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Abstract

Simulating rainfall is one of the valuable methods of measuring hydrological data and soil erosion processes. Rapid evaluation, high repeatability, and low cost are the reasons of using rain simulators. In this study, a rain simulator was constructed in dimensions of 3.0 × 3.0 × 3.0 m and it was protected on three sides by a plastic cover. An inclined table was used to create slopping surfaces of 5, 10, and 15%. Microplots were used in the dimensions of 0.2 × 0.4 × 1.0 m to collect and measure direct runoff in a bucket outside the device. Nozzles were calibrated to produce two different rainfall intensities 10 and 20 mmh−1 using sprinkler Model 5B at 8 and 12 psi, respectively. Furthermore, three different soil types, namely, clay loam (CL), silty clay (SC) loam, and SC were examined. In general, it was observed that with increasing the rainfall intensity and slope, the rate of runoff and sedimentation increase. SC soil at 15% slop offered the highest performance under the intensity of 20 mmh−1. SC and the CL soils produced the highest and lowest runoff coefficients, respectively. The CL soil produced the highest soil loss (1 kgm2 at 15% and I = 20 mmh−1). Further, it was concluded that a significant change (an average increase of 53%) in soil loss can be achieved as the rainfall intensity increased from 10 to 20 mmh−1.

Keywords

Soil erosion, Rainfall simulator, Raindrop diameter, Runoff coefficient, Sedimentation

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RESEARCH ARTICLE

Simulation of Rainfall Intensity and Slope Gradient to Determination the Soil Runoff Coefficient at Microplot Scale

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ABSTRACT

Simulating rainfall is one of the valuable methods of measuring hydrological data and soil erosion processes. Rapid evaluation, high repeatability, and low cost are the reasons of using rain simulators. In this study, a rain simulator was constructed in dimensions of 3.0 × 3.0 × 3.0 m and it was protected on three sides by a plastic cover. An inclined table was used to create slopping surfaces of 5, 10, and 15%. Microplots were used in the dimensions of 0.2 × 0.4 × 1.0 m to collect and measure direct runoff in a bucket outside the device. Nozzles were calibrated to produce two different rainfall intensities 10 and 20 mmh^{-1} using sprinkler Model 5B at 8 and 12 psi, respectively. Furthermore, three different soil types, namely, clay loam (CL), silty clay (SC) loam, and SC were examined. In general, it was observed that with increasing the rainfall intensity and slope, the rate of runoff and sedimentation increase. SC soil at 15% slop offered the highest performance under the intensity of 20 mmh^{-1}. SC and the CL soils produced the highest and lowest runoff coefficients, respectively. The CL soil produced the highest soil loss (1 kgm^2 at 15% and $I = 20\ mmh^{-1}$). Further, it was concluded that a significant change (an average increase of 53%) in soil loss can be achieved as the rainfall intensity increased from 10 to 20 mmh^{-1}.

Keywords: Soil erosion; Rainfall simulator; Raindrop diameter; Runoff coefficient; Sedimentation

INTRODUCTION

Essentially, the study of water erosion under natural conditions is crucial, as it requires a long-term research program. Simulation of erosion factors on a small scale, with high repeatability, creates the opportunity to achieve results with less cost and time (Sushil et al., 2018). Rainfall simulators have been used to apply uniform rainfall rates over land surfaces or packed soil boxes to evaluate runoff under controlled conditions. Rainfall simulators were initially used to study soil erosion (Moussouni et al., 2012; Mutchler and Hermsmeier, 1965). To create artificial environment for rainfall research, rainfall simulators have been widely used as a research tool (Ellison and Pomerene, 1944; Mutchler and Hermsmeier, 1965; Laflen and Moldenhauer, 1979).

Rainfall simulators can be divided into two groups: Non-pressurized and pressurized simulators (Clarke and Walsh, 2007). In the non-pressurized nozzle rainfall simulators, droplets are mostly generated through hypodermic needles, polyethylene tube, and capillary tube (Chow and Harbaugh, 1965). Pressurized simulators use nozzles to initiate flow (Imeson, 1977). A variety of rainfall simulators have been developed, which includes a small portable infiltrometer with a circular rainfall area of 6 inch diameter as well as the Kentucky rainfall simulator which covered a relatively large area of dimensions 4.5 m by 22 m (Moore et al., 1983).

