DESIGN AND DEVELOPMENT OF A LOCALLY MADE RAINFALL SIMULATOR

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Abstract

Over the years, scientists have found the need for water erosion experiments to be undertaken in a controlled environment which has given rise to the different types and designs of rainfall simulators. The availability of such equipment is found to be rare in most universities in Nigeria especially due to its high cost of purchase and installation. This study discussed the design and fabrication of a small scale pressurized rainfall simulator. The rainfall simulator is 2.2m x 2.2m by size, resting on a wooden frame 2m x 2m by size, made using a 0.0508m x 0.0508m sized wood, at 1.65m in height and 2m by length and breadth, with 0.3m of each leg buried into the ground to stand firmly. The rainfall simulator has a main-pipe connection which receives water from the pump and supplies the laterals which in turn distributes water to the sub-lateral where the water is sprayed through the shower roses. Each of the shower roses is 90mm in diameter, made up of 105 holes with each of the holes have an approximate diameter of 2 mm and provides the simplest form of spray. The drop velocity (DV) was calculated to be 8.101m/s and 2.443 m/s when operated at maximum and at minimum intensity respectively. Performance test revealed the experimental coefficient of uniformity (CU) and rainfall intensity from the simulator to be 79.86% at 31.79mm/hr and 78.03% at 16.08mm/hr when run at maximum and minimum intensity respectively. The results of drop velocity (DV) and experiment coefficient of uniformity (CU) were within the acceptable range respectively. The intensity of water dropping from the simulator depends on the inflow rate of water which could be regulated by the control valve fixed at the main-pipe. Thus, this locally rainfall simulator meets the minimum requirements and can used for erosion studies.

Keyword: Erosion, rainfall simulator, terminal velocity, uniform coefficient

INTRODUCTION

In erosion studies, the need for more control over the experiments brought about the rise of rainfall simulators by researchers especially when natural rainfall is the primary agent of erosion. (Horne, 2017). Thus, the use of artificial rainfall simulation has been long used to study rainfall effects on erosion and over the years, it has become a very effective technique for assessing particle detachment, soil erosion, overland flow and chemical runoff (Tossell *et al.,* 1987).

Over the years, researchers have proposed several types and designs of rainfall simulators and the main types are the drop-forming rainfall simulators (non-pressurized simulators) and the pressurized nozzle simulators (spray type) (Yusuf *et al.,* 2016). Rainfall simulators, with drop-forming mechanisms such as hypodermic needles and string to generate drops were the earliest types (Mutchler and Hermsmeier, 1965). Such rainfall simulators operated with no pressure in them, hence, the raindrops had to be released at heights as high as 9metres (30 feet) to attain terminal velocity before reaching the ground, thus, these constraints limited its use to outdoor laboratory experiments. As cited by Wilson *et al*., (2014), the drop-forming rainfall simulators usually require high elevation, 10 to 12metres of range to attain terminal velocity and they are not portable in nature. On the other hand, the pressurized nozzle rainfall simulators, just as the name imply, operate under a pressurized system and rely on sprinkler heads or nozzles to produce rain-like drops which have the ability to attain terminal velocity quicker, thereby allowing for a more portable simulator (Horne, 2017). The pressurized nozzle rainfall simulators are pointed out to consume more water because of the wide area of coverage while discharging water when compared to the drop-forming rainfall simulators (Yusuf *et al.,* 2016).

Since 1930s, over a 100 rainfall simulators have been developed, with plot dimensions ranging less than 5m^2 with most of them less than 1m^2, with differences in rainfall intensities, spatial rainfall distribution, design, drop sizes and velocities and of all these designs, there isn't any standard to it. (Iserloh *et al*., 2013.). Thus, the fundamental requirement is the accuracy of test conditions, in which, it is essentially interpreted, combined and classified. Iserloh *et al*., (2013) further stated that the critical and most important properties of a simulated rainfall are the drop size distribution (DSD), the fall velocities of the drops (drop velocity) and the spatial distribution of the rainfall on the plot-area. As cited by Yusuf *et al.,*(2016), rainfall intensity is one of the many rainfall characteristics that influences drop size ditribution,, with median drop size distribution to be estimated at 2.25mm for high intensity storm. It was further stated that there is a strong correlation between the drop velocity of the rainfall drops and rainfall drop sizes as presented on Table 1.

