A study on topography versus sediment yield under simulated rainfall

L K Yong¹, P L Law¹, S N L Taib¹, J O K Ngu¹, D Y S Mah¹ and S L G Law²

¹ Department of Civil Engineering, Universiti Malaysia Sarawak, 93000, Kota Samarahan, Sarawak, Malaysia
² Faculty of Engineering, Computing and Sciences, Swinburne University of Technology, Kuching, Sarawak, Malaysia
*Corresponding author: yongleongkong@gmail.com

Abstract. This study investigates the effects of topography on the amount of sediment yield under simulated rainfall. The slope gradient and length would affect the runoff depth (V) and peak flow volume (Qp) and thus the amount of surface runoffs. In this study, the simulated 150mm/hour rainfall intensity was applied on triangular prism-shaped, cone-shaped and pyramid-shaped models for determination of the amount of respective sediment yields (tons/storm event). It was observed that the sediment yields of the triangular prism-, cone- and pyramid-shaped amounted to 0.144, 0.143 and 0.125 tons/storm event, respectively. The triangular prism-shaped topography has the highest sediment yield amount as it experiences highest runoff depth and highest surface runoff velocity at downslope. Based on the experimental outcomes, it was shown that MUSLE could over-estimate sediment yield as much as 3.6 times for areas characterized by hilly landscape.

1. Introduction

The term “Sediment Yield” can be defined as the amount of eroded soils collected at the outflow end of an observation plot, field, channel, or watershed [1]. In a watershed, sediment yield refers to the amount of eroded material at a designated point remote from the origin of the detached particles; includes the soil loss from slopes and channels, mass wasting and deposition of eroded material on both slopes and in channels [1,2]. The quantity of sediment yield and sediment’s size characteristics are important in analyses of the scale of pollution in a watershed and indicate the decision-making for best management practices [2].

The Modified Universal Soil Loss Equation (MUSLE) has been widely used to predict sediment yield amount for a watershed or a catchment area [3,4,5]. The MUSLE is a modified version of Universal Soil Loss Equation (USLE) used to predict the amount of sediment yield on a storm basis from the outlet of watershed based on the runoff characteristics [5,6,7,8]. Williams and Berndt [5] developed a runoff factor 11.8(V×Qp)⁰.⁵⁶ by investigating 778 individual storm events in 18 catchments with areas ranging from 15 to 1500 ha, and subsequently replaced the Rainfall Erosivity Factor (R) in the Universal Soil Loss Equation (USLE) to become MUSLE [5,7]. The MUSLE was recognized by United States of America, Department of Agriculture (USDA) as the best single indicator for sediment yield prediction, the amount of sediment yield in a watershed to a specific location for a specific storm as expressed in equation 1 [7,8]. Equation 1 was later revised by CPESC,
Inc. (2010) and rewritten as in equation 2 [9]. Table 1 illustrates some of the researchers who adopted the MUSLE to estimate sediment yield at different regions.

\[ T = 11.8(V \times Q_p)^{0.56} \times K \times LS \times C \times P \] 
\[ T = 95(V \times Q_p)^{0.56} \times K \times LS \times C \times P \]  

(tons/storm event) \hspace{2cm} (tons/storm event) 

where,
- \( V \) = Runoff Depth (inch)
- \( Q_p \) = Peak flow rate for the storm event (cfs)
- \( K \) = Soil erodibility factor (tons•ac•hr/10^2 ft•tonf•in)
- \( LS \) = Topographical factor, unitless
- \( C \) = Cover management factor, unitless
- \( P \) = Support practice factor, unitless

### Table 1. Sediment Yield Assessments at Different Regions

| Researchers                     | Study Area                        | Sediment Yield (tons/storm event) |
|---------------------------------|-----------------------------------|-----------------------------------|
| Sadeghi & Mizuyama, 2007 [7]    | Khanmirza watershed, Iran         | 7,495.8                           |
| Fu et al., 2006 [10]            | Pataha Creek Watershed, USA       | 3.1                               |
| Santhi et al., 2006 [11]        | West Fork Watershed, USA          | 3,160 .0                          |
| Hao et al., 2004 [12]           | Yellow River Basin, China         | 770.0                             |
| Jain & Kothyari, 2000 [13]      | Nagwa Watershed, India            | 4,187.6                           |
| Karso Watershed, India          |                                   | 191.6                             |
| Meyer et al., 1997 [14]         | Mississippi, USA                  | 30.0                              |

Generally, higher rainfall intensity comprises of higher percentage of larger raindrops and thus generate higher volume of surface runoffs [15]. Previous studies show that the rainfall intensities and raindrops size in equatorial region are comparatively higher than other regions [16-23]. Besides, the terrains in equatorial region comprise of comparatively more cone-shaped and pyramid-shaped topography characterized with steeper slopes and shorter slope lengths as compared to agricultural lands in the eastern USA [24].

