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Full Length Research Paper

Calibration of a portable single nozzle rainfall simulator for soil erodibility study in hyrcanian forests

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A portable rainfall simulator must be calibrated before its application in field experiments. In order to calibrate a portable single nozzle rainfall simulator for a soil erodibility study in Afra Chal site in northern forests of Iran, the following rainfall parameters were assessed; rainfall Intensity-Duration-Frequency (IDF), kinetic energy, drop size and coefficient of uniformity. The results obtained show that for a given return period, the IDF curves decreased with increasing time interval. The velocity of raindrops with an average diameter of 3 mm was 780 cm/s. The simulated rainfall with intensity 32.4 mm/h had kinetic energy at the rate of 25.06 $Jm^{-2}mm^{-1}$. A rain event with this intensity occurs every 20 years for 20 min in the Afra Chal site and it was randomly selected for calibrating the simulator. Rainfall uniformities that was estimated by the coefficient of uniformity, fell within acceptable limit of 81 to 82%.

Key words: Rainfall simulator, drop size, kinetic energy, coefficient of uniformity, intensity-duration-frequency.

INTRODUCTION

To assess soil erosion under natural conditions, long term and comprehensive data is required (Epstein and Grant, 1966). Furthermore, the characteristics of natural rainfall such as kinetic energy, falling velocity, drop size and amount of rainfall is variable in time and space (Williams et al., 1998). Rainfall simulators have been developed rapidly because of their precision and manageability in the recent 50 years. They are, depending on the type, easy to transport. Furthermore, working with rainfall simulator is cost effective (Grierson and Oades, 1977). Portable rainfall simulators are commonly used for determining runoff, soil erodibility, soil infiltration, sediment yield and mineral lost in the field condition (Yu et al., 2003).

Rainfall simulators are classified by drip tube and nozzle type simulators. The drip tube design consists of a constant water reservoir placed at the top of the simulator, which feeds a grid of several hundred capillary tubes. The nozzle design uses a water source that feeds one or more nozzles at a constant specified pressure (Covert and Jordan, 2009). The natural rainfall includes wide spread of drops from diameter of 0.2 to 6 mm (Wischmeier and Smith, 1958). The mean diameter of drops for erosive rainfall is 3 mm and increases with increasing rainfall intensity. In rainfall simulations, the intensities of 12 to 120 mm h^{-1} is often used (Smith, 1993). Accuracy of rainfall simulator is achieved by creating uniform rainfall across the test plot (Blanquies et al., 2003).

Wilcox et al. (1986) developed a 1 m^2 plot rainfall simulator operational on steep terrain in the Guadalupe Mountains of New Mexico. The simulator developed is hand-portable and consists of a spray head assembly mounted on 3 adjustable legs. A 946 L tank equipped with a gasoline powered pump was connected to the spray head assembly via rubber garden hoses. A portable rainfall simulator featuring a rotating disc and nozzle was developed by Thomas and El Swaify (1989). Their uniformity coefficients ranged from 91.2 to 94.3%.

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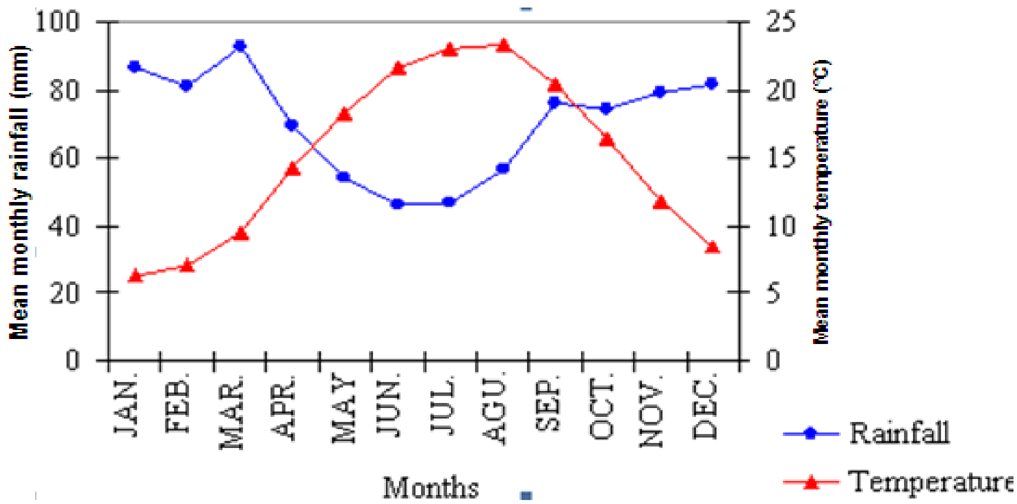

