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Design, Development and Testing of a Hydrological Process Demonstration System

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Abstract **Original Research Article**

Most previous hydrological studies advanced mainly by the collection of data from the field. This research aimed at developing and testing of a hydrological demonstration system using a rainfall simulator as a laboratory-scale model. Locally available materials were used to construct the model. It has six major components: reservoir, plot (sandbox), water pump, simulator, a network of pipes and frame. Some rainfall characteristics like intensity, distribution uniformity, drop size diameter, raindrop velocity and kinetic energy (KE) and runoff were used to evaluate the system's performance. The demonstration system produced rainfall intensity ranging from 56.9 to 91.1 mm/hr with an average uniformity of 88.5%. The obtained rainfall drop size varied from 0.96 mm to 2 mm with an average of 1.62 mm. The velocity and kinetic energy of the rain varied from 63.56 to 86.47 m/s and 27.22 to 29.0 $Jm^{-2}mm^{-1}$ respectively. A 7-minutes rainfall was observed which recorded a peak runoff discharge of 8.343×10^{-2} m^3 in 10 minutes 30 seconds after which it recessed to 1.67×10^{-2} m^3. The system is capable of producing rainfall characteristics similar to that of natural rainfall and therefore can be used for demonstration in the laboratory.

Keywords: Development, Hydrological processes, Rainfall, Runoff, Rainfall characteristics.

1.0 INTRODUCTION

Hydrological cycle study focused on the evaluation of water resources through the measureable investigation of the distribution and assessment of the hydro-meteorological factors that regulate the circulation and transfer of water under all of its phases (Shiklomanov, 2011). It deals with the components of the water balance and it quantitative estimation, which consists of the following phases: the transfer of water from atmosphere to the soil by precipitation, the relocation of water from the soil and open surface water to the atmosphere by evaporation and transpiration, the variation in the distribution and storage of water in various reservoirs, that is surface and groundwater reservoirs and the distribution and redistribution of water on both the surface and subsurface of the earth through overland, surface runoff in streams and rivers, and groundwater flow

The hydrological cycle can be scaled to laboratory size for easy research and repeatability of the system. However, most hydrological research focused on either one or two components of the hydrological cycle without considering recycling of the water (Chouksey *et al.*, 2017; Raudkivi, 2013). Aksoy, *et al.*, (2012) designed a laboratory-scale model for assessment of rainfall-runoff-sediment transport processes, but could not take into consideration recycling of the water. But, the management of hydrological cycle is an effective way to accomplish efficient utilization of water resources and solve water resource calamities at homes and in irrigated agriculture regions. Also, non-recycling of water in the laboratory is not economical in terms of managing the available water source. Using such system in the laboratory could be labour-intensive as water is needed for replication of the experiment. This research therefore aimed at designing a hydrological cycle demonstration system based on rainfall simulator.

1.1 Rainfall simulator

Rainfall simulator is a research tool developed to mimic the characteristics of the natural rainfall. It is classified into three; drop former, pressurized nozzle(s) (Yakubu and Yusop, 2017) and hybrid (Wildhaber *et al.*, 2012) rainfall simulator. The drop former (DF) also known as non-pressurised simulator uses hanging yarn often placed at height ranging from 7 m to 14 m depending on the desired results (Lassu *et al.*, 2015). The rainfall drop size depends on the sizes of the holes on the yarn. It produces drop size range from 3 mm to 6 mm diameter. However, DF is impractical in the field due to the huge height required to attain terminal velocity and drops are limited to the number of holes on the hanging yarn. The pressurised nozzle (PN) rainfall simulator as the name implies requires an external force per the area of the nozzle to mimic rainfall. It produces both small and large drop size range and impact velocity similar to that of the natural rainfall (Lassu, *et al.*, 2015; Yakubu and Yusop, 2017). PN rainfall simulator can be used in the field with varied intensities at shorter height than that of the DF rainfall simulator (Wilson *et al.*, 2014). The hybrid rainfall simulator utilizes the principles of the drop former and pressurised nozzle rainfall simulator (Egodawatta, 2007). It was developed to reduce the kinetic energy of the raindrop on the soil, but was detrimental to the rainfall uniformity (Yakubu and Yusop, 2017). However, all the developed hybrid rainfall simulator was noted to be good for examining soil erodibility.

