**DESIGN OF A PORTABLE RAINFALL SIMULATOR DEVICE TO EVALUATE THE FACTORS AFFECTING SOIL WATER EROSION**

***Egypt. J. of Appl. Sci., 34 (11) 2019 335-358***

**Salem, H. M. and A. A. Meselhy**

Soil conservation Department, Desert Research Center, Mataria, Cairo, Egypt

**Key Words:** Rainfall simulation, Rainfall intensity, Soil slope, Runoff, Soil loss, Northwestern Coast of Egypt.

**ABSTRACT**

A portable low-cost field rainfall simulator was designed to provide rainfall intensities in the range of 14 to 80 mm h−1. The designed simulator is easy to assemble, transport and its portability and flexibility enable the necessary experimental replicates in remote locations. The simulator was tested in terms of Christiansen Uniformity coefficients that ranged from 89 to 94% for the three Full-jet nozzles used in this study, with median diameters ranged from 0.836 to 2.113 mm, showing an appropriate degree of accuracy. The terminal velocities of the raindrops was also examined and ranged from 3.35 to 6.83 m s−1. Furthermore, kinetic energy values ranged from 12.7 to 18.9 J m−2 mm−1, showing similarity to the natural rainfall occurs in the Mediterranean regions under conditions of low rainfall intensity. The applicability of the rainfall simulator in the dynamic processes of erosion characteristics was investigated in the northwestern coastal zone of Egypt, where erosion is an important threat of sustainability. Five rainfall intensities (14, 21, 30, 36, and 45 mm h−1) were evaluated in three repetitions at three uncultivated sites having slope gradients of 5, 9 and 12 %, forming 45 simulated rainfall. The changes of sediment yield, sediment concentration, runoff rate and runoff coefficient for the 45 simulated rainfall were quantified. Altogether, the results indicated that runoff and sediment yield rates were substantially different between the rainfall intensities of 14 and 45 mm h−1than those obtained between any other pairs of intensities under all soil gradients. Summing up the results, the designed portable rainfall simulator can be effectively used in studying the dynamic processes of soil erosion in field scale, specifically quantifying these processes in the presence of variability in rainfall intensity and soil slope.

**1. INTRODUCTION**

Soil erosion is one of the major threats to the sustainability of natural ecosystems and is considered the main mechanism of land degradation **(Dlamini et al., 2011).** Soil erosion by water involves the processes of detachment, transport and deposition of soil materials **(Kinnell, 2000).** Knowledge of the mechanism of the erosion process will help to develop reliable prediction models and improve erosion management **(Wu et al., 2017).**

In the northwestern coastal zone of Egypt, soil erosion hazard is a serious problem that reduce soil quality and increase the degradation of soil resources **(Afifi and Gad, 2011).** This region is located in an arid environment, and land use and human settlements are entirely dependent on rainfall and on various forms of water harvesting. Therefore, it is obvious that understanding the behavior of soil erosion will help planners to control the degradation of productive soils, to decrease expenses caused by erosion, and to optimize the benefits of precipitation **(Vahabi and Nikkami, 2008).**

***336 Egypt. J. of Appl. Sci., 34 (11) 2019***

Soil erosion by water is related to a number of factors such as rainfall characteristics, including rainfall intensity and duration, also, soil surface conditions such as (slope length and steepness, antecedent moisture content, vegetation cover) **(Angulo-Martinez et al., 2012; Defersha and Melesse, 2012; Mahmoodabadi and Sajjadi, 2016).** Rainfall intensity and slope gradient are two important influencing factors to erosion. Usually erosion increased with the increasing of rainfall intensity and slope gradient **(Römkens et al., 2001; Berger et al., 2010).**

In an arid environment, rainfall intensity significantly influenced the amount of soil erosion **(Ziadat and Taimeh, 2013).** In addition, slope gradient affects splash erosion, because as steepness increases, more soil particles are splashed downslope than upslope **(Grismer, 2012).** Indeed, slope gradient significantly influences downslope splash loss **(Fu et al., 2011)** soil erosion rate in uncultivated land was primarily affected by slope steepness, while, in cultivated land, it was mostly influenced by moisture content **(Ziadat and Taimeh, 2013).** Consequently, it is imperative to evaluate the dynamic mechanisms of soil erosion and surface runoff.

Rainfall simulators are essential tools for investigating the dynamic processes of surface runoff, infiltration, and erosion characteristics **(Grismer, 2016)** and research involving sediment, nutrient, and pollutants’ transport as well as for evaluating the impacts of tillage management on compaction and infiltration in agricultural soils **(Aksoy et al., 2012; Boulange et al., 2019).** Its application allows a quick, specific and reproducible assessment of the meaning and impact of several factors, such as slope, soil type, soil moisture, splash effect of raindrops, surface structure, vegetation cover and vegetation structure **(Iserloh et al., 2012; Iserloh et al., 2013a).**

Rainfall simulators on small plots represent an important category because they make it possible to distinguish the different sub-processes related to runoff generation and erosion **(Iserloh et al., 2012).** In most cases, the rainfall simulators employed for field experiments are characterized by simple and low cost components, also enable data to be obtained under controlled conditions and over relatively short time periods compared to the simulator used in laboratory studies. This is because the experiment sites are sometimes difficult to reach, moreover, energy and water supplies are usually limited **(Vergni et al., 2018).**

There are two common types of rainfall simulators that are classified according to how they produce raindrops: (i) drip (or drop) formers, usually built with hypodermic needles, and (ii) nozzle-type **(Esteves et al., 2000; Battany and Grismer, 2000)**. The choice is usually based on geometrical constraints, portability, and costs.

***Egypt. J. of Appl. Sci., 34 (11) 2019 337***

As to the size of the rainfall devices, a plot size of 1 m2 being a frequently used format **(Iserloh et al., 2013a, 2013b).** There is no standardization of rainfall simulation and these rainfall simulators differ in design, rainfall intensities, spatial rainfall distribution, drop sizes and drop velocities, which impede drawing a meaningful comparison between results **(Iserloh et al., 2013b)**. Nevertheless, the data have become progressively important for soil erosion assessment and decision-making in application-oriented erosion protection. Therefore, the accurate knowledge of test conditions is a fundamental requirement and is essential to interpret, combine and classify results **(Boulal et al., 2011; Clarke and Walsh, 2007; Ries et al., 2013).**

Desirable characteristics for rainfall simulators used in erosion and hydrological studies include the rainfall intensity, spatial rainfall uniformity over the entire test plot, the drop size, its distribution and terminal velocity. Other important factors including the accurate control of rainfall intensity, the similarity to natural rainfall in terms of kinetic energy. Additionally, the repeatability of the simulated rainstorms, and the improved mechanical and technical reliability for simple and easy transportation within research areas **(Lascano et al., 1997; Cerdà, 1999; Humphry et al., 2002; Clarke and Walsh, 2007; Abudi et al., 2012).**

Many techniques were used to characterize simulated rainfall, such as the flour pellet method **(Hudson, 1963),** laser particle measuring system **(Salles and Poesen, 1999; Salles et al., 1999),** plastermicro plot **(Ries and Langer, 2001),** indication paper **(Brandt, 1989; Cerdà et al., 1997a; Salles et al., 1999),** and Joss-Waldvogel Disdrometer **(Hassel and Richter, 1988)** among others. It was shown that the results of the characterization of simulated rainfall were extremely dependent on the particular method that was applied **(Ries et al., 2009).**

