Experimental Study on Effects of Plot Length on Runoff Depth Under Natural Precipitation

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Abstract. This paper focuses on the experimental study to determine the relationship of slope length on runoff depth and runoff coefficient. Based on the thorough review of different plot sizes (lengths) for soil loss estimation, the slope of the current experimental plots was designed with an angle of 22.78° from horizontal. The plots were grouped into Plot A (1 m wide x 1 m slope long), Plot B (1 m wide x 2 m slope long) and Plot C (1 m wide x 3 m slope long). Homogenous soil samples were used for all the 3 experimental plots and a tipping bucket rain gauge with automatic data logger was installed at the experimental plot for rainfall intensities collection for the individual rainfall events. Runoff volumes were recorded for the individual rainfall events for determination of runoff coefficients. The rainfall intensities are grouped into ≤30 mm/h, 30-60 mm/h and ≥60 mm/h. It was found that the shorter plot (Plot A) has the highest runoff coefficients of 96.34%, 69.89% and 96.26% for 3 different precipitation groups ≤30 mm/h, 30-60 mm/h and ≥60 mm/h, respectively. Based on results, the longest plot (Plot C) shows that an increase in mean values of 33.59%, 38.30% and 49.45% as the intensity increased from ≤30 mm/h to ≥60 mm/h. From this study, it can be concluded that comparatively longer slope length tends to result in lower runoff depth.

Keywords. Plot Length, Rainfall Intensity, Runoff Depth, Runoff Coefficient.

1. Introduction
Some of the principal factors that would interfere with outcomes of erosion estimation include rainfall intensities, surface conditions, slope length, slope gradient and soil conditions [1]. It is mainly due to the momentum of the raindrops that would generate shear stresses on the soil surface [2], [3]. Meyer [4] demonstrated the importance of rainfall intensities on soil erosion rate including the factors of rainfall impacts and surface runoff. Surface runoff is defined as the water flow that occurs when excess sources of flow over the ground surface and this process is also called “infiltration excess overland flow” [5].

Rainfall-runoff phenomena is one of the most significant and complex relationships [6] whereby it involves a lot of factors, such as infiltration rate, evaporation rate, etc [7]. Tokar & Johnson [8] pointed out that many authoritative researchers studied for years on the transformation of rainfall to runoff in order to forecast water sources. A more suitable elaboration is that during storm events, the ground experiences infiltration process, whereby the infiltration rate would be slowed down when the
moisture content of soil reaches its full saturation. Excess amount of water is not able to infiltrate the ground and thus the formation of surface runoff or surface overflow. Runoff coefficient is the ratio of the total amount of runoff to total rainfall amount. The higher the runoff coefficient, the higher the runoff amount on the surface due to the infiltration properties of the surface. For example, a concrete surface has a relatively higher runoff coefficient than a grass surface, because the grass surface has a higher infiltration rate and, thus lower runoff.

The rainfall-runoff relationship and runoff coefficient are highly attributed to size of the area understudy, whereby a different area brings different results on runoff effects under various precipitation rates. Although the application of the experimental plots is widely practised by several researchers [9], [10], there have been very limited studies on the effects or the relationships of plot length on runoff depth and runoff coefficient. To date, there is no well-defined classification on plot lengths and boundary conditions and there are, to numerous terminologies and definitions for different plot sizes or lengths.

For instance, some specific terminologies would refer to the microplot and large plot that would lead to different interpretations on the application of plot dimensions. Based on the description of previous researchers, there are no clear description on the characteristics and the definitions of soil loss plot as microplot, small plot, large plot, small microplot, large microplot and so on. There should have more precise definitions and justifications that qualitatively define plot size for various research and study purposes. Lal [11] put forward the clarification and understanding of the types of plots that are generally adopted by researchers including small plot, Universal Soil Loss Equation (USLE) plot and large plot.

Table 1 summarizes the characteristics of the plots in addition to the details and functions of the relevant plots, including its advantages and disadvantages. The most important determining elements are the relationship of experimental outcomes and different types of plot adopted, including runoff coefficient, soil loss amount outside the site boundary, average soil movement rate on the plots, rainfall intensities, slope steepness, ground conditions, and the ratio of errors with respect to other plots.

| Types of Plot | Descriptions | Sources |
|---------------|--------------|---------|
| Small Plot    | • Used to study fundamental erosion process that is harder to be observed on bigger plots. | Meyer & Harmon [12] |
|               | • Provides more detailed information on inter-rill erosion and sediment yield. | Bagarello & Ferro [13] |
|               | • Recommended for use below 40 m². | Moldenhauer [14] |
| USLE Plot     | • Standard erosion and sediment yield plots developed from USLE with the dimension of 22.1 m long and 9% slope. | Wischmeier & Smith [15] |
|               | • The size is suitable to study combine erosion process (rill and inter-rill). | Renard et al. [10] |
| Large Plot    | • It is more representative of the outcomes on the study of sediment yield at a practical scale. | Mayerhofer et al. [16] |
|               | • Recommended to be between 40 m² to 100 m², and an area larger than 100 m². | Van Es, Van Es & Cassel [17] |

2. Materials and Methods
The site is located within the residential area of Pending Area, Kuching, Malaysia, with coordinate of 1°32’ 47.99” N, 110° 22’ 26.37” E and the climate is humid most of the time that contributes to high rainfall intensities [18], [19]. The site provided enough space for the setup of experimental plots and
the surroundings of the plots and the surroundings of the plots are low rise residential buildings (detached houses with a maximum of two-story), which provides sufficient clearance for the installation of the tipping bucket rain gauge. The site is flat terrain to ensure no topographical factors (ground slope = 0%) would affect the gradient of the soil plots.