Table 1: Relationship between rainfall drop diameter and terminal velocity

Diameter (mm)	1	2	2.4	3	3.4	4	4.4	5
Terminal velocity (m/s)	4.03	6.49	7.27	8.06	8.44	8.83	8.98	9.09

Source: Olaoke (2012)

Uniform drop distribution of a rainfall simulator can be difficult to achieve because the pressurized nozzles of the simulators sacrifice uniformity to produce higher intensities (Horne, 2017). It was further stated that uniformity of drop distribution is dependent upon spacing, nozzle pressure and oscillation with more concentration spray occuring directly under the nozzle. (Paige *et al.,* 2003). Thus nozzles are spaced so that areas of less coverage from the nozzles are overlapped. The objective of this study was to design and construct a locally made rainfall simulator capable of producing rainfall similar to natural rain at different intensities under an acceptable coeffient of uniformity and drop velocity.

MATERIALS AND METHODS

Design Consideration of the Rainfall Simulator

According to Bansal (2003) and Douglas *et al.,* (2008) as cited in Yusuf *et al.,* (2017), the capacity of the discharge pump determines the inflow/outflow discharge of the rainfall simulator, so it is necessary for the properties of the simulator to be determined which will in turn help in the pump selection. The pump selection was based on the pumps available in the local market so as to carefully choose the right pump for the simulator. In the design of rainfall simulators, the mass flow rates, area, velocity of water to the main pipe, lateral and sub-lateral were determined using Eq.1a, 1b, 2, 3, 4 and 5 respectively while losses through the main, lateral and sub-lateral pipes of the simulator were determined using Equations 6, 7 and 8 respectively (Bansal, 2003 and Douglas *et al.* 2008);

Mass flow rates, Area and Velocity of water

$$m = \rho \times Q. \quad (1a)$$

$$m = \rho \times V \times A. \quad (1b)$$

$$A = \frac{\pi D^2}{4} \quad (2)$$

$$V_m = \frac{m}{\rho \times A_m} \quad (3)$$

$$V_L = \frac{m}{\rho \times A_L} \quad (4)$$

$$V_s = \frac{m}{\rho \times A_s} \quad (5)$$

Where;

m = mass flow rate (kg/s),

ρ = density of water (kg/m^3)

Q = discharge of water (m^3/s)

D = internal diameter of the pipe (m)

A_m = area of the main-pipe (m^2)

A_L = area of the lateral (m^2)

A_S = area of the sub–lateral (m^2)
V_m = velocity of flow of water in the main–pipe (m/s)
V_L = velocity of flow of water in the lateral–pipe (m/s) and
V_S = velocity of flow of water in the sub–lateral pipe (m/s)

Losses through the Main, Lateral and Sub-lateral pipes

$$h_m = \frac{k_e V_m^2}{2g} \quad (6)$$

$$h_L = \frac{k_T V_L^2}{2g} \quad (7)$$

$$h_S = \frac{k_T V_s^2}{2g} (8)$$

$$H_t = h_m + h_l + h_s (9)$$

$$V = \sqrt{\frac{2gH_t}{k_T}} \quad (10)$$

Where;
h_m = Frictional head loss in the main-pipe (m)
h_L = head loss in the lateral (m)
h_s = head loss in the sub-lateral (m)
V_m = velocity of flow of water in the main-pipe (m/s)
V_L = velocity of flow of water in the lateral (m/s)
V_s = velocity of flow of water in the sub-lateral (m/s)
H_t = head loss in the simulator network pipe due to T – joints (m)
V = mean velocity of water dropping from the rainfall simulator to the ground surface (m/s) and g = acceleration due to gravity (m/s^2)
k_e = entry loss constant
k_T = T – joint loss constant

The values of constant k_e and k_T were 0.5 and 1.8 as given by Douglas *et al.* (2008).