Figure 1. Ombrothermic diagram for Afra Chal station.

Table 1. Temperature and precipitation data for the Afra Chal station.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Agu.	Sep.	Oct.	Nov.	Dec.
Mean monthly temperature (°c)	6.2	7.0	9.6	14.2	18.2	21.6	23.1	23.3	20.4	16.4	11.8	8.4
Mean monthly rainfall (mm)	86.4	80.8	92.9	69.3	54.1	45.9	46.8	56.4	76.3	74.4	79.4	81.4

The kinetic energy of the simulated rainfall at intensities above 30 mm h^{-1} was close to that of natural rainfall. A small portable rainfall simulator of Trier University was used since 1995 in Germany, Spain and Morocco. It had a full cone nozzle (Lechler, 460.608), which was fed with a pressure of about 40 kPa at a height of 2 m. The rainfall intensity was maintained throughout experiments at around 40 mm h^{-1} (Iserloh et al., 2010). Rainfall simulators were designed to simulate high intensity, short duration rainfalls which cause the dislocation and transport of surface material due to raindrop impact and overland flow of excess water. A rainfall simulator at the Sari Agricultural Sciences and Natural Resources University of Iran was designed and constructed by Aidin Parsakhoo for the study of soil erodibility. The main objectives of this study were to (i) calibrate a portable single nozzle rainfall simulator and (ii) calculate rainfall parameters including kinetic energy, drop size and uniformity coefficient.

MATERIALS AND METHODS

Description of the study area

The rainfall simulator was calibrated based on precipitation data achieved from Afra Chal weather station in Mazandaran province with an elevation of about 1300 m a. s. l. (36° 14´N, 53° 15´E). The average annual precipitation in a 52 year period is 800 mm at the Afra Chal weather station, about 57% which occurs in autumn and winter. Figure 1 shows the Ombrothermic diagram of the study area. The average wind speed is 8.5 m/s (Figure 1). The average temperature in spring, summer, autumn and winter is 18, 22, 12 and 8°C, respectively (Table 1). Figure 2 illustrates the observed rainfall performed in the Afra Chal site.

Experimental method

The experiment was carried out using a portable single nozzle rainfall simulator similar to that mentioned by Arnaez et al. (2004), Martínez-zavala et al. (2008) and Jordán-López et al. (2009). The simulator was supported by four telescopic metal legs. After evaluating a number of different nozzles, the Schlick r18650 spraying systems nozzle was selected. The r18650 nozzle is connected through a rubber pipe to a mobile pump. The opening angle of the spray cone of this nozzle is generally in the range from 10 to 120°. Rainfall was simulated using a single nozzle 2 m above the ground. The water for duration of 20 min at intensity of 32.4 mm h^{-1} was fallen from the nozzle onto a squared area of 0.48 m^2 that was limited by a steel structure. In Afra Chal weather station, the recurrence period of this intensity was 20 years. Rainfall intensity was calibrated by pressure gauge and five rain gauges distributed uniformly over the plot (10 cm in diameter). This procedure was repeated twice at nozzle pressures varying from 0.7 to 0.8 g cm^{-2} to ensure rate stability during simulations. Water in rain gauges was measured every 5 min.