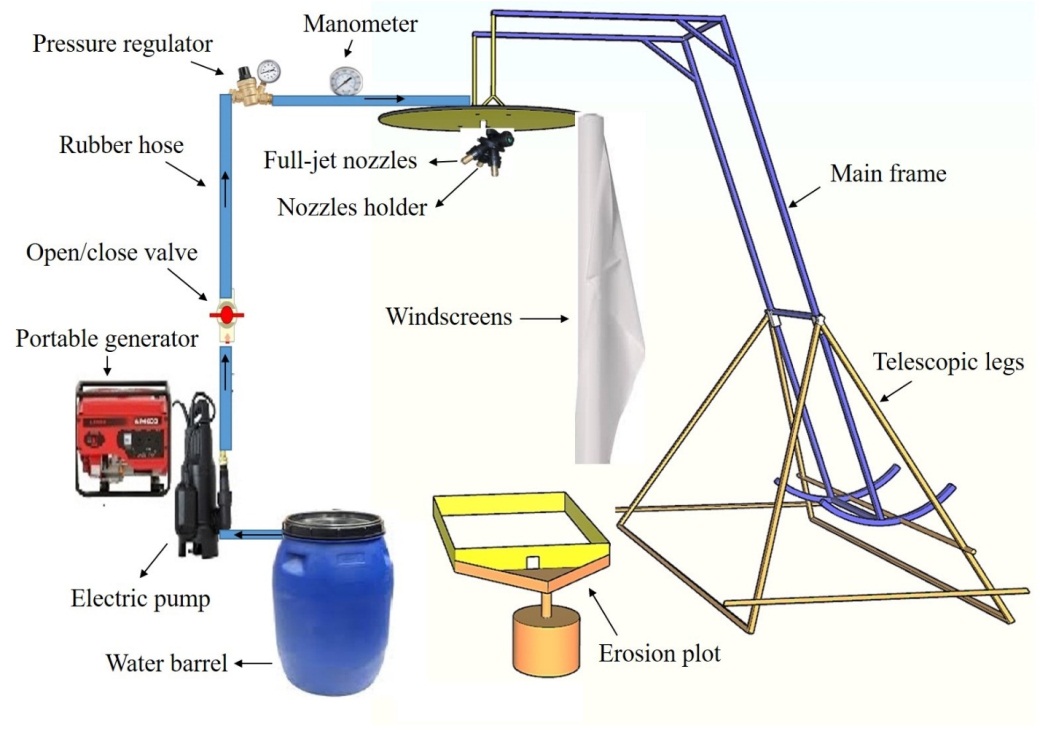
To the best of our knowledge, there is a lack of studies regarding the dynamic processes of erosion characteristics in the northwestern coastal zone of Egypt. A large amount of information is needed to understand behaviors and interaction of the different components that govern the erosion processes. In view of that, the objectives of this study are (1) to describe the portable rainfall simulator design, its performance, and testing its efficacy in simulating rainfalls that induce runoff and soil erosion, and (2) to investigate impacts of rainfall intensity and slope gradient on sediment yield, sediment concentration, runoff rate, and runoff coefficient.

**2. MATERIALS AND METHODS**

***338 Egypt. J. of Appl. Sci., 34 (11) 2019***

**2.1. General design of the portable rainfall simulator**

In the present study, a pressurized-nozzles rainfall simulator has been designed for field soil erosion study. The simulator is designed to be completely portable and made from readily available and inexpensive materials, and requires minimal construction and operational process (Fig. 1). The rainfall simulator can hold different spray nozzles with homogeneously producing water distribution drops with a drop size distribution similar to that of natural rainfall in the region. According to **Covert and Jordan (2009),** rainfall simulators should be designed with the nozzles at a height of 3 m to replicate the velocity and kinetic energy of natural rainfall. Therefore, nozzles of the designed simulator were raised to a height of 3 m to ensure that the raindrops achieve their terminal velocity. The main components of the rainfall simulator are water-feeding system, spray nozzles, supporting metal frame, and windscreens surrounding the irrigated area.



**Fig. 1.** The portable rainfall simulator

In the water-feeding system setup, a 300 L water storage barrel was connected with ¾ hp electric pump, which is driven by a 3000-W portable gasoline-powered generator, rubber garden hose distributes water from the pump to the spray nozzles. Three Full-jet nozzles with a full cone spray angle of 1200 including the 1/8GG 4.3W, 1/4GG 10W, and the 1/4GG 14W were selected.

A triplet nozzle holder was used for switching between the three nozzles. The flow rate was controlled by using open/close valve. These nozzles have already been used successfully in rainfall simulation studies **(Tossell et al., 1987)**, and provided different rainfall intensities between 14 and 80 mm h−1 at pressure between 48 and 69 KPa. The pressure in these nozzles was monitored by glycerin manometer. The required pressures were easily achieved by connecting a pressure regulator to the nozzle inlet.

***Egypt. J. of Appl. Sci., 34 (11) 2019 339***

Circular steel holder hanged these nozzles and a 20 mm steel pipe to the main frame. The main frame of the apparatus was constructed from a 32 mm diameter aluminum pipes. This component was mounted on telescopic tripod legs to ensure that the nozzles are perpendicular to the horizon of the soil surface and to guarantee stability of the simulator during the experiment. Windscreens made from PVC plastic traps were fitted to the circular steel holder that is easily attached and detached for transport.

**2.2. Rainfall simulator calibration**

***2.2.1. Spatial rainfall distribution***

To generate quantitative information about the homogeneity of produced rainfall and its reproducibility, we covered the 1 × 1.4 m2 plot areas according to a regular grid (20×20 cm) by 48 circular rain gauges; each has a diameter of 82 mm. Water was collected in these gauges for 15 min of continuous flow from each nozzle. Collected volumes in each gauge were measured using a graduated cylinder in (ml), and three repetitions were undertaken, then the results converted into intensity values (mm h–1). The spatial distribution of rainfall was described by using Sigmaplot 11.0 software. Coefficient of Variation (CV) and mean Christiansen Uniformity (CU) coefficient **(Christiansen, 1942)** were adopted to describe the uniformity of the rainfall events, and CU was calculated using Eq. (1).

CU = 100% (1)

Where is the sum of the absolute deviations from mean water amount of all rain gauges (ml), x**i**is individual water amount per rain gauge (ml), is the arithmetic mean of applied water amount per rain gauge (ml), and is the total number of rain gauges.

***2.2.2. Drop size distribution and fall velocity***

Assessing the drop size distribution of rainfall is necessary to evaluate the erosive potential of soil surfaces **(Lora et al., 2016)**. Several authors have reported that the drop sizes of natural low rainfall intensities were characterized by the median drop size (D50) and it is varying from 1.5 to 2.5 mm **(Assouline et al., 1997; Uijlenhoet and Stricker, 1999; Krajewski et al., 2005; Abudi et al., 2012).** Characteristics of the artificial rainfall were examined by using indication paper (water sensitive paper/card) method that described by **Hall (1970)**, and it could be considered the most frequently used method for measuring the drop size distribution of natural or simulated rainfall **(Cerdà et al., 1997; Erpul et al., 1998; Ries et al., 2009; Salem et al., 2014).** This method is based on the assumption that a drop falling upon a uniform absorbent surface produces blue spots with a diameter proportional to the diameter of the drop. Thirty water sensitive cards were exposed to the simulated rainfall for two seconds under different rainfall intensities; the dimensions of each card were 52 mm ×76 mm. All of these cards were photographed with high-resolution RGB camera 120 Mpix, and then all images were subsequently processed by Matlab 7.0 software in order to estimate the D50.

The drop velocity was calculated according to the Eq.(2) proposed by **Beard and Pruppacher, (1969)**, and mentioned by **Van Dijk et al., (2002)** these works showed that under standard conditions of air pressure (1 bar) and air temperature (20 0C) and for drop sizes of 0.1–7 mm, this equation is approximated very well by the third-order polynomial equation:

***340 Egypt. J. of Appl. Sci., 34 (11) 2019***

Vd = 0.0561D3 – 0.912D2 + 5.03D – 0.254 (2)

D, is the drop size. This equation agrees to within 3% with the more complex equations of **Beard (1976).** Therefore, it can be considered accurate enough for the purpose of this study.