Coefficient of Uniformity and Rainfall Intensity

To verify uniformity of drop distribution, Christensen's coefficient of uniformity is adopted (Christiansen, 1942; Horne, 2017 and Yusuf *et al.*, 2017) which is expressed in Eq. 11 while the average intensity of rainfall over the entire plot is express in Eq.12;

$$CU = 100 * \left(1 - \frac{\sum /x - \bar{x}/}{\sum x}\right) \quad (11)$$

$$i = \frac{\bar{x}_h}{A_s} \quad (12)$$

Where;
n = number of observation (containers used)
x = volume of water in each bucket (Litre)

$\bar{x}$ = mean volume of water in the bucket (Litre)
$|x - \bar{x}|$ = absolute deviation.
Σx = summation of x
S.D = standard deviation
CU = coefficient of the uniformity
i = intensity of rainfall (mm/hr)
$\bar{x}_h$ = average volume of water falling on the ground surface under the entire area of rainfall simulator in hour (Litre/hr)
A_s = area coverage of the rainfall simulator

Rainfall Simulator Design

The constructed simulator functioned as a continuous sprinkler system with pressurized water (Figure 1). PVC pipes, shower roses of and pipe fittings were the main components used in the fabrication of the simulator and they are readily available in the local markets in Nigeria. The simulator is made up of the main-line pipe, lateral pipes and the sub-lateral pipes. The main-line pipe receiving water from the pump has an internal diameter of 0.0381m (3.81cm) and it covers a horizontal distance of 8m while the section connecting to the pump covers a vertical distance of approximately 1.7m. Two sides of the horizontal main-line have 5 holes each, at interval of 0.3m of each other where the laterals were connected to the mainline pipe with the help of a T–joint pipe and 0.4m from both side of the main-pipes. Each of the laterals have a diameter of 0.0254 m (2.54cm) and 2.0m long, with each of them having 5 holes of diameter 0.019m at interval of 0.3 m where the sub–lateral (distribution pipe) was connected to the lateral and 0.5m to the end of each lateral pipe. The distribution pipe was 0.0195m in diameter (1.95cm) which was 0.08m long fitted to the lateral with help of T–joint. The shower roses were of galvanized metal material, 90cm in diameter, each having 105 holes period. With each hole having an approximate diameter of 2mm and they are known to provide the simplest form of sprays under pressurize (Yusuf *et al.,* 2017). In which, each of it was fixed to each sub–lateral using adaptor, for easy removal, when required.

Figure 1: Development of Rain Simulator in Progress

A wooden frame, was used as the support for the simulator, upon which the operation was carried out as shown in Figure 4. The frame was made using 0.0508m x 0.0508m sized wood at a height of 1.65m and length and breadth of 2m with 0.3m of each leg buried into the ground to stand firmly.