Calculation of the rainfall intensity-duration-frequency (IDF)

The purposes of the investigations of IDF curves are to assess rarity of the observed rainfalls and estimate extreme rainfalls for design purposes (Daniall and Tabios, 2008). Having rainfall intensity in different return periods is necessary for many hydrology

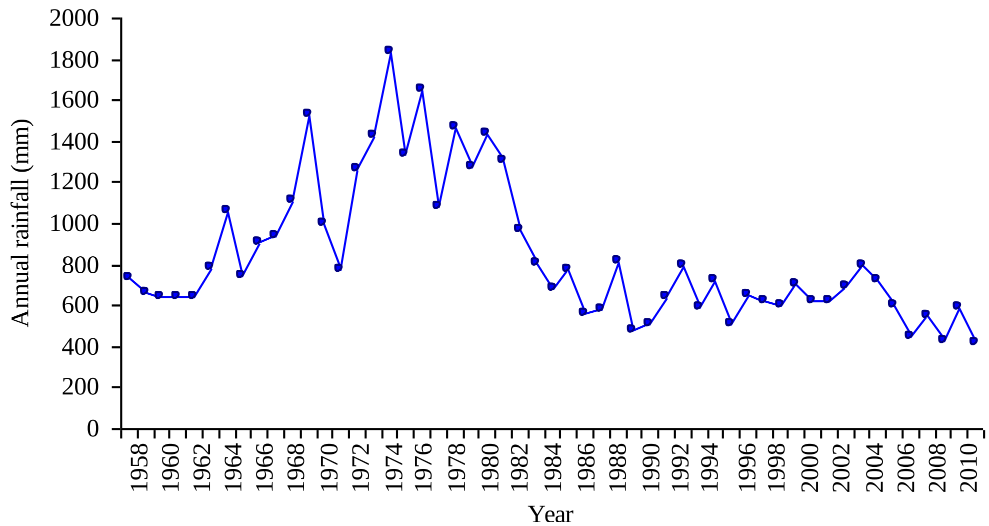

Figure 2. Status of annual rainfall in a 52-year period in Afra Chal station.

Table 2. Constant coefficients for IDF equation (Ghahraman and Abkhezr, 2004).

Rainfall duration	≤ 1 h				≤ 2 h				
	A	B	R^2*	STE	α_1	α_2	α_3	R^2	STE
Value	0.1299	0.4952	0.982	0.0419	0.4608	0.2349	0.62	0.9972	0.0222

*R-square: Coefficient of determination, STE: Standard error.

models. Estimation of the 10 year hourly rainfall is a key parameter in preparing IDF curves. Ghahraman and Abkhezr (2004) proposed Equations 1 and 2 to describe the rainfall intensity duration relationship for north of Iran as:

$$P_t^T = At^B\left[\alpha_1 + \alpha_2 Ln(T-\alpha_3)\right]p_{60}^{10} \quad (1)$$

$$p_{60}^{10} = 9.99 + 0.212(P\max) \quad (2)$$

Where *A*, *B*, α_1, α_2 and α_3 are constant coefficients, *T* is return period (year), *t* is rainfall duration (minute), *P*max is mean of maximum daily rainfall (mm), P_t^T is *t* minute precipitation in return period of *T* and p_{60}^{10} is 10 year hourly rainfall.

To prepare the best model for calculation of rainfall intensity in IDF table, the constant coefficients were determined according to the findings of Ghahraman and Abkhezr (2004) (Table 2).

Calculation of the kinetic energy of rainfall

Rainfall produced by the simulators should have a kinetic energy similar to natural rainfall and it should be uniform (Foltz et al., 1995). In this study, the kinetic energy of the rainfall intensity of 32.4 mm h^{-1} was calculated using Equation 3 (Wishmeier and Smith, 1958):

$$K_E = 11.87 + 8.73\log I \quad (3)$$

Where K_E is kinetic energy (J m^{-2} mm^{-1}) and *I* is rainfall intensity (mm h^{-1}).