Kinetic energy of rain is usually expressed as the amount of rain kinetic energy expended per unit volume of rain, KE (J m−2 mm−1) was estimated by applying the standard kinetic energy equation, under the assumption that the Drop size distribution obtained from the water sensitive card method is representative of the entire plot area. More specifically, the equation applied was the following Eq. (3):

KE = (3)

Where *i*, is the single drop diameter with *i*=1,…; Nd, is the total number of drops; mi (kg), is the mass of the single drop derived from its diameter; vd,i (m s–1), is the velocity of ith drop; *ρ*, is the water density (1000 kg m–3).

**2.3. Field experiments**

Field experiments to measure water runoff and sediment loss were established in three uncultivated sites having different slope gradients at El-Qasr region. These sites lies approximately 10 km Southwest of the Marsa Matruh city and 3 km from the Mediterranean sea in Egypt’s northwestern coastal zone (latitude: 31° 21' 08''; N, longitude: 28° 08' 40''; E, and an altitude of 30 m above sea level). The soil slopes in these sites are in South–North direction. The climate is arid and the mean annual temperature is 20.4 0C (based on locally recorded data covering the period from 1961 to 2019). The mean annual precipitation ranges from 86 mm to over 225 mm, over 85% of the precipitation occurs between December and February in a short and intensive storms. Both water and wind erosion are severe in this region due to the erodible soil and the concentrated rainfall season. The soil is sandy loam, with a low organic content and high calcareous. The soil physical and chemical characteristics of the study area are presented in (Table 1).

**Table 1. Physical and chemical properties of the soil measured at 0-20 cm of the three sampling sites.**

***Egypt. J. of Appl. Sci., 34 (11) 2019 341***

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Sampling sites** | **Soil slope (%)** | **pH** | **ECe**  **(dS m−1)** | **O.M**  **(%)** | **CaCO3**  **(%)** | **Particle size distribution (%)** | | | **Bulk density (Mg m-3)** | **Cone index (MPa)** | **Volumetric moisture content**  **(cm3 cm−3)** |
| **Sand** | **Silt** | **Clay** |
| **1** | **5** | **7.9** | **1.14** | **0.58** | **15.35** | **64.1** | **21.2** | **14.7** | **1.53** | **1.35** | **0.15** |
| **2** | **9** | **7.7** | **0.95** | **0.53** | **15.49** | **62.9** | **20.1** | **17.0** | **1.55** | **1.47** | **0.15** |
| **3** | **12** | **7.8** | **1.13** | **0.36** | **15.80** | **61.6** | **21.2** | **17.2** | **1.56** | **1.49** | **0.13** |

The experimental design included two factors: rain intensity and bare soil slope gradient. Rainfall intensities of 14, 21, 30, 36, and 45 mm h−1 were applied sequentially at 5, 9, and 12 % slope gradients in three repetitions using the developed rainfall simulator. Each experiment had a duration of 45 min, divided into fifteen measuring intervals (3-minute duration).The rain intensity was calibrated before and after each simulated rain. The slope inclination was measured by using a digital inclinometer.

The size of the homogeneously wetted area becomes very important when dealing with runoff generation on natural soils **(Abudi et al. 2012);** therefore, forty-five erosion plots with 1 m × 1.4 m dimensions were established in the region based on the plot sizes used in the studies of **Barthes and Roose (2002).** The plots were surrounded with galvanized frames of 15 cm height inserted 5 cm into the soil to control lateral water movement. The galvanized frame included a collection system made of a gutter located at the down-slope edge of the frame and connected to a pipe and a container (Fig. 2).

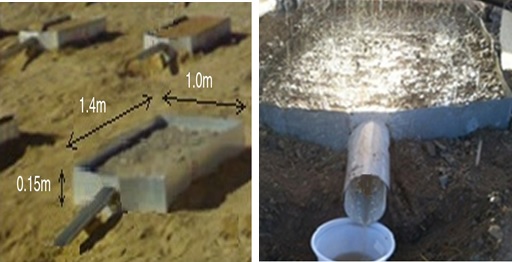
The rainfall simulations were conducted in May 2018 during one field campaign under dry soil conditions in order to avoid any variability induced by changes in soil moisture conditions. The initial and final soil water content were measured before and after the simulations.

Both water and wind erosion are severe in this region due to the erodible soil and the concentrated rainfall season: over 85% of the precipitation occurs between December and February in a short and intensive storms.

During the simulation, the following data were collected from each plot: the time lag (the number of seconds between the beginning of the rainfall simulation and the beginning of the runoff). Once the generation of runoff occurred, runoff and sediment samples were collected every 3 min, and in each sampling inter-time, all the runoff were gathered using bucket and measured the total volume (ml) then converted to mm h−1. Runoff coefficient (the percentage of rainfall that become runoff) was calculated. The sediment in the runoff was filtered by dry filter papers, then dried the filter papers at 60 °C for 24 h and weighed by high-precision (0.001 g) scales to calculate the sediment concentration (g L−1). The sediment concentration was defined as the ratio of dry sediment mass to runoff volume, while the sediment yield rate was determined by dividing the sediment yield per unit area for the sampling inter-time.

***342 Egypt. J. of Appl. Sci., 34 (11) 2019***

Analysis of variance (ANOVA) was conducted to examine significant differences among group mean. The values presented in this study were the mean with standard deviations. A general linear model (GLM) was used to statistically analyze the main and interactive effects of the variables. All the data analysis was conducted by SPSS version 19 (SPSS Inc., Chicago, Illinois, USA).



**Fig. 2.** The erosion plots used in this study

**3. RESULTS AND DISCUSSION**

**3.1. Rainfall simulator calibration**

***3.1.1. Spatial rainfall distribution***

The rainfall simulator achieved a uniform rainfall distribution, the simulator provided rainfall intensities between 14 to 80 mm h−1 obtained from different water pressures that ranged from 48 to 69 kPa using three different nozzles. The coefficients of Christiansen Uniformity (CU) ranged from 89 to 94% for the three nozzles used in this study (Table 2). The CU values are satisfactory and in agreement with previous studies **(Aksoy et al., 2012; Iserloh et al., 2013; Lora et al., 2016).** Additionally, the coefficients variation (CV) ranged from 7.8 to 13.1% and these values demonstrate the reproducibility of artificial rainfall of most of the simulators tested in previous studies **(Iserloh et al., 2013).**

**Table 2. Rainfall intensities, coefficients of Christiansen Uniformity (CU), and coefficients of variation (CV) for different nozzles working at different pressures over a 1 m × 1.4 m surface.**

***Egypt. J. of Appl. Sci., 34 (11) 2019 343***

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Nozzle type** | **Pressure (kPa)** | **Rainfall intensity**  **( mm h−1)** | **CU (%)** | **CV (%)** | **Median diameter D50 (mm)** | **Terminal velocity**  **(m s−1)** |
| **1/8GG 4.3W** | **48** | **14** | **89.8** | **13.1** | **0.836** | **3.35** |
| **1/8GG 4.3W** | **51** | **19.2** | **88.3** | **13.6** | **1.018** | **3.98** |
| **1/8GG 4.3W** | **52** | **21.1** | **90.1** | **12.9** | **1.118** | **4.31** |
| **1/4GG 10W** | **50** | **26.3** | **91.4** | **12** | **1.331** | **4.96** |
| **1/4GG 10W** | **55** | **30.2** | **91.7** | **11.6** | **1.532** | **5.64** |
| **1/4GG 10W** | **63** | **36** | **92.1** | **10.4** | **1.584** | **5.69** |
| **1/4GG 14W** | **49** | **45.2** | **93.2** | **9.4** | **1.714** | **6.05** |
| **1/4GG 14W** | **56** | **51.5** | **93.4** | **9.1** | **1.843** | **6.27** |
| **1/4GG 14W** | **61** | **68.4** | **94.7** | **7.8** | **1.960** | **6.52** |
| **1/4GG 14W** | **69** | **80.1** | **94.5** | **7.8** | **2.113** | **6.83** |