Nevertheless, any developed rainfall simulator should model the following natural rainfall characteristics; drop size distribution, terminal velocity, uniformity and kinetic energy (Lassu, *et al.*, 2015; Mutchler and Hermsmeier, 1965).

2.0 MATERIALS AND METHODS

2.1 Design Considerations

2.1.1 Water Pumping and hydraulic system

Pump consideration was based on two important parameters; the total dynamic head (TDH) and the system flow rate (Q). Eqn. 1 was used to compute the TDH, Eqn. 2 was used to compute the flow rate in pipe and velocity of flow in individual pipes (i.e main, sub-main and lateral pipes) were determined using Equation 3a, 3b and 3c respectively.

$$TDH = H_e + H_s + H_f \quad \ldots\ldots\ldots 1$$

Where, H_e = elevation head (static discharge head) – elevation from the centre of the impeller to the highest sprinkling point (i.e. 3.15 m),

H_s = static suction head which is the elevation from the centre of the impeller down to the level while pumping (i.e. 0.15 m),

H_f = friction head that is in main pipe (entry loss), sub-main pipe (due to reducer bend) and laterals (due to T-joints)-(m). Equations 1a, 1b and 1c were used.

$$h_m = \frac{k_e v_m^2}{2g} \quad \ldots\ldots\ldots 1a$$

$$h_{sm} = \frac{k_t v_{sm}^2}{2g} \quad \ldots\ldots\ldots 1b$$

$$h_l = \frac{k_t v_l^2}{2g} \quad \ldots\ldots\ldots 1c$$

Where; h_m, h_{sm} and h_l are head losses in main, sub-main and lateral pipes respectively, k_e and k_t are entry loss constant and T-joint loss constant given as 0.5 and 1.8 respectively. g is acceleration due to gravity (m/s^2).

Recalling that $Q = V * A$ ……………………….. 2

Where; Q is flow rate (m^3/s), V is mean flow velocity = $\sqrt{\frac{2gH_f}{k_t}}$ (m/s); A is the cross sectional area of the flow medium which is $\pi\frac{d^2}{4}$ and d is the diameter of the flow medium.

$$M = \rho * Q \quad \ldots\ldots\ldots 3$$

By substituting Eqn. 2 into Eqn. 3, Eqn. 3a, 3b, and 3c were obtained

$$V_m = \frac{M}{\rho A_m} \quad \ldots\ldots\ldots 3a$$

$$V_{sm} = \frac{M}{\rho A_{sm}} \quad \ldots\ldots\ldots 3b$$

$$V_l = \frac{M}{\rho A_l} \quad \ldots\ldots\ldots 3c$$

Where: M is mass flow rate (kg/s); V is velocity of flow through the pipe (m/s); A is the cross sectional area of the flow medium (m^2); ρ is density of fluid (kg/m^3); V_m and A_m are velocity and area of the main pipe respectively; V_{sm} and A_{sm} are velocity and area of the sub-main pipe respectively; V_l and A_l are velocity and area of the lateral pipe respectively

2.1.2 Flow velocity and head losses in the pipes

The flow velocity, area and head losses were computed based on the pipe diameter (size) and the results were as presented on Table 1. The system also produced a mass flow of 1.11kg/s.