Estimation of drop size and velocity

Rainfall is a population of raindrops of various sizes (Adetayo et al., 2008). In this study, the drop sizes were measured using the flour tray method defined by Carter et al. (1974) (Figure 4). The drop impact on flour was estimated using a ruler. According to the drop diameter, the velocity of each drop was extracted from Refahi (2005) curve (Figure 7). Figure 3 shows the rainfall simulator and nozzle used in current study.

Calculation of the uniformity coefficient of rainfall

In the past few decades, several coefficients of uniformity (CU) were developed to express the uniformity of water distribution for different irrigation systems (Ayalew et al., 2012). Christiansen's uniformity coefficient seems to be the most popular CU used by researchers on the global scale (Maroufpoor et al., 2010). The rain in rain-gauges tends to follow a normal distribution when the CU value is approximately 70% or higher (Esteves et al., 2000; Maroufpoor et al., 2010). To evaluate rainfall distribution in time and space scale, we used Christiansen CU (Christiansen, 1942; Equation 4):

$$CU = 100\left(1 - \left(\frac{\sum_{i=1}^{i=n}\left|X_i - \overline{X}\right|}{\overline{X}}\right)\right) \quad (4)$$

Figure 3. Spraying rain drops from nozzle.

Figure 4. Measuring the diameter of drop impact on flour.

Where $\overline{X}$ is the mean rainfall intensity (mm h^{-1}), n is the number of observations, and X_i (i = 1, 2,. . .,n) are the individual observations. Figure 5 shows the field testing of rainfall simulator to evaluate coefficient of uniformity.

RESULTS AND DISCUSSION

Rainfall simulator must be calibrated based on regional conditions of precipitation before applying in field experiments. Foltz et al. (2009) calibrated a rainfall simulator at nozzle pressure varying from 41 to 42 kpa to produce rainfall with an intensity of 100 mm h^{-1} in a duration of 30 min. Arnaez et al. (2004) simulated a rainfall for duration of 30 min at intensity of 75 mm/ha. The drops size of this simulator was 0.8 to 2 mm. Results indicated that the 10-year hourly rainfall was 16.35 mm h^{-}

Figure 5. Calibration of the simulator using rain gauges.

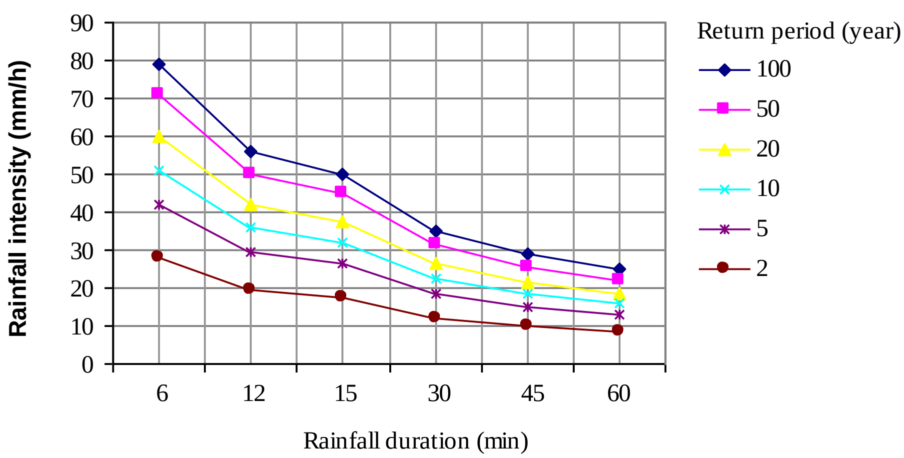

Figure 6. IDF Curves for short duration rainfalls in Afra Chal station.