The CU is a useful index of spatial uniformity of rainfall. The more uniform the pattern of rainfall is, the closer CU approaches to 100% **(Aksoy et al., 2012).** A rainfall can be considered uniform when CU is higher than 80% **(Moazed et al., 2010).** Even, for large plot, rainfall can be accepted as uniform if CU value is greater than 70% **(Luk et al., 1993).** Although, it is seen that the spatial rainfall distribution under low rainfall intensity shows a concentric pattern with the highest rainfall amount recorded in the center and the lowest rainfall amount recorded around the rim of the plot (Fig. 2, a). In general, the rainfall simulator can be considered good enough in reproducing spatially uniform rainfall over the plot. The applied water pressure and nozzle’s physical properties cause this deviation under low rainfall intensity. The good spatial reproducibility of the rainfall events and the higher values of coefficients of uniformity is the main reason to accept this drawback. The water pressure system was reduced as much as possible to create the largest possible drop size and this reduction created a slighter heterogeneity of spatial distribution across the plot under low rainfall intensity, however, the heterogeneity decreased with increasing rainfall intensities (Fig. 3, b and c). The variation across the plots can be considered acceptable (e.g., in the range described by **Humphry et al., (2002) and Pérez-Latorre et al., (2010).**



***344 Egypt. J. of Appl. Sci., 34 (11) 2019***

**Fig. 3 (a, b, and c**). Distribution of simulated rainfall intensities over 100 × 140 cm plot area using (a) nozzle 1/8GG 4.3W, pressure 48 kPa, (b) nozzle 1/4GG 10W, pressure 55 kPa, and (c) nozzle 1/4GG 14W, pressure 49 kPa.

***3.1.2. Drop size distribution and fall velocity***

***Egypt. J. of Appl. Sci., 34 (11) 2019 345***

The median diameters and terminal velocities of raindrops are given in (Table 2), Drop size increased with rainfall intensity. The median diameter (D50) ranged from 0.836 to 2.113 mm. It was 0.836 mm for the 14 mm h−1 rainfall intensity, whereas for intensities of 26 and 80 mm h−1, the diameters reached 1.331 and 2.113 mm, respectively (Fig. 4). These sizes are slightly smaller than the typical drop sizes of natural rainfall, which are reported as varying from 1.5 to 2.5 mm **(Laws and Parsons, 1943; Assouline et al., 1997; Krajewski et al., 2005; Abudi et al., 2012).** However, our results in agreement with previous studies **(Cerdà, 1997a,b)** which indicated that the drop diameter of natural rainfall is usually smaller than 2 mm **(Cerdà, 1997a,b).** In addition, similar ranges of D50 have been measured using other rainfall simulators **(de Limaetal et al., 2009; Iserloh et al., 2013).**



**Fig. 4 (a, b, and c**). The median droplets diameters (D50) measured for rainfall intensities of (a) 14 mm h−1, (b) 26 mm h−1, and (c) 80 mm h−1.

Terminal velocities of the raindrops increased with the increasing value of raindrop diameters as mentioned by **Kesgin et al. (2018),** the terminal velocities values ranged from 3.35 to 6.83 m s−1. It was 3.35 m s−1 for the 14 mm h−1 rainfall intensity, whereas for intensities of 30 and 45 mm h−1, the terminal velocities reached 5.64 and 6.05 m s−1, respectively.

***346 Egypt. J. of Appl. Sci., 34 (11) 2019***

Kinetic energy associated to the mean raindrop diameter calculated on the basis of the corresponding terminal velocity was in the range of (12.7 to 18.9 J m−2 mm−1), lower than 23.9 J m−2 mm−1 obtained by **Miller (1987)** and in the range obtained by **Assouline et al. (1997) and Lascano et al. (1997)**. This difference in kinetic energy can be ascribed to the lower mean drop diameter obtained in our study. Moreover, this kinetic energy can be considered usual in natural rainfall in Mediterranean regions for low rainfall intensities **(Salles et al., 2002; Pérez-Latorre et al., 2010)**, and it is similar to the median value observed by **Ramos and Martınez-Casanovas (2006)** for rainfall intensities between 10 and 100 mm h−1.

**3.2. Runoff and soil loss processes**

The GLM analysis identified significant effects (P < 0.05) of soil slope and rainfall intensity on runoff depth, time lag, sediment concentration, and sediment yield rate (Table 3). The interactions of soil slope and rainfall intensity on runoff depth, time lag, sediment concentration, and sediment yield rate were significant.

**Table 3. Results of the GLM test for evaluating the individual and interactive effects of soil slope and rainfall intensity on runoff and soil loss.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Source** | **Dependent**  **variable** | **Type III sum of squares** | **df** | **Mean square** | ***F*-value** | ***P*-value** |
| **SS** | **RD (mm)** | **45.02** | **2** | **22.51** | **358.08** | **0.000** |
|  | **TL (s)** | **999, 31.91** | **2** | **499, 65.95** | **18.03** | **0.000** |
|  | **RC (%)** | **566.51** | **2** | **283.25** | **398.05** | **0.000** |
|  | **SC (g L−1)** | **44.06** | **2** | **22.03** | **21.33** | **0.000** |
|  | **SY (g m−2.h−1)** | **2354.40** | **2** | **1177.20** | **101.51** | **0.000** |
| **RI** | **RD (mm)** | **36.07** | **4** | **9.02** | **141.44** | **0.000** |
|  | **TL (s)** | **754, 204.00** | **4** | **188, 551.00** | **68.02** | **0.000** |
|  | **RC (%)** | **10.87** | **4** | **2.72** | **3.82** | **0.013** |
|  | **SC (g L−1)** | **35.78** | **4** | **8.95** | **8.66** | **0.000** |
|  | **SY (g m−2.h−1)** | **4035.58** | **4** | **1008.90** | **86.10** | **0.000** |
| **SS × RI** | **RD (mm)** | **5.19** | **8** | **0.65** | **10.18** | **0.000** |
|  | **TL (s)** | **605, 37.20** | **8** | **756, 7.15** | **2.73** | **0.022** |
|  | **RC (%)** | **16.43** | **8** | **2.05** | **2.87** | **0.016** |
|  | **SC (g L−1)** | **39.76** | **8** | **4.97** | **4.81** | **0.001** |
|  | **SY (g m−2.h−1)** | **358.76** | **8** | **44.22** | **3.81** | **0.003** |

**SS, soil slope; RI, rainfall intensity; RD, runoff depth; TL, time lag; RC, sediment concentration; SY, sediment yield rate.**

The average of time lag, runoff coefficient, and sediment concentration for different rainfall intensities and soil slope gradient are presented in Table 4. For time lag, both slope gradient and rainfall intensity had an accelerating effect on runoff generation, which is in accordance with most of previous studies **(Zhao et al., 2013; Deng et al., 2019).** The runoff starting time (time lag) lagged behind the starting time of rainfall simulation, for instance, the time lag of the rainfall intensity of 14 mm h−1 started after the beginning of rainfall simulation by 16.2, 13.6, and 12.8 min under the soil gradient of 5, 9, and 12%, respectively. This can be explained by the fact that soil is moistened and the soil pores are filled with water at the beginning of rainfall simulation, which accounts for the hysteresis effect of runoff occurrence **(Deng et al., 2019).**

**Table 4. Mean time lag, runoff coefficient, and sediment concentration for different rainfall intensities and soil slope gradient.**