The experimental plots were constructed with reference to the required dimensions by the plot, which are (1) 1 m x 1 m plot, (2) 1 m x 2 m plot, and (3) 1 m x 3 m plot, which represent Plot A, Plot B and Plot C, accordingly. The structures and dimensions were designed to adequate height so that runoffs are collected. The soil loss plot and runoff collection points were designed to stand at 550 mm and 300 mm from the ground, respectively to ensure that the sampling of the runoff can be easily executed and collected at the runoff collection point. An angle of 22.78° from horizontal was designed for the plot to ensure that the runoff during low rainfall intensity storm event. Surfaces of the formwork (wood structures) were painted with waterproof paint and the gaps and openings on the formworks are sealed with waterproof silicone to prevent moisture (water) from entering the formwork. All the layers and structures were installed and checked before the formworks were filled up with soil samples. Runoff collection points were designed to be located at the ends (lowest point) of the individual plots. Aluminium plates were shaped to guide the runoff from the plots and plastic containers were used to collect the runoff during a rainfall event. The containers measured 250 mm (H), 550 mm (W) and 850 mm (L) or equivalent to 117 Litres each. Transparent roofing was installed for observation purposes and at the same time preventing rainwater from getting into the containers. The final setup of the experimental plots is shown in Figure 1.

The criteria of the Three (3) plots are shown in Table 2. All the soil samples fall under the definition as homogenous topsoil with no addition of sand or organic materials. The sample soils were loaded onto the test bay could be considered as disturb condition, whereby poor compaction applied on the soil samples but only flatten the surface for the simulation of natural flat ground with disturbed soil condition. The continuous erosion process would occur to the surface of the plot and that would increase the number of granular particles protruding on the surface. Removal of granular particles and a small portion of the soil to flatten the surface and fresh soil samples were refilled to replace the volume removed.

A standard rain gauge was used for determination of rainfall depth for a certain time period or a rainfall event (Figure 1). It is possible to get the rainfall intensity with the recorded duration of rain and the collected amount of rainwater the rain gauge. For this tipping bucket rain gauge, it was designed as 0.5 mm per tick. Every tick made by the lever arm was recorded by a contact a sensor underneath the lever and the signal was transmitted to the data logger.

During the experimental stage, the total runoff volume for each plot was determined after the rainfall event. Five different positions from the containers were marked and used as water level measuring points by using measuring tape. Average readings of the measuring points were taken as records to minimise errors during the readings. The rainfall data from the data logger were plotted in intensity-duration graph for perspective data display. The rainfall intensities were classified into 3 groups; <30 mm/h, 30-60 mm/h and >60 mm/h. The data were analysed and presented in box and whisker plot (Figure 2) for comparison of different plot lengths under various ranges of rainfall intensities on the runoff coefficient by using Equation 1, where RC is runoff coefficient (%), D_{runoff} is total runoff depth (mm) and D_{rainfall} is total rainfall depth (mm).

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RC = \frac{D_{runoff}}{D_{rainfall}} \times 100\% 
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The rainfall data were extracted from the data logger as the number of raw data from the logger in “tick-timing” and the “total ticks” as continuously recorded. Figure 3 shows the data displayed in bar chart format for rainfall depth. The data logger recorded rainfall details from 1st December 2019 to 21st January 2020. The highest daily rainfall depth recorded as high as 115 mm (230 ticks) over 24-hour period. As shown in Figure 3, from December 2019 to January 2020, the experimental plots experienced high-intensity rainfall events and low-to-medium rainfall intensities but long rainfall duration. A total of 26 storm events were recorded by the plots.
Figure 3. Measured Rainfall Intensity-Duration Data (01/12/2019 to 21/01/2020).

The rainfall-runoff relationship for Plot A (1 m x 1 m), Plot B (1 m x 2 m) and Plot C (1 m x 3 m) for this study are shown in Figure 4 and the regression results for the plots are shown in Table 3. The results shown in Figure 4 illustrate that the data distribution in similar ranges for all plots under the same precipitation. Plot A shows a comparatively higher response in the linear relationship of precipitation (P) and runoff depth (R), suggesting that intensity generates comparatively higher runoff amount as the precipitation rate increases, as compared to Plot B and Plot C. For Plot B, it tends to produce relatively higher R compared to Plot C with higher P, but Plot C has comparatively higher runoff production compared to Plot B for lower P. The relationship equation of R and P for the plots are listed in Table 3.