As it is obvious from the Universal Soil Loss Equation (USLE), the rate of loosed soil is directly proportional to the rainfall intensity (erosivity power). In the same conditions, more intense rainfall causes more erosion. As well as, there is a close relationship between runoff and rainfall intensity. Many studies have been conducted on the relationship between rainfall intensity and runoff (Rajurkar et al., 2004; Anctil et al., 2006; Boughton, 2006; Jacquin and Shamseldin, 2006; Al-Qurashi et al., 2008; Bahat et al., 2009).

Along with the rainfall intensity, slope length (L), and gradient (S), which can be assessed through a combined LS factor (Wischmeier et al., 1958), are another two fundamental factors of erosion. The effect of slope length on erosion occurs through an increase in the volume and the speed of runoff, resulting in increased capacity of the runoff to disaggregate and transport sediments (Bagarello and Ferro, 2010).

The risk of erosion is affected by soil erodibility. Wischmeier and Smith (1978) used sand and silt fractions as indices for estimating the soil erodibility factor in the USLE model. Erodibility is low for clay-rich soils (ÓGeen et al., 2006), but height for sandy soils since they have a low cohesive force and are more prone to detachment and transportation by water and wind (Aba Idah et al., 2008). However, Duiker et al. (2001) stated that soil loss is negatively correlated with clay content but positively correlated with very fine sand and silt + very fine sand contents.

In the present study, the simultaneous influence of rainfall intensity, land slope, and soil type (soils surrounding Erbil city in terms of the particle size and compaction) on erosion and runoff generation was studied using a rainfall simulator.

MATERIALS AND METHODS

Rainfall Simulator

A rainfall simulator device has been manufactured with iron frame of 4 × 4 cm and 3 mm in thickness and was assembled around a 3.0 m by 3.0 m level area with a coverage area of about 9 m^2 and 3.5 m in height. The machine is portable as the frame structure can be opened and closed with screws. A plastic fabric is covering the outer surface in three sides to protect the rainfall simulator from wind effects. Figure 1 shows the general view of the simulator with associated components such as sprinkler manifolds, pump, and flow meter. All the rainfall simulation experiments were conducted over a selected area at the Agricultural Research Center at Ainkawa, which is about 5 km to the northwest of Erbil city.

The water distribution was made by plastic pipes with a sprinkler system equipped with eight nozzles (Model 5B, commercial name). The spray angle was constant. The sprinklers were stationary and mounted over two lateral pipes, each carries four sprayers. The spacing along the lateral pipes was 0.70 m, while the lateral spacing was 1.4 m [Figure 2]. An electric pump was used with one horsepower to create pressure on the system. The water gauge and manual valve installed for controlling rain speed. Two rates of rainfall intensity were created; 10 and 20 mmh^{-1} at 8 and 12 psi, respectively. Calibration was done empirically by adjusting a flow meter in the line to control the inflow of water from the storage tank to ensure the required rainfall intensity. Calculation of raindrop diameter for rainfall simulator with varying intensity was studied according to Laws and Parsons (1943).

Soil Samples

Three soil samples with different texture were collected from the surface 0.30 m. Samples were air-dried, nodule and coarse particles were broken up with a wooden hammer and passed through a 2-mm sieve. Physical characteristics of the soil samples were listed in Table 1.

Table 1: Particle size distribution for studied soils

No.	Geographic coordinate		Soil particle distribution (%)			Soil texture class
	Latitude	Longitude	Sand	Clay	Silt	
1.	36.144295°	44.020969°	23.25	28.50	48.25	Clay loam
2.	36.113581°	44.015567°	10.50	37.00	52.50	Silty clay loam
3.	36.245487°	43.994296°	13.50	42.50	44.00	Silty clay