***Egypt. J. of Appl. Sci., 34 (11) 2019 347***

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Soil slope (%)** | **Rainfall intensity**  **(mm h–1)** | **Time lag**  **(s)** | **Runoff coefficient**  **(%)** | **Sediment concentration**  **(g l–1)** |
| **5** | **14** | **969.3 ± 77.6 a** | **4.12 ± 0.26 b** | **9.83 ± 0.14 b** |
| **21** | **775.3 ± 85.7 b** | **5.31 ± 0.42 a** | **10.73 ± 0.25 ab** |
| **30** | **620 ± 42.7 bc** | **4.75 ± 0.32 ab** | **10.78 ± 0.24 ab** |
| **36** | **600.7 ± 35.0 bc** | **4.55 ± 0.23 ab** | **13.36 ± 1.14 a** |
| **45** | **563.3 ± 43.9 c** | **5.20 ± 0.38 a** | **10.09 ± 0.17 b** |
|  |  |  |  |  |
| **9** | **14** | **817.7 ± 40.1 a** | **10.36 ± 0.57 a** | **6.47 ± 1.26 b** |
| **21** | **773.7 ± 53.5 a** | **9.24 ± 0.79 ab** | **9.64 ± 1.33 a** |
| **30** | **565.3 ± 42.6 b** | **8.79 ± 0.69 ab** | **11.43 ± 1.05 a** |
| **36** | **562.8 ± 33.5 b** | **8.48 ± 0.56 b** | **9.21 ± 0.39 a** |
| **45** | **448.7 ± 46.0 b** | **7.67 ± 0.72 b** | **11.24 ± 0.46 a** |
|  |  |  |  |  |
| **12** | **14** | **765.7 ± 42.7 a** | **15.20 ± 1.27 a** | **7.85 ± 1.00 a** |
| **21** | **644.7 ± 53.6 a** | **13.37 ± 1.20 a** | **8.24 ± 0.90 a** |
| **30** | **636.3 ± 41.9 a** | **12.89 ± 1.49 a** | **9.52 ± 0.55 a** |
| **36** | **465.0 ± 57.6 b** | **12.55 ± 0.78 a** | **8.65 ± 1.36 a** |
| **45** | **441.7 ± 60.0 b** | **13.35 ± 1.42 a** | **8.54 ± 0.52 a** |

**Values for different rainfall intensity treatments with the same soil slope gradient followed by different letters (a, b and c) are significantly different at *p* < 0.05 according to the LSD test.**

Rainfall intensity of 36 and 45 mm h−1 significantly accelerated time lag by about 4 and 6 min compared to rainfall intensity of 14 mm h−1 under soil slope of 9%. Similar trend was found under soil slope of 12%, however, there were no significant differences in time lag between rainfall intensities of 14 and 21 mm h−1, also, between rainfall intensities of 36 and 45 mm h−1 under both slope gradients. There were no significant differences in runoff coefficient among rainfall intensities under soil slope of 12%; however, runoff coefficient values between rainfall intensities of 14 and 45 mm h−1 were of greater differences, especially for soil slope of 5 and 9%. On the other hand, there were some fluctuations in runoff coefficient values for the 14 mm h−1 rainfall intensity especially with the slope gradient of 9 and 12% and opposite trend was observed under slope gradient of 5%. Overland flow and raindrops under slope gradients and rainfall intensities can temporarily damage thin soil seals and then infiltrate into the soil layers, which causes fluctuations and decreasing trends in surface flow yield **(Ribolzi et al., 2011).**

The observed values of sediment concentration ranged from 6.47 and 13.36 g l–1 .When rainfall intensity was increased from 14 and 45 mm h−1 under slope gradients of 5 and 9%, sediment concentration greatly increased. Nevertheless, there were no significant differences between most of rainfall intensities regarding sediment concentration. The 36 mm h−1 rainfall intensity increased sediment concentration by 26.4, 29.8, and 9.4% compared to the 14 mm h−1 rainfall intensity under soil gradients of 5, 9, and 12%, respectively.

***348 Egypt. J. of Appl. Sci., 34 (11) 2019***

In this study, under The 45 mm h−1 rainfall intensity, the value of sediment concentration with the 12% slope gradient was relatively lower than the 9% slope gradient. The reason might be that the runoff coefficient value with the 12% slope gradient was greatly higher than the 9% gradient. Sediment concentration was positively correlated with runoff coefficient **(Wu et al., 2017).**

Our result showed that sediment concentration was more sensitive to rainfall intensity changes than to slope gradient changes, in agreement with previous studies **(Ziadat and Taimeh 2013; Qian et al., 2016)** they reported that rainfall intensity was the most important factor affecting soil erosion. However, other studies found the opposite **(Liu et al., 2015),** this might be associated with the difference in simulated rainfall intensity, slope gradient, and soil type.

Hydrographs and sediment graphs were analyzed to obtain the hydrological and erosion responses at the three slope gradients. The temporal variations of runoff volume (ml), and soil loss (g) for the five rainfall intensities have been depicted in Fig.5 and 6.

Fig. 5. Shows the temporal variations in runoff volume for different slope gradients and rainfall intensities. The changing trends in runoff volume for all rainfall intensities under different slope gradients were very similar, which clearly could be divided into three stages, that is, the initial stage, the rapid increasing stage and the relatively stable stage, this was also consistent with the results by **Shen et al., (2016).** In general, the starting time of initial stage ranged from 7.4 to 16.2 min after the beginning of rainfall simulation, and the runoff volume of this stage ranged from 2 to 129, 14 to 190, and 71 to 234 ml under soil gradients of 5, 9, and 12%, respectively.

At the beginning of rainfall simulation under unsaturated surface conditions, the high infiltration capacity delayed the runoff generation **(Wu et al., 2017).** As rainfall continued, soil surface structure was gradually compacted by the raindrop impact which facilitated the generation of runoff **(Lado and Ben-Hur, 2004; Shi et al., 2010).**

The runoff volume of the rapid increasing stage ranged from 34 to 245, 58 to 309, and 117 to 726 ml under soil gradients of 5, 9, and 12%, respectively. Additionally, the runoff volume of the relatively stable stage ranged from 76 to 280, 211 to 382, and 299 to 726 ml under soil gradients of 5, 9, and 12%, respectively.



***Egypt. J. of Appl. Sci., 34 (11) 2019 349***

**Fig. 5. Temporal changes in runoff volume for different rainfall intensities and soil slope gradients. Error bars show the standard derivation among the repetitions (n = 3).**

In general, runoff volume increased with the increasing of rainfall intensity and soil gradient **(Römkens et al., 2001; Berger et al., 2010).** Runoff volume differed more between the rainfall intensities 14 and 45 mm h−1 than between any two-rainfall intensities under all soil gradients. The low rainfall intensities of 14 and 21 mm h−1 produced a small amount of runoff due to higher infiltration, similar to those in other studies **(Sadeghi et al., 2016; Wang et al., 2018).** The runoff volume differed a little with fluctuations between the 30 and 36 mm h−1 especially under soil gradient of 9 and 12%.

Temporal variations in soil loss for different rainfall intensities and slope gradients are presented in Fig. 6. The changing trends in soil loss were similar to the changes of runoff, and could also be divided into three stages. Soil loss was lower in the initial stage; there was no significant differences between the 36 and 45 mm h−1 rainfall intensities especially for the 5% slope gradient. Moreover, an increase in slope gradient caused initial soil loss to increase significantly, in agreement with previous studies **(Shen et al., 2016).** The soil loss of the rapid increasing stage ranged from 0.35 to 2.68, 0.47 to 3.9, and 0.74 to 4.6 at slope gradients of 5, 9, and 12%, respectively. In the stable stage, the soil loss firstly fluctuated at a relatively stable value, and then decreased with time **(Shen et al., 2016).** The soil loss of this stage ranged from 1.13 to 2.45, 1.42 to 3.9, and 2.57 to 5.47 g at slope gradients of 5, 9, and 12%, respectively.