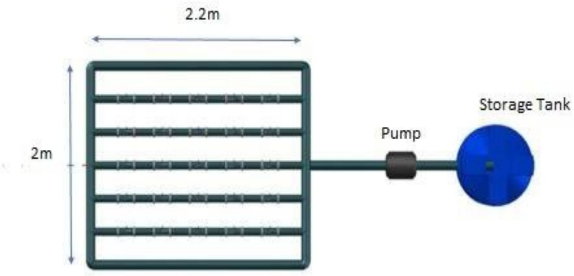

Figure 2: Aerial view of the rainfall simulator

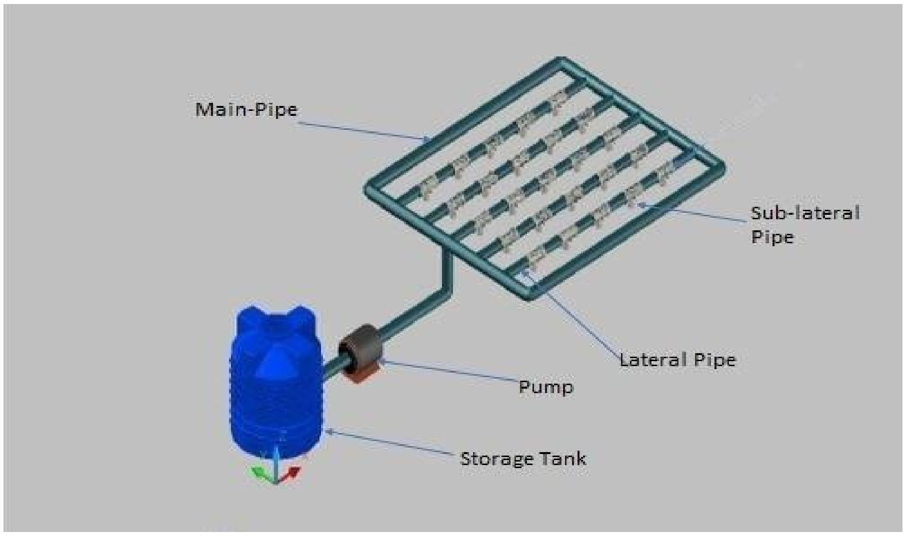

Figure 3: 3D View of the rainfall simulator

Figure 4: Rainfall simulator in operation

RESULTS AND DISCUSSIONS

Terminal Velocity and Head losses in the Pipes

Equations 3, 4 and 5 were used to determine the flow rate velocities in the main-line, laterals and sub-laterals respectively while equations 6, 7 and 8were used to determine the head losses of the respective pipes stated above. The Total head loss due to friction and the mean velocity (terminal velocity of discharge from the rainfall simulator to the ground) were determined using equations 9 and 10. Table 2 below presents the velocities, cross-sectional area and head losses of the various sections of the pipes.

Table 2: Estimated Total Head Loss and Terminal Velocity using a 60L/min Pump

Parameter	Area (m^2)	Velocity (m/s)	Head loss (m)
Main-Pipe	0.00114	0.877	0.022
Lateral	0.00051	1.973	0.181
Sub-lateral	0.00029	3.507	0.322
Total Head loss			0.525
Terminal Velocity		2.392	

The design results as presented in Table 2 shows that the rainfall simulator when connected to the pump with a 60L/min (use standard unit for this pls) maximum discharge would exhibit a total head loss of 0.525m and a terminal velocity of 2.392m/s which is far below the required terminal velocity for high intensity rainfall (Parsakhoo *et al.,* 2012; Gunn and Kinzer, 1987). This is as a result of the low capacity of the pump which also means that a bigger pump with higher discharge would be needed if the required terminal velocity is to be attained. Table 3 shows the estimated total head loss and terminal velocity for the rainfall simulator in connection to a 116.7L/min pump;

Table 3: Estimated Terminal Velocity and Total Head Loss using a 116.67L/min Pump (Fully opened)

Parameter	Area (m2)	Velocity (m/s)	Head loss (m)
Main-Pipe	0.00114	1.754	0.078
Lateral	0.00051	3.945	1.428
Sub-lateral	0.00029	7.014	4.514
Total Head loss			6.020
Mean Velocity		8.101	

Table 3 presents the result of the rainfall simulator when connected to a pump with a 116.7L/min maximum discharge rate. A total head loss of 6.02m and a terminal velocity of 8.101m/s which slightly surpasses the required terminal velocity for high intensity rainfall was observed (Parsakhoo *et al.* 2012; Gunn and Kinzer, 1989). This is as a result of the high capacity of the pump to apply adequate pressure to attain the required terminal velocity needed. It was also noted that the total head loss of the rainfall simulator using a 116.7L/min pump in Table 3 increased more than ten times that of the total head loss in Table 2, this shows the high sensitivity of the rainfall simulator to change in flow rate of the system. In view of all analysis, the 116.7L/min capacity pump was selected to be used with the rainfall simulator.

The rainfall simulator was designed with a control valve close to the pump for throttling, so as to be able to control the inflow of water into the rainfall simulator and in turn control the spray water from the shower roses. That way, the varying of the rainfall intensity from rainfall simulator can be achieved. For the sake of this experiment, the rainfall simulator was calibrated for two distinct rainfall intensities, and they were achieved by;

a) Fully opening the control valve for maximum intensity.
b) Partially opening the valve (half way) for minimum intensity.

Table 4: Estimated Terminal Velocity and Total Head Loss for 116.67L/min Pump when partially opened valve (half way)

Parameter	**Area (m2)**	**Velocity (m/s)**	**Head loss (m)**
Main-Pipe	0.00114	1.754	0.045
Lateral	0.00051	1.973	0.181
Sub-lateral	0.00029	3.507	0.322
Total Head loss			1.564
Mean Velocity		2.443	

The results in Table 4 reveals that the rainfall simulator, when operated with the valve partially opened (half way) would have a total head loss of 1.564m and a terminal velocity of 2.443m/s. This correlates to drop size of light stratiform rain type between 0.5mm – 2.0mm as seen in Table 5below.