Table 1: Characteristics of pipes used for the system

Pipe	Diameter (mm)	Velocity (m/s)	Area (m^2)	Head loss (m)
Main	25.4	1.96	5.068 x 10^{-4}	0.098
Sub-main	19.3	2.14	2.917 x 10^{-4}	0.420
Lateral	12.7	8.76	1.267 x 10^{-4}	7.040
Total head loss (H_f)	-	-	-	7.558
System mass flow rate	1.11 kg/s			

2.2 Material considerations

Materials considered for construction of the hydrological cycle demonstration system were locally available in our markets. These were as outlined below.

2.2.1 Rainfall Simulator

Plastic shower roses with orifices of 2mm were adopted as nozzle for the system to avoid rusting. Since the project aimed at developing a scale model, the simulator size was 1 m x 2 m and an area of 2 m^2. The nozzles were arranged on a 12.7 mm diameter pipes to spray water vertically downwards. The nozzle arrangement was 200 mm x 240 mm apart as presented by the drawing in Figure 1.

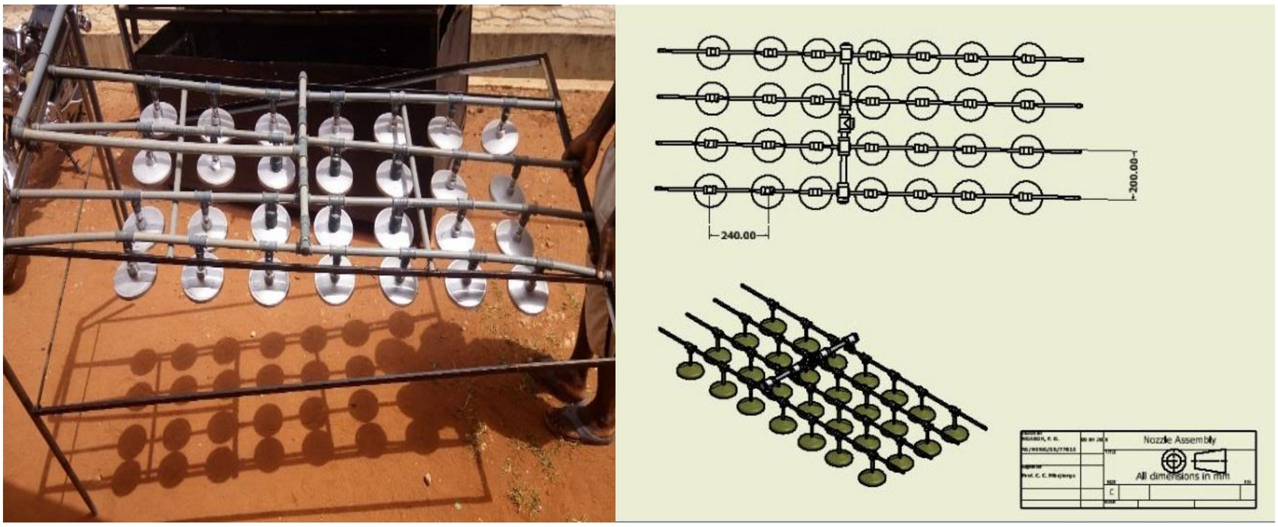


Figure 1: Nozzles arrangement

2.2.3 Plot

The overall dimension of the sand box was 1 m x 1.9 m. The total volume of sandbox was approximately 1 m x 1.9 m x 0.5 m (0.95 m^3) with a surface area of 0.95 m^2. Perspex was used to construct the plot (sand box) with provision made for surface and subsurface runoff collection. The plot was smaller than the dimension of the network of rainfall simulator to maximise rainfall uniformity. The runoff lines were made of flexible pipes which were connected at 0.25 m to the brim and at the base of the sandbox (See Figure 2).