***350 Egypt. J. of Appl. Sci., 34 (11) 2019***

**Fig. 6**. Temporal changes in soil loss for different rainfall intensities and soil slope gradients. Error bars show the standard derivation among the repetitions (n = 3).

Generally, the temporal variation of soil loss increased with rainfall intensity because of the detachment of soil particles by the higher raindrop force **(Wang et al., 2018).** The simulator provides relatively the same number of raindrops for different rainfall intensities, but raindrop size and thus force increases with intensity **(Yakubu et al., 2016).**

Figure 7 shows total trends of runoff rate under different rainfall intensities and slopes. The difference between the 14 and 21 mm h−1 rainfall intensities was not significant at slope gradient of 12%. Additionally, the differences between the 30 and 36 mm h−1 rainfall intensities were also not significant at the three slope gradients, but there were significant differences between rainfall intensities of 14 and 45 mm h−1 at the three slope gradients. Moreover, the 36 mm h−1 rainfall intensity significantly increased runoff rate by 31.7, 36.4, and 37.8% compared to the 21 mm h−1 rainfall intensity at slope gradients of 5, 9, and 12%, respectively. Runoff rate markedly different among different slope gradients, an increase in slope gradient enhanced flow velocity and reduced the chance that runoff would be infiltrated into the soils **(Fang et al., 2015).**



***Egypt. J. of Appl. Sci., 34 (11) 2019 351***

**Fig. 7**. Total trends of runoff rate under different rainfall intensities and soil slope gradients. Values for different rainfall intensity treatments with the same soil slope gradient followed by different letters (a, b and c) are significantly different at *p* < 0.05 according to the LSD test. Error bars show the standard derivation among the repetitions (n = 3).

Figure 8 shows total trends of sediment yield rate under different rainfall intensities and slopes. The differences between the 21 and 30 mm h−1, also, between the 36 and 45 mm h−1 rainfall intensities were not significant at slope gradient of 5%. In addition, the differences between the 14 and 21 mm h−1, also, between the 30 and 36 mm h−1 rainfall intensities were not significant at slope gradient of 12%. The 36 mm h−1 rainfall intensity significantly increased sediment yield rate by 45.4, 33.1, and 40.5% compared to the 21 mm h−1 rainfall intensity at slope gradients of 5, 9, and 12%, respectively. There was significant statistical difference in the sediment yield rate among different slope gradients. Sediment yield rates increased with increases in both rainfall intensity and slope gradient. This pattern accorded with other studies **(Zhang et al., 2002; Defersha and Melesse, 2012; Wang et al., 2015; Qian et al., 2016).**



***352 Egypt. J. of Appl. Sci., 34 (11) 2019***

**Fig. 8**. Total trends of sediment yield rate under different rainfall intensities and soil slope gradients. Values for different rainfall intensity treatments with the same soil slope gradient followed by different letters (a, b and c) are significantly different at *p* < 0.05 according to the LSD test. Error bars show the standard derivation among the repetitions (n = 3).

**4. CONCLUSIONS**

The portable field rainfall simulator developed in this study is capable of producing realistic rainfall intensities ranged from 14 to 80 mm h−1 over a 1.4 m2 rainfall catchment area in the northwestern coastal zone of Egypt. The rainfall simulator is easy to assemble, transport and use in remote locations. The portability and the flexibility of this simulator to operate at a continuous flow without any complexity to control rainfall intensity are enable the necessary experimental replicates to be done in the field. The simulator achieved a uniform rainfall distribution, and the coefficients of uniformity ranged from 89 to 94% for the three nozzles used in this study. Additionally, the droplets median diameters of the artificial rainfall were found to be similar to those of natural rainfall, and the median diameters ranged from 0.836 to 2.113 mm. However, the kinetic energy produced by the rainfall simulator was lower than the reported ranges of other rainfall simulators, but was within the range of natural precipitation in Mediterranean regions for low rainfall intensities. Consequently, the applicability of the rainfall simulator in the dynamic processes of erosion characteristics studies was investigated and a methodology was presented to evaluate the impacts of rainfall intensity and slope gradient on sediment yield, sediment concentration, runoff rate, and runoff coefficient. Generally, an increase in rainfall intensity or slope gradient caused erosion more easily to occur.

The results showed that runoff and sediment yield rates increased with the increasing of rainfall intensity and soil gradient. Furthermore, changing the rainfall intensity or slope gradient caused temporal variation of soil loss and runoff volume and some fluctuations occurred in the trends.

***Egypt. J. of Appl. Sci., 34 (11) 2019 353***

In summary, therefor, there were important impacts of rainfall intensity and slope gradient on erosion processes and the portable rainfall simulator is considered to be suitable for use in environmental studies involving these erosion processes in northwestern coastal zone of Egypt.

**REFERENCES**

**Abudi, I.; G. Carmi and P. Berliner (2012).** Rainfall simulator for field runoff studies. Journal of Hydrology, 454, pp.76-81.

**Afifi, A. and A. Gad (2011).** Assessment and mapping areas affected by soil erosion and desertification in the north coastal part of Egypt. Int. J. Water., 1 (2): 83–91.

**Aksoy, H.; N.E. Unal ; S. Cokgor ; A. Gedikli ; J. Yoon ; K. Koca ; S.B. Inci and E. Eris, (2012).** A rainfall simulator for laboratory-scale assessment of rainfall-runoff-sediment transport processes over a two-dimensional flume. Catena, 98, pp.63-72.

**Angulo-Martinez, M. ; S. Begueria ; A. Navas and J. Machin (2012).** Splash erosion under natural rainfall on three soil types in NE Spain. Geomorphology 175–176, 38–44.

**Assouline, S. ; A. El Idrissi and E. Persoons (1997).** Modeling the physical characteristics of simulated rainfall: a comparison with natural rainfall. J. Hydrol., 196: 336–347.

**Barthes, B. and E. Roose (2002).** Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. Catena, 47: 133–149.

**Battany, M.C. and M.E. Grismer (2000).** Development of a portable field rainfall simulator for use in hillside vineyard runoff and erosion studies. Hydrological Processes, 14: 1119–1129.

**Beard, K.V. (1976).** Terminal velocity and shape of cloud and precipitation drops aloft. Journal of Atmospheric Sciences., 33: 851–864.

**Beard, K.V. and H.R. Pruppacher (1969).** A determination of the terminal velocity and drag of small water drops by means of a wind tunnel. Journal of Atmospheric Sciences, 26: 1066–1072.

**Berger, C. ; M. Schulze ; D. Rieke-Zapp and F. Schlunegger (2010).** Rill development and soil erosion: a laboratory study of slope and rainfall intensity. Earth Surf. Process. Landf., 35: 1456–1467.

**Boulal, H. ; H. Gómez-Macpherson ; J.A. Gómez and L. Mateos (2011).** Effect of soil management and traffic on soil erosion in irrigated annual crops. Soil and Tillage Research, 115: 62-70.

**Boulange, J. ; F. Malhat ; P. Jaikaew ; K. Nanko and H. Watanabe (2019).** Portable rainfall simulator for plot-scale investigation of rainfall-runoff, and transport of sediment and pollutants. International Journal of Sediment Research, 34(1):38-47.

***354 Egypt. J. of Appl. Sci., 34 (11) 2019***

**Brandt, C. (1989).** The size distribution of throughfall drops under vegetation canopies. Catena, 16: 507–524.

**Cerdà, A. (1997 a).** Rainfall drop size distribution in Western Mediterranean Basin, València, Spain. Catena, 31: 23–38.

**Cerdà, A. (1997 b).** The effect of patchy distribution of Stipa tenacissima L. on runoff and erosion. J. Arid. Environ., 36: 37–51.