The rainfall intensity of 32.4 mm h^{-1} occurred every 20 years for duration of 20 min. For a given return period, the rainfall intensity decreased with increasing rainfall duration (Figure 6):

$$p_{60}^{10} = 9.99 + 0.212(30) = 16.35mm$$

$$P_t^T = 0.1299t^{0.4952}[0.4608 + 0.2349Ln(T - 0.62)]16.35$$

Raindrop velocity can be calculated from the drop size characteristics in a steady state condition (Figure 7) after the findings by Refahi (2005). Results of the current study showed that the velocity of raindrop with diameter of 3 mm was 780 cm s^{-1}. The simulated rainfall with intensity of 32.4 mm h^{-1} gave kinetic energy at the rate of 25.06 J m^{-2} mm^{-1} (calculated after Equation 3). The results obtained show that the uniformity coefficient of the simulator rainfall was 81 to 82% (Table 3). Shelton et al. (1985) reported a minimum CU value of 84% with nozzle heights averaging 2.5 m. Lascano et al. (1997) reported CU values ranging from 84 to 94% for a 1.25 m^2 plot with nozzles at a 2 m height.

Conclusion

Rainfall simulator is a useful tool for soil erosion study. But before staring of each experiment, simulator must be calibrated based on the properties of regional precipitation especially, IDF. Several factors including drop size, velocity, kinetic energy, rainfall intensity and coefficient of uniformity should be considered to calibrate this tool. We found out that rainfall uniformities estimated

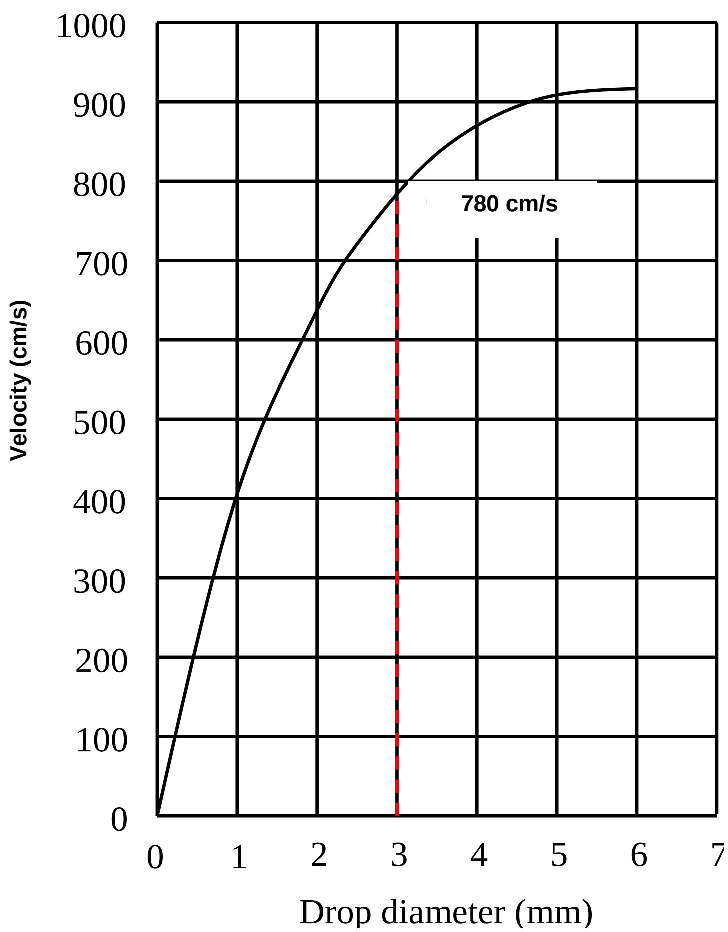

Figure 7. Determination of drop velocity from drop diameter (after Refahi 2005).

by the coefficient of uniformity was 81 to 82% and this fell within acceptable limits (≥70%), but were affected by water pressure variation and as such, rainfall simulator could be calibrated and controlled easily for field experiments.

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