*Source: Keya, 2009

Figure 1: General view of rainfall simulator used in this study

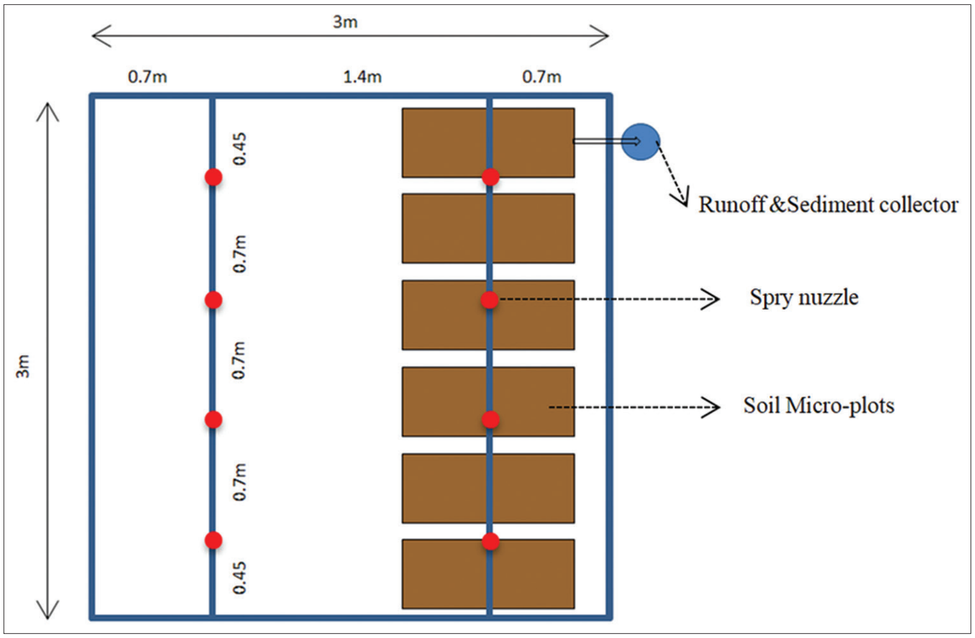

Figure 2: Layout of sprinkler system

Microplots

The handpicked soil samples were collected, mixed thoroughly, and moistened with a fine mist from a hand sprayer to raise the soil moisture content to optimum soil water content for compaction. Each soil sample packed in perforated trays (1 m × 0.40 m × 0.2 m) in form of three layers with a special wooden hammer designed for this purpose to achieve the bulk densities of 1.5, 1.4, and 1.3 Mgm^{-3}, respectively. These values approximate the *in situ* bulk densities of the investigated soils. The compacted soil was underlain by a perforated metal sheet to allow free drainage of percolated water. Before treating the soils and exposing them to rainfall, they were exposed to open air to attain near air-dry soil moisture content, as illustrated in Figure 3.

Calibration and Uniformity Test

The rainfall simulator used in this research was calibrated to give 10 and 20 mmh^{-1} using available spraying nozzles at 8 and 12 psi, respectively. To ensure that the studying area is entirely covered and uniform rainfall over the tested area is properly achieved, the spray was captured by a grid-work of 3 inch stainless steel cans on the surface of the soils in the microplots. The volume of water was measured with a graduated cylinder recorded after operating the system for 1 h. The microplots were placed under the rain with a slope ratio of 5, 10, and 15% by raising the upper part of plots.

Calibration was done empirically by adjusting a flow meter in the line to control the inflow of water from the storage tank to ensure the required rainfall intensity.

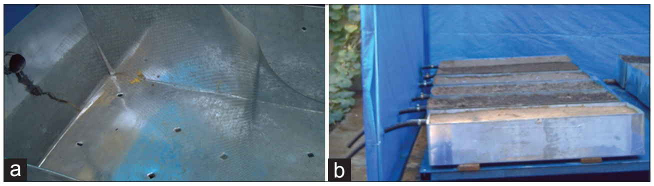

Figure 3: (a) holes and metal sheet in bottom of microplot, (b) prepared microplots under rainfall simulator

Measurement of Runoff and Sediment

A series of rainfall simulation experiments was conducted. The running water from the surface of microplots was driven from the outlet point by a hose toward the collection bucket, outside the windshield. After operating the system for 1 h (each replication), the volume of water was measured with a graduated cylinder and recorded as the runoff volume. The deposited soil was oven-dried and measured by a scale (accuracy ±1).

The experiment under rainfall simulator encompassed the study of a host of factors using three replicates. The factors were type of soil (three types), slope (three levels), and rainfall intensity (two levels). The responsible variables include runoff coefficient and soil loss were measured by:

$$Runoff\ coefficient = V_{CW} / V_R \tag{1}$$

Where; V_{CW} is volume of collected water (lit) and V_R is volume of rainfall in 1 h (l).

$$Soil\ loss = S_w / A_m\ (Kg/ha) \tag{2}$$

Where; S_w is Sediment weight and A_m is Microplot area

Each combination was replicated thrice. MS Excel program was used to analyze the results and generate graphs.