Table 5. Tabular relationship showing rain types, drop sizes and their respective terminal velocity

Rain Type	**Sizes of drop**		**Terminal Velocity**	
	mm	*in*	*m/s*	*miles/hr*
Light Stratiform Rain (.04" per hour)				
Smaill Drop	0.5	0.02	2.06	4.06
Large Drop	2	0.08	6.49	14.4
Moderate Stratiform Rain (.25" per hour)				
Small Drop	1	0.04	4.03	8.9
Large Drop	2.6	0.1	7.57	16.1
Heavy Thundershower (1.0" per hour)				
Small Drop	1.2	0.05	4.64	10.3
Large Drop	4	0.16	8.83	19.6

Largest Possible Drop	5	0.2	9.09	20.2
Hailstone	10	0.4	10	22.2
Hailstone	40	1.6	20	44.4

Source: (Horstmeyer, 2008)

Experimental Coefficient Uniformity and Rainfall Intensity

In the determination of coefficient of uniformity, five buckets (3Litres capacity each) were randomly placed under the rainfall simulator and the rainfall simulator was activated for 60 seconds as shown in Fig 5. The volume from each bucket were measured using a measuring cylinder and recorded. After each successful experiment, the buckets were randomly rotated before the next experiment. This experiment was repeated fifty times at maximum and minimum intensity each and the coefficient of uniformity and rainfall intensity was estimated as shown in Table 6a and 6b below;

Figure 5: Buckets randomly placed under the simulator for determination of uniformity coefficient

Table 6a: Volume of water in each tagged bucket after each experimental run at maximum intensity

RUNS	Bucket Tags	Vol (litre)	$\bar{x}$	$x - \bar{x}$	$/x - \bar{x}/$	$(x - \bar{x})^2$
1	B1	2.50	2.12	0.38	0.38	0.14
	B2	2.15	2.12	0.03	0.03	0.00
	B3	2.61	2.12	0.49	0.49	0.24
	B4	1.98	2.12	-0.14	0.14	0.02
	B5	2.06	2.12	-0.06	0.06	0.00
2	B1	2.95	2.12	0.83	0.83	0.70

	B2	1.25	2.12	-0.87	0.87	0.76
	B3	1.12	2.12	-1.00	1.00	1.00
	B4	3.01	2.12	0.89	0.89	0.79
	B5	1.80	2.12	-0.32	0.32	0.10
3	B1	1.98	2.12	-0.14	0.14	0.02
	B2	2.90	2.12	0.78	0.78	0.61
	B3	2.40	2.12	0.28	0.28	0.08
	B4	1.36	2.12	-0.76	0.76	0.58
	B5	2.37	2.12	0.25	0.25	0.06
4	B1	2.07	2.12	-0.05	0.05	0.00
	B2	2.26	2.12	0.14	0.14	0.02
	B3	3.10	2.12	0.98	0.98	0.96
	B4	2.99	2.12	0.87	0.87	0.76
	B5	1.73	2.12	-0.39	0.39	0.16
5	B1	2.06	2.12	-0.06	0.06	0.00
	B2	1.41	2.12	-0.71	0.71	0.50
	B3	2.75	2.12	0.63	0.63	0.40
	B4	1.58	2.12	-0.54	0.54	0.29
	B5	2.77	2.12	0.65	0.65	0.42
6	B1	2.00	2.12	-0.12	0.12	0.01
	B2	1.58	2.12	-0.54	0.54	0.29
	B3	1.88	2.12	-0.24	0.24	0.06
	B4	2.46	2.12	0.34	0.34	0.12
	B5	2.48	2.12	0.36	0.36	0.13
7	B1	1.87	2.12	-0.25	0.25	0.06
	B2	2.57	2.12	0.45	0.45	0.20
	B3	1.60	2.12	-0.52	0.52	0.27
	B4	1.52	2.12	-0.60	0.60	0.36
	B5	2.25	2.12	0.13	0.13	0.02
8	B1	2.46	2.12	0.34	0.34	0.12
	B2	1.76	2.12	-0.36	0.36	0.13
	B3	1.89	2.12	-0.23	0.23	0.05
	B4	1.67	2.12	-0.45	0.45	0.20
	B5	1.27	2.12	-0.85	0.85	0.73
9	B1	3.27	2.12	1.15	1.15	1.31