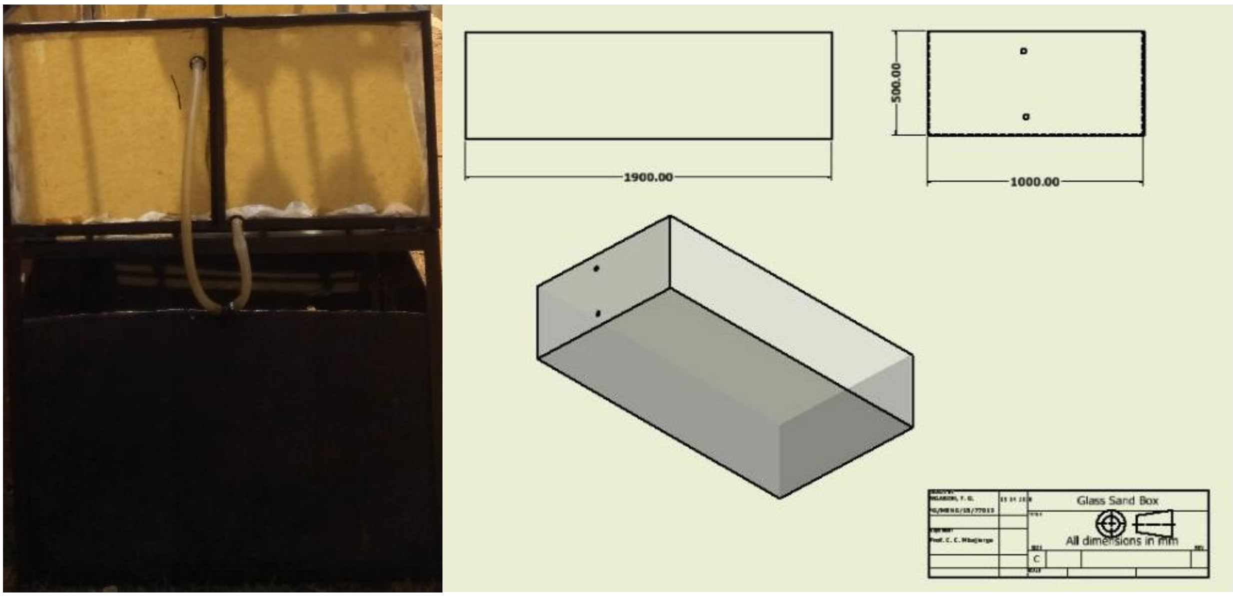


Figure 2: Sandbox (plot)

2.2.4 Reservoir

The reservoir was constructed from 16 gauge of hot rolled carbonate sheet metal which were bought from Nsukka timber shed market. It has a volume 1 m x 2 m x 0.61 m (1.22 m^3) or 1220 litres. It has two openings; one at the top of the reservoir, 0.01 m to the brim to serve as return and another one at 0.05 m to the bottom to serve as discharge to the suction. Figure 3 presents the drawing and constructed reservoir.