RESULTS

Raindrop Diameter and Median Raindrop (D50)

The obtained results are demonstrated in Figure 4 which shows that the correlation for both rainfall intensities examined in this study was close ($R^2 >95$). The raindrop diameter varied from 0.56 to a maximum of 2.01 mm, with an average of 1.5 mm at 10 mmh^{-1}, and 0.85 to 2.42 mm and the average diameter of the drops was 1.7 mm at an intensity of 20 mmh^{-1}. Further, as it can be seen in Figure 4, the median raindrop diameter was increased with increasing rainfall intensity. The same observation was made by (Laws and Parsons, 1943), (Hudson, 1995), and (Van Dijk et al., 2002). Table 2 presents the results of calculating the median raindrop (D_{50}) for two events. The raindrop size varied from 0.754 to 2.076 (D_{50} = 1.2 mm) at an intensity of 10 mmh^{-1} and from 0.742 to 2.421 (D_{50} = 1.32 mm) at an intensity of 20 mmh^{-1}.

Runoff Coefficient

Figure 5 is the plot of runoff coefficient for three different soil types and three various slopes/gradients considered in this study. It is clear from this figure that as the clay content

Table 2: Calculation of D_{50} for two events from rainfall simulator

Sieve size, mm	Number of pellets retained on,		Average pellet mass, mg		Average mass ratio		Average mass of drop, mg		Average drop diameter, mm		D_{50}, mm	
	I_1	I_2	I_1	I_2	I_1	I_2	I_1	I_2	I_1	I_2	I_1	I_2
3	5	3	4.820	7.740	0.972	0.960	4.685	7.430	2.076	2.421	1.2	1.32
2	10	5	4.480	5.140	0.975	0.970	4.368	4.986	2.028	2.119		
1.4	99	86	1.890	2.310	1.010	0.993	1.909	2.294	1.539	1.636		
1	159	181	0.990	1.350	1.025	1.020	1.015	1.377	1.247	1.380		
0.5	82	214	0.210	0.200	1.070	1.070	0.225	0.214	0.754	0.742		

I1=10 mmh^{-1} and I2=20 mmh^{-1}

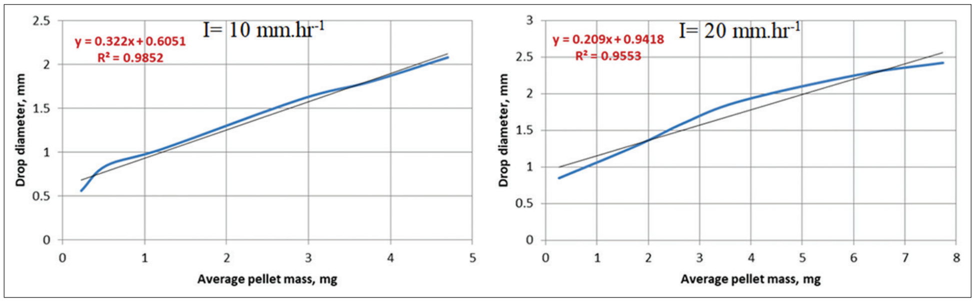

Figure 4: Correlation between the raindrop diameter and the rainfall intensity

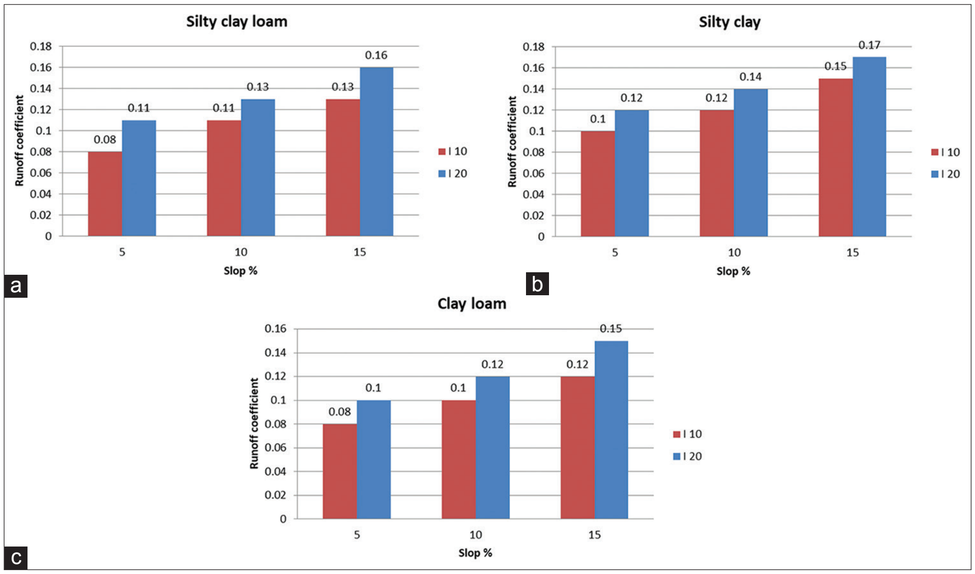

Figure 5: (a-c) Replotting the runoff coefficient under simulated rainfall with two different intensities as affected by type of soil, for different land slopes/gradients