	B2	2.07	2.12	-0.05	0.05	0.00
	B3	2.53	2.12	0.41	0.41	0.17
	B4	1.89	2.12	-0.23	0.23	0.05
	B5	1.71	2.12	-0.41	0.41	0.17
10	B1	1.73	2.12	-0.39	0.39	0.16
	B2	1.76	2.12	-0.36	0.36	0.13
	B3	2.15	2.12	0.03	0.03	0.00
	B4	2.09	2.12	-0.03	0.03	0.00
	B5	2.37	2.12	0.25	0.25	0.06
	Total	105.96			21.34	13.43
	Mean	2.12			0.43	

Table 6b: Volume of water in each tagged bucket after each experimental run at minimum intensity

RUNS	Bucket Tags	Vol (litre)	$\bar{x}$	$x - \bar{x}$	$/x - \bar{x}/$	$(x - \bar{x})^2$
1	B1	1.23	1.072	0.16	0.16	0.02
	B2	1.03	1.072	-0.04	0.04	0.00
	B3	1.36	1.072	0.29	0.29	0.08
	B4	1.05	1.072	-0.03	0.03	0.00
	B5	0.99	1.072	-0.08	0.08	0.01
2	B1	1.39	1.072	0.32	0.32	0.10
	B2	0.61	1.072	-0.47	0.47	0.22
	B3	0.59	1.072	-0.48	0.48	0.23
	B4	1.49	1.072	0.41	0.41	0.17
	B5	0.92	1.072	-0.15	0.15	0.02
3	B1	1.03	1.072	-0.04	0.04	0.00
	B2	1.50	1.072	0.43	0.43	0.19
	B3	1.17	1.072	0.10	0.10	0.01
	B4	0.68	1.072	-0.39	0.39	0.15
	B5	1.25	1.072	0.18	0.18	0.03
4	B1	1.05	1.072	-0.03	0.03	0.00
	B2	1.16	1.072	0.08	0.08	0.01

	B3	1.47	1.072	0.40	0.40	0.16
	B4	1.52	1.072	0.45	0.45	0.20
	B5	0.77	1.072	-0.30	0.30	0.09
5	B1	1.00	1.072	-0.07	0.07	0.00
	B2	0.57	1.072	-0.51	0.51	0.26
	B3	1.31	1.072	0.23	0.23	0.05
	B4	0.84	1.072	-0.23	0.23	0.05
	B5	1.49	1.072	0.42	0.42	0.18
6	B1	1.25	1.072	0.18	0.18	0.03
	B2	0.66	1.072	-0.41	0.41	0.17
	B3	1.12	1.072	0.05	0.05	0.00
	B4	1.24	1.072	0.17	0.17	0.03
	B5	1.28	1.072	0.21	0.21	0.04
7	B1	0.87	1.072	-0.20	0.20	0.04
	B2	1.42	1.072	0.35	0.35	0.12
	B3	0.81	1.072	-0.26	0.26	0.07
	B4	0.82	1.072	-0.25	0.25	0.06
	B5	1.22	1.072	0.15	0.15	0.02
8	B1	1.35	1.072	0.27	0.27	0.07
	B2	1.00	1.072	-0.07	0.07	0.00
	B3	0.87	1.072	-0.20	0.20	0.04
	B4	0.82	1.072	-0.25	0.25	0.06
	B5	0.55	1.072	-0.53	0.53	0.28
9	B1	1.63	1.072	0.56	0.56	0.31
	B2	1.11	1.072	0.04	0.04	0.00
	B3	1.18	1.072	0.11	0.11	0.01
	B4	1.16	1.072	0.09	0.09	0.01
	B5	0.76	1.072	-0.31	0.31	0.10
10	B1	0.91	1.072	-0.17	0.17	0.03
	B2	0.77	1.072	-0.30	0.30	0.09
	B3	1.19	1.072	0.12	0.12	0.01
	B4	0.97	1.072	-0.10	0.10	0.01
	B5	1.21	1.072	0.14	0.14	0.02
	Total	53.61			11.78	3.90