Table 3. Regression Results for Plot A, Plot B and Plot C.

| Plot Type | Plot A | Plot B | Plot C |
|-----------|--------|--------|--------|
| Dimension | 1 m x 1 m | 1 m x 2 m | 1 m x 3 m |
| Pearson’s r | 0.916 | 0.935 | 0.911 |
| R-Square (COD) | 0.839 | 0.875 | 0.830 |
| Adj. R-Square | 0.827 | 0.863 | 0.816 |
| Equation | $R = 0.813P - 9.175$ | $R = 0.627P - 7.062$ | $R = 0.686P - 9.686$ |
Figure 4. Scatter Plot and Linear Fit of Plot A, Plot B and Plot C.

Plot A, Plot B and Plot C showed high linear correlation between R and P with Pearson correlation coefficient, PCC (Pearson’s r) of 0.916, 0.935 and 0.911, respectively. All the plots show a positive linear correlation of R and P, which indicates that the plots are appropriate for the data set. The $R^2$ value of 0.839, 0.875 and 0.830 for Plot A, Plot B and Plot C, respectively, suggests that all the variability responses data are around the mean value (insignificant deviation from the mean value). To date, there are only a few researchers studied on the relationship plot length and runoff volume. However, generally the results are comparable with the theory as part forward by Beven [5]. For shorter plot (Plot A), it would achieve soil moisture content saturations faster due to smaller areas as compared to longer plots (Plot B and Plot C). From this study, it is shown that the longer the plot length, the higher the area for infiltration to occur that results in lower runoff volume.

For this study, the data from natural rainfall were collected for a wide range of rainfall intensities and they are plotted in groups on runoff coefficients of the individual plots for the rainfall intensities (Figure 5) There is a common perception that larger areas of the plot could bring about a relatively higher runoff depth than a smaller plot. From this study, the results demonstrate that it is not necessarily true. From the results of precipitation groups of $\leq$30 mm/h, 30-60 mm/h and $>$60 mm/h, Plot A shows the highest runoff coefficient of 96.34%, 69.89% and 96.26%, respectively. The increments in the mean values for Plot C are 33.59%, 38.30% and 49.45% for precipitation groups of $\leq$30 mm/h, 30-60 mm/h and $>$60 mm/h, respectively.
Figure 5. Box and Whisker Plots for Different Ranges of Rainfall Intensity.

Based on the results, the shorter plots would result in high runoff coefficients under various rainfall intensities as compared to longer plots. Alternatively, it could simply mean that during the runoff process, longer plot trends to have higher rates of infiltration along the contact surfaces on the plot. The shorter plot has lesser contact time with the plot surface resulting in high runoff depth and low infiltration rate during the storm events. It is notable that the data distribution characteristics depict a similar pattern with small data differences; indicating minor variations of median and minimum values. However, it is also found that there are minority outliers that could affect the distribution curves, especially in Plot A, even though insignificant on overall findings of various plots. With respect to the contact durations and infiltration processes on the plots, it can be concluded that plot size or length can be one of the most significant factors on the outcome of the runoff coefficients.

4. Conclusion
From this study, the following conclusions can be drawn: As shown in Fig. 4, shorter plot (Plot A) has relatively higher runoff volume as compared to the comparatively longer plots (Plot B and Plot C). The relationship of precipitation (P) and runoff depth (R) can be expressed as: Plot A: \( R = 0.813P - 9.175 \); Plot B: \( R = 0.627P - 7.062 \); Plot C: \( R = 0.686P - 9.686 \). The correlation of precipitation (P) and runoff (R) shows are showing positive linear relationships with \( R^2 \) of 0.839, 0.875, 0.830 for Plot A, Plot B and Plot C, respectively. Comparatively shorter slope length of Plot A shows the highest runoff coefficient in all the precipitation groups, with the highest runoff coefficients of 96.34%, 69.89% and 96.26% for \( \leq 30 \) mm/h, 30-60 mm/h and >60 mm/h, respectively. Comparatively longer slope length of Plot C shows an increase in runoff coefficient in the precipitation groups of \( \leq 30 \) mm/h, 30-60 mm/h and >60 mm/h with the mean values of 33.59%, 38.30% and 49.45%, respectively.

5. References
[1] T. J. Toy, G. R. Foster, and K. G. Renard, Soil Erosion. New York: John Wiley & Sons, 2002.
[2] W. S. Merritt, R. A. Letcher, and A. J. Jakeman, “A review of erosion and sediment transport models,” Environ. Model. Softw., vol. 18, no. 8–9, pp. 761–799, 2003.
[3] L. L. G. Samuel and K. K. Kuok, “Sensitivity Analysis of the Revised Universal Soil Loss Equation’s Rainfall Erosivity Factor (R-Factor),” Test Eng. Manag., vol. 83, no. May-June, pp. 6809–6815, 2020.
[4] L. D. Meyer, “How rain intensity affects interrill erosion,” Trans. ASAE, vol. 24, no. 6, pp. 1472–1475, 1981.
[5] K. Beven, “Robert E. Horton’s perceptual model of infiltration processes,” Hydrol. Process.,
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