Hence, in equatorial areas, higher rainfall intensity coupled with steeper and shorter hill slopes would result in higher volume and velocity of surface runoff (as compared to RUSLE’s 37 experimental sites in eastern USA). Obviously, higher surface runoff has higher runoff depth (V) and higher peak runoff volume (\( Q_p \)) that would produce higher amount of sediment yield at downslope and in a catchment. In addition, MUSLE LS-Factor only consider inclined plane-surface slope, while triangular prism-, cone- and pyramid-shaped terrains with steeper and shorter horizontal slope length are commonly in equatorial region. Thus, the adoption/application of RUSLE’s LS-Factor (inclined plane-surface) in the MUSLE used to predict the sediment yield in equatorial region would undoubtedly been underestimated. Figure 1 shows the differences between MUSLE and current research.
2. Methods and Materials
Experimental trails on sediment yield under simulated rainfall on three different topographical soil models (pyramid-, triangular prism- and cone-shaped) were carried out at Geotechnical Engineering laboratory of Universiti Malaysia Sarawak (UNIMAS). Soil samples were put inside the designed moulds and well compacted in accordance to Standard Protocol Test (SPT). A rainfall simulator was fabricated to simulate high rainfall intensity of approximately 150 mm/hr. Surface runoffs were collected for 30-minute rainfall duration, and the collected surface runoffs were weighed and recorded. One liter (1-L) of water sample from each topographical shape was also taken to dry for determination of Total Suspended Solids (TSS).

2.1. Rainfall Simulator to Simulate Equatorial Rainfall Intensity
The experimental rainfall simulator consists of a water tank, pump, hose, valve, steel structure and sprinkler as shown in figure 2. The mobility of the rainfall simulator is high because the structure is lightweight and provided with rollers. Supporting equipment such as toolbox, extension wire and hose could be stored at the drawer of the structure of simulator rainfall after use to keep the experimental site clean and tidy. The rainfall simulator produces a rainfall intensity of approximately 150 mm/hr. The raindrop falling height was setup at 10 meters above the peak of soil sample to ensure that the largest possible raindrop (5mm) would achieve terminal settling velocity ($V_s$) [25].

**Figure 2. Rainfall Simulator**
2.2. Soil Samples

Two types of mineral soils were used in this study to examine the amount of sediment yield after each rainfall event. The soil samples were taken at Kuching, Sarawak: Sample A was collected at a field near Santubong River and Sample B was collected from downslope of a hill located at Kota Samarahan, Kuching as shown in figure 3. The Grain size distribution and hydrometer analysis were performed to determine the soil particle sizes and subsequently categorized the soil groups by using the Soil Textural Triangle. Grain size distribution curves of the Sample A and Sample B are shown in figures 4 and 5, respectively. Based on the results of grain size distribution analysis, Sample A recorded 17.05% gravel, 82.85% sand and 0.1% silt and clay, and thus Sample A can be classified as Poorly-graded Sand (S-P). The soil compositions of Sample B are 17.2% gravel, 81.3% sand and 1.5% silt and clay, classified as Poorly-graded Sand (S-P) based on the Soil Textural Triangle.