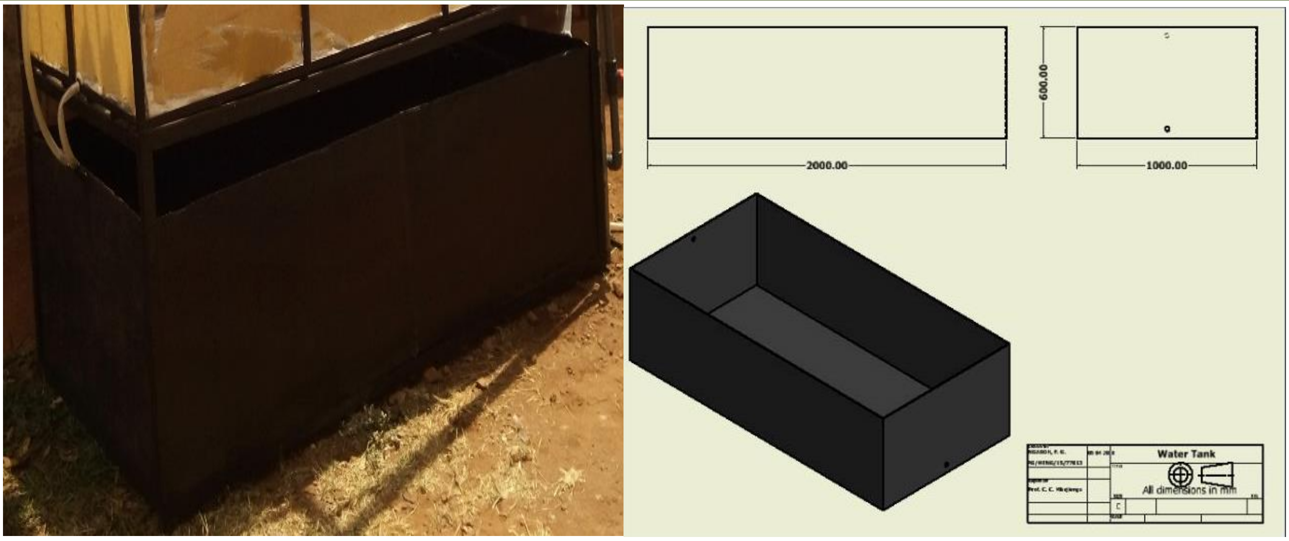


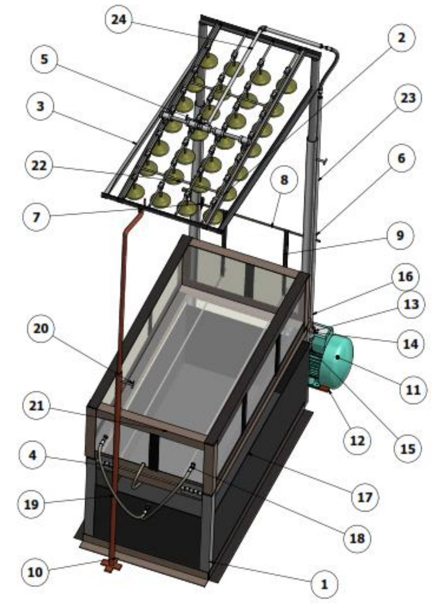
Figure 3: Designed Water tank (reservoir)

3.3 Description of the designed and constructed system

The hydrological cycle demonstration system is a laboratory scale model designed to serve as demonstration and research tool for students and researchers. The model is made of six major components; reservoir, water pump, PVC pipes (main, sub-main and laterals lines), nozzles (shower roses), plot (sandbox) and frame.

The reservoir is made of 16-gauge plate (metal sheet) with size of 1000 mm width, 2000 mm length, and 610 mm maximum depth with volume capacity of 1220 litres. A 1 Hp water pump is connected to suck water from the reservoir into the main pipe which is made of 25.4 mm PVC pipe through a height of 3000 mm from the pump discharge. Between the pump and reservoir, is a ball gauge to stop flow into the pump when not in use, and along the 25.4 mm pipe is another ball gauge positioned at 0.35 m from the pump discharge to regulate the flow at the shower rose. The water is then discharged into the sub-main line which is made of 19.3 mm PVC pipe. On the sub-main line, four reducing T-joints are fitted to reduce the flow from 19.3 mm pipe to 12.7 mm pipe (lateral line).

There are four lateral lines spaced 200 mm across the width fitted with seven (7) T-joints on each. The T-joints are spaced at 240 mm across the length of the laterals. The perforated discharge surface of the shower roses is 150 mm and has 82 orifices each. The nozzles are tied to 12.7 mm adopter fitted to 12.7 mm T-joints on the laterals lines. The networked nozzles are positioned 1.8 m from the plot. They are supported by three scaffolds made of two different sizes of galvanized pipes (12.7 and 19 mm). The 19.3 mm pipe is housed in the 1inch pipe for easy adjustment all through the three scaffolds. The larger pipe has lock to fasten every adjustment level. The area of plot is 1.9 m^2 and maximum depth of 0.5 m bounded by Perspex (fibre glass). A 16 mm iron rods are braced under the sandbox to avoid sagging when sand is loaded into it, likewise the glass is framed with a 25.4 mm angular bar. The sandbox has two openings (up at 250 mm from the bottom and at the base) for surface and subsurface runoff discharge. The runoff is collected through a flexible hose connected to a Y-shape extruded from the upper part of the reservoir. Networked nozzles and pipes are tied on a constructed angular bar frame and scaffold with a binding wire to overcome shifts as a result of vibration due to pressure from water pump. Figure 4 present the 3D view of the full assembly drawing and fully constructed hydrological cycle demonstration system.