**Cerdà, A. (1999).** Simuladores de lluvia y su aplicación a la Geomorfología. Estado de la cuestión. Cuadernos de I. Geográfica 25, 45–84.

**Christiansen, J.E. (1942).** Irrigation by sprinkling. Univ. Calif. Agric. Exp. Stn. Bull., 670.

**Clarke, M.A. and R.P.D. Walsh (2007).** A portable rainfall simulator for field assessment of splash and slopewash in remote locations. Earth Surface Processes and Landforms, 32: 2052–2069.

**Covert, A. and P. Jordan (2009).** A portable rainfall simulator: Techniques for understanding the effects of rainfall on soil erodibility. Streamline, 13 (1): 5-9.

**De Lima, J.L.M.P. ; P. Tavares ; V.P. Singh and M.I.P. de Lima (2009).** Investigating the nonlinear response of soil loss to storm direction using a circular soil flume. Geoderma, 152(1-2): 9-15.

**Defersha, M.B. and A.M. Melesse (2012).** Effect of rainfall intensity, slope and antecedent moisture content on sediment concentration and sediment enrichment ratio. Catena, 90: 47–52.

**Deng, L.; T. Sun; K. Fei; L. Zhang; X.Fan; Y. Wu and L. Ni (2019).** Effects of erosion degree, rainfall intensity and slope gradient on runoff and sediment yield for the bare soils from the weathered granite slopes of SE China. Geomorphology, p.106997.

**Dlamini, P.; C. Orchard; G. Jewitt; S.Lorentz; L. Titshall and V. Chaplot (2011).** Controlling factors of sheet erosion under degraded grasslands in the sloping lands of KwaZulu- Natal, South Africa. Agric. Water Manage., 98: 1711–1718.

**Erpul, G.; D. Gabriels and D. Janssens (1998).** Assessing the drop size distribution of simulated rainfall in a wind tunnel. Soil and Tillage Research, 3–4: 455–463.

**Esteves, M.;O.Planchon; J.M.Lapetite; N.Silvera and P. Cadet (2000).** The “EMIRE” large rainfall simulator: design and field testing. Earth Surface Processes and Landforms., 25 (7): 681–690.

**Fang, H.; L. Sun and Z. Tang (2015).** Effects of rainfall and slope on runoff, soil erosion and rill development: an experimental study using two loess soils. Hydrol. Process., 29 (11): 2649–2658.

***Egypt. J. of Appl. Sci., 34 (11) 2019 355***

**Fu, S.; B.Liu; H. Liu and L. Xu (2011).** The effect of slope on interrill erosion at short slopes. Catena, 84 (1–2): 29–34.

**Grismer, M. (2012).** Standards vary in studies using rainfall simulators to evaluate erosion. Calif. Agric., 66 (3): 102–107.

**Grismer, M.E. (2016).** Determination of watershed infiltration and erosion parameters from field rainfall simulation analyses. Hydrology, 3(3): p.23.

**Hassel, J. and G. Richter (1988).** Die Niederschlagsstruktur des Trierer Regensimulators. Mitteilungen der Deutschen Bodenkundlichen Gesellschaft, 56: 93–96.

**Hudson, N. (1963).** Raindrop characteristics in south central United States. Rhodesian Journal of Agricultural Research, 1: 6–11.

**Humphry, J.B. ; T.C. Daniel; D.R. Edwards and A.N. Sharpley (2002).** A portable rainfall simulator for plot-scale runoff studies. Appl. Eng. Agric., 18: 199–204.

**Iserloh, T.; W. Fister; M. Seeger; H. Willger and J.B. Ries (2012).** A small portable rainfall simulator for reproducible experiments on soil erosion. Soil and Tillage Research 124, 131–137.

**Iserloh, T.; J.B. Ries; A. Cerdà; M.T. Echeverría; W. Fister; C. Geißler; N.J. Kuhn ;F.J.León; P. Peters; M. Schindewolf; J. Schmidt ; T. Scholten and M. Seeger (2013 a).** Comparative measurements with seven rainfall simulators on uniform bare fallow land. Zeitschrift für Geomorphologie Supplementband, 57 (1): 11–26.

**Iserloh, T.; J.B. Ries; J. Arnáez; C. Boix-Fayos; V. Butzen; A. Cerdà; M.T. Echeverría; J. Fernández-Gálvez; W. Fister; C. Geißler; J.A. Gómez; H. Gómez-Macpherson; N.J. Kuhn; R. Lázaro; F.J. León; M. Martínez-Mena; J.F. Martínez-Murillo; M. Marzen; M.D. Mingorance; L. Ortigosa; P. Peters; D. Regüés; J.D. Ruiz-Sinoga; T. Scholten; M. Seeger; A. Solé-Benet; R. Wengel and S. Wirtz (2013 b).** European small portable rainfall simulators: a comparison of rainfall characteristics. Catena, 110: 100–112.

**Kesgin, E.; A. Dogan and H. Agaccioglu (2018).** Rainfall simulator for investigating sports field drainage processes. Measurement,125: 360-370.

**Kinnell, P.I.A. (2000).** The effect of slope length on sediment concentrations associated with side-slope erosion. Soil Sci. Soc. Am. J., 64:1004–1008.

**Krajewski, W.F.; A. Kruger; C. Caracciolo; P. Gole; L. Barthes; J.D. Creutin; J.Y. Delahaye; E.I. Nikolopoulos; F. Ogden and J.P. Vinson (2005).** DEVEX-disdrometer evaluation experiment: basic results and implications for hydrologic studies. Adv. Water Resour., 29: 311–325.

**Lado, M. and M. Ben-Hur (2004).** Soil mineralogy effects on seal formation, runoff and soil loss. Appl. Clay Sci., 24: 209–224.

***356 Egypt. J. of Appl. Sci., 34 (11) 2019***

**Lascano, R.J.; J.T.Vorheis; R. L. Baumhardt and D.R.Salisbury (1997).** Computer-controlled variable intensity rain simulator. Soil Sci. Soc. Am. J., 61: 1182–1189.

**Laws, J.O. and D.A. Parsons (1943).** The relation of raindrop size to intensity. Eos. Trans. AGU., 26: 452–460.

**Liu, D.D. ; D.L. She ; S.E. Yu ; G.C. Shao and D. Chen (2015).** Rainfall intensity and slope gradient effects on sediment losses and splash from a saline-sodic soil under coastal reclamation. Catena, 128: 54–62.

**Lora, M.; M. Camporese and P.Salandin (2016).** Design and performance of a nozzle-type rainfall simulator for landslide triggering experiments. Catena, 140:77-89.

**Luk, S.H. ; A.D. Abrahams and A.J. Parsons (1993).** Sediment sources and sediment transport by rill flow and interrill flow on a semi-arid piedmont slope, Southern Arizona. Catena, 20 (1/2): 93–111.

**Mahmoodabadi, M. and S.A. Sajjadi (2016).** Effects of rain intensity, slope gradient and particle size distribution on the relative contributions of splash and wash loads to rain-induced erosion. Geomorphology, 253: 159–167.

**Miller, W.P. (1987).** A solenoid-operated, variable intensity rainfall simulator. Soil Sci. Soc. Am. J., 51: 832–834.

**Moazed, H. ; A. Bavi ; S. Boroomand-Nasab ; A. Naseri and M. Albaji (2010).** Effects of climatic and hydraulic parameters on water uniformity coeffcient in solid set systems. Journal of Applied Sciences, 10 (16): 1792–1796.

**Pérez-Latorre, F.J. ; L. de Castro and A. Delgado (2010).** A comparison of two variable intensity rainfall simulators for runoff studies. Soil and Tillage Research, 107(1):11-16.

**Qian, F.; D. Cheng; W. Ding; J. Huang and J. Liu (2016).** Hydraulic characteristics and sediment generation on slope erosion in the Three Gorges Reservoir Area, China. Journal of Hydrology and Hydromechanics, 64(3):237-245.