![Figure 3. Soil Samples A and B](image)

![Figure 4. Soil Sample A - Grain Size Distribution of Soil](image)
2.3. Laboratory Analysis of Total Suspended Solids (TSS)

The total suspended solids (TSS) measures the amount of solid materials content in the runoff waters. In this study, one liter (1-L) of runoff water sample was taken from sediment basin after a 30-minute simulated rainfall event; the water in the basin was agitated to make sure the water was completely mixed before sampling. The water sample was transferred to tray, weighed and recorded. After weighing, the tray was put into the oven and dried for 24 hours (to make sure the oven was on and oven temperature was set at 104°C). After oven-dried at 104°C for 24 hours, the tray was removed from the oven and left to cool. The tray was put on the scale and waited until the reading stabilized. The TSS can be computed by using the following equation:

\[
TSS \text{ (mg/L)} = \frac{\text{Oven dried mass (mg)} - \text{Empty tray (mg)}}{\text{Sample volume (L)}}
\]

2.4. Topographical Shape and Soil Compaction

The Revised Universal Soil Loss Equation (RUSLE) is based on the unit plot design of 72.6ft slope length and slope steepness of 9%. Normalization of slope length and slope steepness are based on the unit plot [26,27]. The Modified Universal Soil Loss Equation (MUSLE) was developed by Williams and Berndt in 1977 by replacing the rainfall erosivity, R to a runoff factor \(11.8(V \times Q_p)^{0.56}\). The runoff factor was later revised by CPESC, Inc. and rewritten as \(95(V \times Q_p)^{0.56}\) in 2010. The other sub-factors such as Soil Erodibility (K), Crop Management (C) and Support Practice (P) were remained. Experimental plots were designed in three topographical landscapes (triangular prism-, cone- and pyramid-shaped) with base area of 1.0 m² as shown in table 2. The horizontal slope length of soil sample is 0.5 m and the slope steepness is 100% (angle of slope 45°).

The experimental soil compaction method and number of blows in accordance with Standard Proctor Test (SPT). A 2.5kg rammer was used to compact the soil samples. However, there were three compartments of experimental moulds and the surface areas are larger than Proctor mould; therefore, each compartment was compacted separately in three layers to ensure that soil samples were well compacted. The number of Rammer blows for triangular-, cone- and pyramid-shape moulds are shown in table 2.
Table 2. Experimental Moulds of Different Topographical Landscapes and Number of Rammer Blows [24]

| Topographical Shape | Moulds’ Design | Mounting Moulds | Number of Rammer Blows |
|---------------------|----------------|-----------------|------------------------|
| Triangular Prism    | ![Triangular Prism Design](image) | ![Mounting Moulds](image) | Top part: 25 blows for 1 layer. Middle part: 621 blows per layer for 3 layers. Bottom part: 1863 blows per layer for 3 layers. |
| Cone                | ![Cone Design](image) | ![Mounting Moulds](image) | Top part: 25 blows for 1 layer. Middle part: 108 blows per layer for 3 layers. Bottom part: 891 blows per layer for 3 layers. |
| Pyramid             | ![Pyramid Design](image) | ![Mounting Moulds](image) | Top part: 25 blows for 1 layer. Middle part: 135 blows per layer for 3 layers. Bottom part: 1134 blows per layer for 3 layers. |

2.5 Surface Runoff Patterns

The amount of surface runoff and sediment yield can be related to the surface runoff pattern of different topographical features. Figure 6 shows the surface runoff pattern for pyramid-, triangular prism- and cone-shaped soil samples. It was observed that surface runoffs of triangular prism-shaped would flow in an evenly dispersed pattern downslope along two sides of plane surfaces, while the pyramid-shaped would flow onto the four sides, and cone-shaped model presented even flow in all directions.

![Figure 6. Flow Direction of Surface Runoff on Soil Samples [24]](image)
3. Results and Analysis

The Modified Universal Soil Loss Equation (MUSLE) is commonly used to estimate sediment yield from a watershed [9]. In this research, the Total Suspended Solids (TSS) can be treated as sediment yield from a watershed as the eroded soil particles (mainly silt and clay particles) are predominantly transported by surface runoffs into sediment basin. Runoff samples were collected from the sediment basin and the dry-mass of sediments are the Total Suspended Solids (TSS) and the results are presented in table 3.