increased from 28% to 42% a very slight change in runoff coefficient occurred. Furthermore, a very slight change in runoff coefficient was observed. The results indicated that the overall runoff coefficient ranged from a minimum of 0.079 for the 5% slop and silty clay loam (SCL) soil to a maximum of 0.153 for the slop 15% and SCL soil at rainfall intensity of 10 mmh^{-1}, and from a minimum of 0.105 for 5% slop and clay loam (CL) soil to a maximum of 0.173 for 15% slop and silty clay (SC) soil at rainfall intensity of 20 mmh^{-1}. Therefore, it can be concluded that the SC soil at 15% slop provided the highest performance under the rainfall intensity of 20 mmh^{-1}.

However, it was found that the SC and the CL soils produced the highest and lowest runoff coefficients, respectively, and those of SCL were intermediate between those of the abovementioned soils. This conclusion is true under different land slopes and two rainfall intensities.

Sediment Yield

According to the results tabulated in Table 3, it can be noticed that for a given land slope/gradient and rainfall intensity, the CL soil produced the highest soil loss. Similar results have been obtained in the researches of (Xinliang and Zhiyuan, 2017), Defersha and Melesse (2012). This may be due to the higher silt content of this soil compared with the other two soil types. Previously published studies reported that the soil erodibility increases when silt and fine sand fractions increase and clay content decreases (Le Bissonnais, 1996, Romkens et al., 1977; and Bradford and Huang, 1992).

Table 3: Soil loss under simulated rainfall for two different rainfall intensities as affected by type of soil and land slope

Sediment yield or soil loss (unit)			
Soil type	**Slop %**	**I_{10}**	**I_{20}**
SCL	5	83.0	150.3
	10	194.2	351.8
	15	262.2	474.9
SC	5	90.0	155.7
	10	228.6	395.4
	15	288.0	498.2
CL	5	278.3	378.8
	10	592.9	806.9
	15	735.1	1000.6

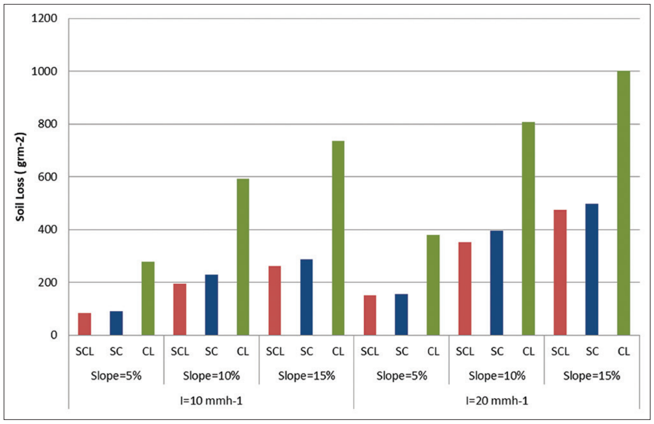

Figure 6: Soil loss from microplots subject to artificial rainfall as influenced by land slope, rainfall intensity, and soil type

It is also evident from the obtained results that a significant change in soil loss was brought about as the rainfall intensity increased from 10 to 20 mmh^{-1}.

However, as shown in Figure 6, it can be seen that as the land slope increased from 5% to 15%, there is a continuous increase in soil loss while keeping other factors constant. This can be attributed to the fact that infiltration rate is greatly increased at a higher intensity. Furthermore, the results of this study agree well with (Liu et al., 1994) whom indicated that the soil loss is directly affected by slope gradient. In addition, Wenbin et al., 2015 reported that there was a strong relationship between rainfall intensity, slope gradient, and runoff.

CONCLUSION

Based on the obtained results from the current study, it can be concluded that the runoff coefficient was increased with an increase in clay content. This conclusion is true under different land slopes and two rainfall intensities. The results also indicated that the runoff coefficient increased with an increase in the land slope in all the study soils, but the increase in slope brought an insignificant change in runoff.

Furthermore, there is indication of an increase in the effectiveness of slope on increasing runoff coefficient with an increase in rainfall intensity from 10 to 20 mmh^{1}.

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