**Ramos, M.C. and J.A. Martınez-Casanovas (2006).** Nutrient losses by runoff in vineyards of the Mediterranean Alt Penede` s region (NE Spain). Agric. Ecosyst. Environ., 113: 356–363.

**Ries, J.B.; T. Iserloh; M. Seeger and D. Gabriels (2013).** Rainfall simulations — constraints, needs and challenges for a future use in soil erosion research. Z. Geomorphol. Suppl., 57 (1): 1–10.

**Ries, J.B. and M. Langer (2001).** Runoff generation on abandoned fields in the Central Ebro Basin. Results from rainfall simulation experiments. Cuadernos de Investigación Geográfica, 27: 61–78.

**Ries, J.B. ; M. Seeger ; T. Iserloh ; S. Wistorf and W. Fister (2009).** Calibration of simulated rainfall characteristics for the study of soil erosion on agricultural land. Soil and Tillage Research, 106: 109-116.

***Egypt. J. of Appl. Sci., 34 (11) 2019 357***

**Römkens, M.J.M.; K. Helming, and S.N. Prasad (2001).** Soil erosion under different rainfall intensities, surface roughness, and soil water regimes. Catena, 46: 103–123.

**Salles, C. and J. Poesen (1999).** Performance of an optical spectro pluviometer in measuring basic rain erosivity characteristics. Journal of Hydrology, 218: 142–156.

**Salles, C.; J. Poesen and L. Borselli (1999).** Measurement of simulated drop size distribution with an optical spectro pluviometer: sample size considerations. Earth Surface Processes and Landforms, 24: 545–556.

**Salles, C.;J. Poesen and D. Sempere-Torres (2002).** Kinetic energy of rain and its functional relationship with intensity. J. Hydrol., 357:256–270.

**Shen, H.;F. Zheng; L. Wen ; Y. Han and W. Hu (2016).** Impacts of rainfall intensity and slope gradient on rill erosion processes at loessial hillslope. Soil and Tillage Research, 155:429-436.

**Shi, Z.H.; F.L. Yan; L.Li ; Z.X. Li and C.F.Cai (2010).** Interrill erosion from disturbed and undisturbed samples in relation to topsoil aggregate stability in red soils from subtropical China. Catena., 81: 240–248.

**Tossell, R.W. ; W.T. Dickinson ; R.P. Rudra and G.J. Wall (1987).** A portable rainfall simulator. Can. Agric. Eng., 29: 155-162.

**Uijlenhoet, R. and J.N.M. Stricker (1999).** A consistent rainfall parameterization based on the exponential raindrop size distribution. J. Hydrol., 218: 101–127.

**Vahabi, J. and D. Nikkami (2008).** Assessing dominant factors affecting soil erosion using a portable rainfall simulator. International Journal of Sediment Research, 23(4), pp.376-386.

**Van-Dijk, A.I.J.M. ; L.A. Bruijnzeel and C.J. Rosewell (2002).** Rainfall intensity–kinetic energy relationships: a critical literature appraisal. Journal of Hydrology, 261: 1-23.

**Wang, Z.; X.Yang; J. Liu and Y. Yuan (2015).** Sediment transport capacity and its response to hydraulic parameters in experimental rill flow on steep slope. J. Soil Water Conserv., 70: 36–44.

**Wu, X.; Y. Wei ; J. Wang ; J. Xia ; C. Cai ; L. Wu ; Z. Fu and Z. Wei (2017).** Effects of erosion degree and rainfall intensity on erosion processes for Ultisols derived from quaternary red clay. Agriculture, Ecosystems & Environment, 249:226-236.

**Yakubu, M.L.; Z. Yusop and M.A. Fulazzaky (2016).** The influence of rain intensity on raindrop diameter and the kinetics of tropical rainfall: case study of Skudai, Malaysia. Hydrol. Sci. J., 61: 944–951.

**Zhang, G.H.; B.Y.Liu; M.A.Nearing; C.H.Huang and K.L. Zhang (2002).** Soil detachment by shallow flow. Trans. ASAE, 45: 351–357.

***358 Egypt. J. of Appl. Sci., 34 (11) 2019***

**Zhao, X. ; P. Wu ; X. Chen ; M.J. Helmers and X. Zhou (2013).** Runoff and sediment yield under simulated rainfall on hillslopes in the Loess Plateau of China. Soil Research, 51(1):50-58.

**Ziadat, F.M. and A.Y. Taimeh (2013).** Effect of rainfall intensity, slope and land use and antecedent soil moisture on soil erosion in an arid environment. Land Degrad. Dev. 24, 582–590.

**تصميم جهاز محاكاه امطار متنقل لتقييم العوامل المؤثرة على انجراف التربة بالمياه**

**هيثم محمد سالم و عادل عبد السميع مصيلحى**

قسم صيانة الأراضى - مركز بحوث الصحراء – المطرية – القاهره

تم تصميم وتقييم جهاز محاكاة أمطار حقلى متنقل ليحاكى خواص الامطار الطبيعية فى منطقة الساحل الشمالى الغربى لمصر ويقوم هذا الجهاز بانتاج شدة هطول امطار تتراوح ما بين 14 و 80 مم / ساعة. حيث يتميز هذا الجهاز بانخفاض تكلفة تصنيعة وسهولة نقلة وتجميعة مما يتيح إجراء العديد من التجارب الحقلية والتى تهدف الى تنمية هذه المنطقة. تم معايرة هذا الجهاز فى المعمل اولا واظهرت النتائج الحصول على معدل مرتفع لانتظامية توزيع الامطار حيث تراوحت النتائج مابين 89 الى 94 % وذلك بالنسبة للرشاشات الثلاثة المستخدمة فى تصنيع هذا الجهاز. بالإضافة إلى ذلك ، تراوحت اقطار قطرات الامطار بين 0.836 و 2.113 مم. وتراوحت ايضا سرعات وصول هذه القطرات ما بين 3.35 و 6.83 متر/الثانية، علاوة على ذلك ، تم الحصول على طاقة حركية للامطار الناتجة عن هذا الجهازوالتى تحاكى الامطار الطبيعية في مناطق البحر الأبيض المتوسط حيث تراوحت قيمتها من 12.7 إلى 18.9 جول /متر مربع . مم. نتيجة لذلك ، تم بحث إمكانية استخدام جهاز محاكى الامطارلتقييم العوامل المؤثرة على انجراف التربة فى منطقة الدراسة. حيث تعتبرعملية تقييم هذه العوامل من اهم العمليات التى تساعد على مجابهة تدهور الأراضي وتطويرعمليات صيانة التربة بهذه المناطق، بناء علية تم اختبار معدلات مختلفة لشدة الامطار وهى 14 ، 21 ، 30 ، 36 ، 45 مم /ساعة في ثلاثة تكرارات وذلك في ثلاثة مواقع بها ميول مختلفة للتربة وهى 5 و 9 و 12٪. حيث تم قياس المتغيرات التالية: الجريان السطحى ومعدلة وفاقد التربة وتركيز الرواسب ومعامل الجريان السطحى. أشارت النتائج الإجمالية إلى أن معدلات الجريان السطحي وفاقد التربة الناتج عن الانجراف تختلف بشكل كبير بين شدة سقوط الأمطار التي تتراوح بين 14 و 45 مم/ساعة مقارنة باى شدات اخرى لهطول الأمطار تحت كل ميول التربة. بايجاز، يمكن القول ان استخدام جهاز محاكاة هطول الأمطار المتنقل اسهم بشكل فعال في دراسة وتقييم العوامل المؤثرة على انجراف التربة فى منطقة الدراسة والتى من اهمها تأثير شدة هطول الأمطار وميل سطح التربة.