| Topographical Landscape | Soil Sample | Oven-dried Sample Mass (g) | Empty Tray Mass (g) | TSS (g/L) | Sediment Yield (tons/storm event per m²) | Sediment Yield (tons/storm event/ac) | Average Sediment Yield (tons/storm event) |
|-------------------------|-------------|-----------------------------|--------------------|-----------|----------------------------------------|--------------------------------------|-----------------------------------------|
| Triangular Prism        | A           | 272.39                      | 237.24             | 35.15     | 35.15 x 10⁻⁶                            | 0.142                                | 0.144                                   |
|                         | B           | 273.64                      | 237.24             | 36.40     | 36.40 x 10⁻⁶                            | 0.146                                |                                         |
| Cone                    | A           | 271.18                      | 237.24             | 33.94     | 33.94 x 10⁻⁶                            | 0.136                                | 0.143                                   |
|                         | B           | 274.31                      | 237.24             | 37.07     | 37.07 x 10⁻⁶                            | 0.150                                |                                         |
| Pyramid                 | A           | 267.93                      | 237.24             | 30.69     | 30.69 x 10⁻⁶                            | 0.121                                | 0.125                                   |
|                         | B           | 269.25                      | 237.24             | 32.01     | 32.01 x 10⁻⁶                            |                                      |                                         |

In table 3, the total suspended solids (TSS) of soil samples A and B after each rainfall event at rainfall intensity of 150mm/hr were recorded 35,150 mg/L and 36,400 mg/L for triangular prism-shaped, 33,940 mg/L and 37,070 mg/L for cone-shaped, and 30,690 mg/L and 32,010 mg/L for pyramid-shaped. The sediment yields of triangular prism-shaped and cone-shaped topography are almost identical, recorded 0.144 and 0.143 tons/storm event, respectively. Pyramid-shaped recorded the lowest sediment yield of 0.125 tons/storm event, which is 13.2% lower than triangular prism-shaped and 12.6% lower than cone-shaped. Sediment yield is the amount of soil particles been washed by surface runoff and deposit at downslope. Thus, the amount of sediment yield depends on the surface runoff depth and velocity. The surface runoff depth and velocity are different for experimental triangular prism-shaped, cone-shaped and pyramid-shaped topography. Surface runoff velocity can be computed by knowing the Surface runoff velocity (RV, m/s), Volume of surface runoff (Q, m³/s), and Slope or gradient of hydraulic (S, m/m). Equation 4 can be used to determine the height of surface runoff on slope (h). Figure 7 shows the cross-sectional length and surface runoff velocity at downslope locations a, b, c, d and e.

\[ h^3 = \frac{Q^2}{2gL_n^2} \quad (n=1,2,3,4,5) \]
In figure 7, triangular prism-shaped recorded highest surface runoff depth of 0.259mm and highest surface runoff velocity of 0.071m/s at location “e” (downslope of experimental plot), and thus the surface runoff would carry more soil particles such as silt and clays as compared to cone-shaped and pyramid-shaped topography.

3.1 Experimentally Observed versus MUSLE Predicted Sediment Yield

The MUSLE was developed using gentle-inclined plane surface with 72.6ft slope length, 6ft width and 9% slope steepness [5,24,27]. The triangular prism-shaped topography has similar shape (inclined plane surface) as MUSLE plot, thus it can be compared with MUSLE prediction. Table 4 shows the MUSLE predicted sediment yield of 0.449tons/storm event, which is found approximately 67.9% higher than triangular prism-shaped topography.

Table 4. MUSLE Predicted Sediment Yield

| Location | Triangular Prism | Cone | Pyramid | Triangular Prism | Cone | Pyramid |
|----------|------------------|------|---------|------------------|------|---------|
| a        | 0.089            | 0.066 | 0.058   | 0.042            | 0.036 | 0.034   |
| b        | 0.141            | 0.104 | 0.092   | 0.053            | 0.045 | 0.043   |
| c        | 0.184            | 0.136 | 0.121   | 0.060            | 0.052 | 0.049   |
| d        | 0.223            | 0.165 | 0.146   | 0.066            | 0.057 | 0.054   |
| e        | 0.259            | 0.192 | 0.170   | 0.071            | 0.061 | 0.058   |

Figure 7. Experimental Runoff Depth and Runoff Velocity at Locations “a” to “e”
4. Conclusions

The sediment yield amount is affected by surface runoff depth and surface runoff velocity, whereby higher surface runoff depth and velocity would generate higher sediment yield amount. Experimental results show that the triangular prism-shaped topography has highest sediment yield amount as compared to cone-shaped and pyramid-shaped topography. A comparison of the experimental outcomes with the MUSLE, it was shown that the MUSLE predicted sediment yield could over-estimate by 3.6 times in hilly areas that comprise of mostly triangular prism-, cone- and pyramid-shaped terrains.

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