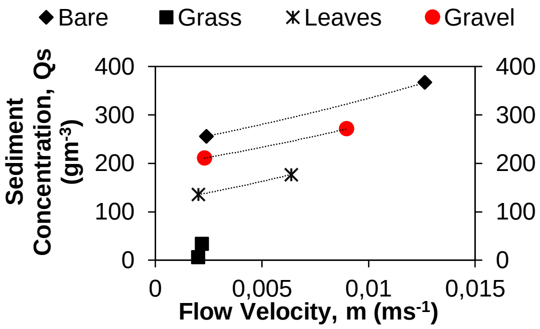

Figure 8. Sediment concentration generation as an exponential function of flow velocity

There is a positive correlation between the two variables, as demonstrated in Figure 9 by the relationship between sediment concentration and flow depth. The greater the depth of flow, the less Qs is produced [23]. Grass on a flat slope only exhibits an adverse relationship as it causes about the same number of Qs as grass cover on a 20° slope with a depth range between the bare, gravel, and leaf surfaces. The highest generation of sediment is produced on bare surfaces on flat slopes, followed by gravel. Conversely, the bare soil on slope 20° demonstrated that a large concentration of sediment will be produced at the lowest flow depth.

Figure 10 displays the relationship between sediment concentration and shear stress. Based on the tangent of the slope being zero, the results demonstrate that there is no shear stress for any underlying surfaces on a flat slope. Though there is a slope, shear stress occurs [24][21]. Nonetheless, the graph indicates that those two factors have a positive relationship. There is significant stress on the grass surface at 20 degrees slope, preventing soil deformation from rainfall.

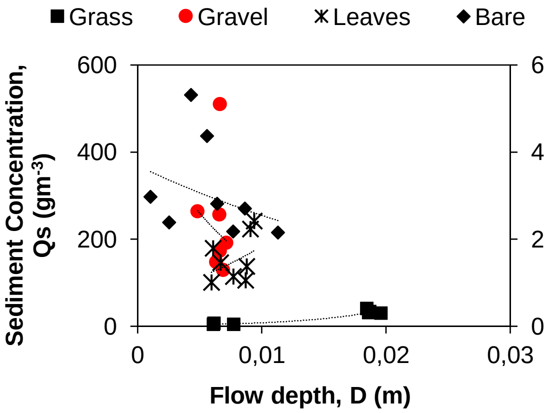

Figure 9. Sediment concentration generation as an exponential function of flow depth

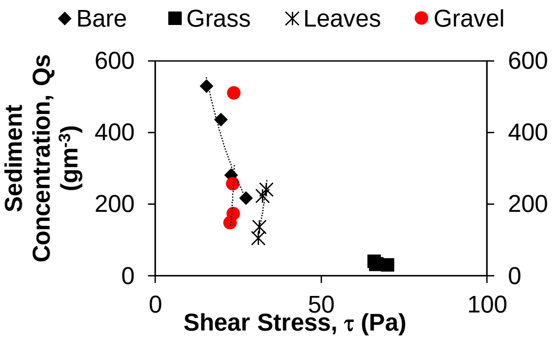

Figure 10. Sediment concentration generation as an exponential function of shear stress

The soil cannot prevent soil deformation due to the impact of rainfall on surfaces with low shear stress. It is difficult for rainfall to erode the soil close to the grass cover because the vegetation's root system has firmly grasped the soil. Since the bare surface in this study experiences the least shear stress, overflow and the effects of rainfall might readily distort the sediment to flow with it.

Since a bare surface lacks a power stream, the relations between Qs and the unit stream of power must similarly disregard the flat slope as shown in Figure 11. Figure 11 illustrates the positive relations between the two variables, showing that the soil surface with the lowest stream power produces less sediment. According to [25], the stream power of the grass is the lowest where the rainfall water stream is interrupted by vegetation on the cover.

The condition of the vegetation determines the distinction between the surface of leaves and grass. For grass, humid leaves indicate dead vegetation, yet the live vegetation is present. High stream power and significant sediment concentration are present in bare surfaces [26]. High stream power affects the strength of the overland flow, which might eventually distort the sediment it flows over [27].

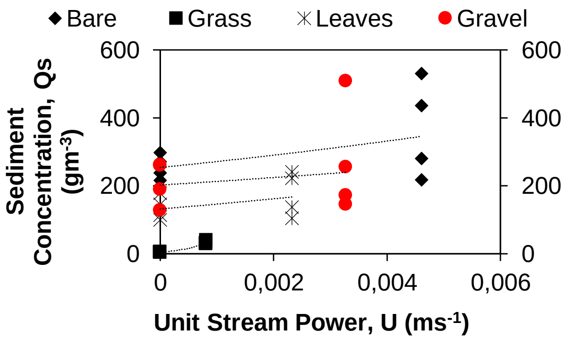

Figure 11. Sediment concentration generation as an exponential function of unit stream power

CONCLUSIONS

This study aims to investigate the relationships between sediment content and the hydraulic characteristics of precipitation-induced overland flow on various underlying surfaces. Overall, the data indicates that sediment content and hydraulic parameters such as flow velocity, shear stress, flow depth, and unit stream power were positively correlated. The steepness of the slope has an impact on sediment generation as well. The most significant component that may potentially affect the creation of sediment is the resulting overland flow, in addition to the many underlying surfaces displaying it. Nevertheless, on the steepest slope and bare surface, the value of sediment concentration increases with low flow velocity and stream power, with no effect on overland flow.

Flow velocity, flow depth, and stream power are hydraulic parameters that exhibit an acceptable coefficient relation with sediment concentration. While the unit stream power parameter shows a low satisfactory coefficient as a predictor of sediment generation. Ultimately, the recommended criteria that may be used to forecast the concentration of sediment are flow velocity, flow depth, and stream power.

The mini scale of the rainfall region replicated in the simulator is believed to have led to the soil surface being entrained by overland stream forces. However, the stream force was insufficient to move sediment that had been pre-deformed by the raindrop contact due to the poor erosivity. These findings show that rainfall may be accurately represented in terms of flow velocity and stream power even when it is simulated on a small scale as the simulation is carried out on a sloping surface. It is essential to keep measuring the stream power and flow velocity throughout the experiment.

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