Mean	1.072	0.24

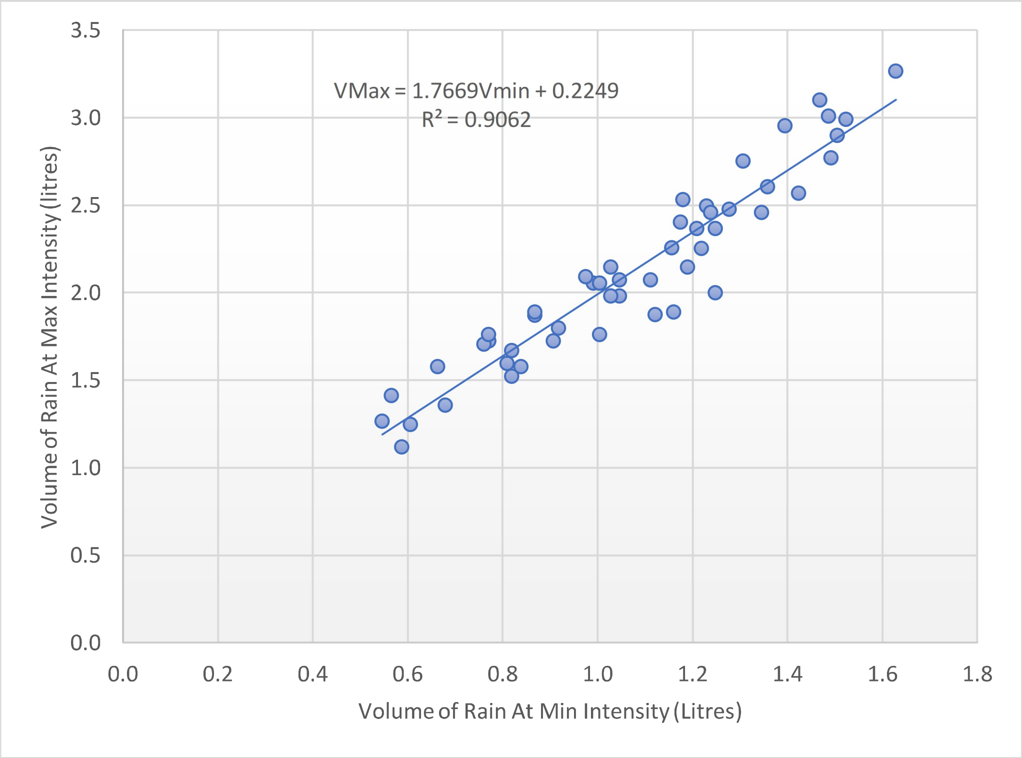

Figure 6: Volume of Rainfall (Maximum Intensity Vs Minimum Intensity)

Table 7: Characteristics of the Rain Simulator at Both Maximum and Minimum Intensity

Flowrate	At Max. Intensity	At Min. Intensity
Coefficient of Uniformity CU (%)	79.86	78.03
Standard Deviation	0.82	0.44
Area (m^2)	4.00	4.00
Average Intensity (mm/hr)	31.79	16.08
Kinetic Energy ($J/m^2/mm$)	26.07	22.23
Erosivity Index R (MJ mm ha^{-1} h^{-1})	1278.63	543.46

The coefficient of uniformity at maximum intensity was found to be 79.86% and that at minimum intensity was found to be 78.03% as seen in Table 7, with both values within the accepted range of 68.3 to 82.2% for a rainfall simulator as stated by Junior and Siqueira (2011). This confirms that the shower roses, sprinkles water at good spacing between themselves, providing a good coverage on the ground. The coefficient of uniformity (CU) when the rainfall simulator was operated at maximum intensity was seen to be higher than when it was operated at minimum intensity but with little variation between the two values, this can also be confirmed in Fig 6, where the correlation coefficient between rainfall volume, maximum and minimum intensity were found to be $R^2 = 0.9062$ and a linear relationship of $Vmax = 1.7669Vmin + 0.2249$ was obtained. This means that the rainfall simulation at both maximum and minimum intensity satisfy the required coefficient of uniformity (CU) needed for operation.

CONCLUSIONS

The locally made rainfall simulator described in this work was able to attain the desired rainfall intensities with the help of the control valve. With its simplicity and cost effectiveness, it can be said that, this rainfall simulator is suitable for erosion studies within the environment of study.

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