PARTS LIST	
ITEM	DESCRIPTION
1	Frame assembly
2	Nozzle Assembly
3	Angular bar frame for nozzle
4	Bar frame for glass
5	Galvanised pipe
6	Bearing holder
7	Bearing
8	Winding shaft
9	Pulley belt
10	Support
11	Water pump
12	Pump mount
13	Valve
14	Tee-Joint
15	90 Deg Elbow
16	Suction pipe
17	water Tank
18	Run off line
19	Flexible hose
20	Lock
21	Glass sand box
22	Lateral pipe
23	Main pipe
24	Sub-main pipe

Figure 4: 3D labelled assembly drawing of hydrological cycle demonstration system

3.5 System Validation

The parameters evaluated on the hydrological cycle demonstration system were rainfall characteristics such as rainfall intensity, distribution uniformity, kinetic energy, drop size distribution, terminal velocity and hydrological cycle components such as runoff.

3.5.1 Soil sample and loading of plot

River sandy sample was collected from Obolo-Afor and transported to the laboratory. The sample was washed to reduce its turbidity when water is passed through. The washed soil sample was loaded in the sand box to the level of the surface drainage line to allow free flow of the surface runoff. The loading was done to attain a sloppy surface as indicated on Figure 5 to enable runoff and sediment transport studies.

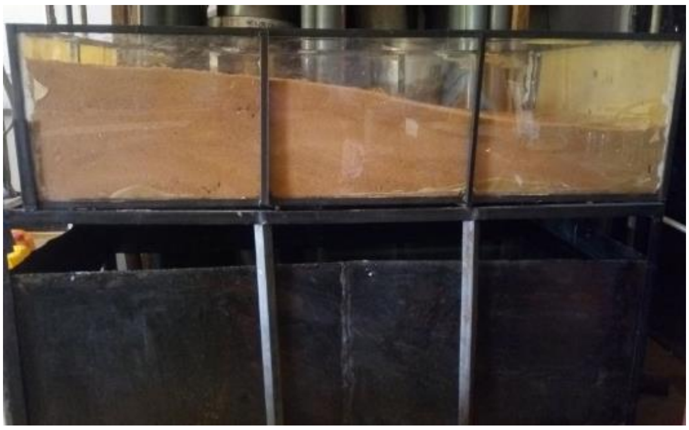


Figure 5: Side view of Plot with reservoir of water

3.5.2 Rainfall Intensity

Rain gauges of mouth diameter 7.5 cm were distributed over the experimental plot (sand bed) at equidistance of 30 cm from each other (ASABE-S4.361, 2009) (Fig. 6). The system was operated for approximately 10 minutes after which it was stopped. The level of individual gauge was recorded. The process was replicated to obtain the average intensity of the rainfall. Eqn. 4 was used to estimate the average intensity of rainfall over the entire area (Cai *et al.*, 2012) and was based upon the area of the mouth of the catch cans.

$$I = \frac{10Vt}{s} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ 4$$

Where; I is the average intensity of rainfall (mm/hr); V is the volume of water in the rain gauge mm^3; t is the run duration (hr) and s is the area of mouth of rain gauge (mm^2).

3.5.3 Distribution Uniformity

Christensen uniformity equation was used to evaluate rainfall uniformity (Christiansen, 1942) as presented by Eqn. 5.

$$CU = [1 - [\frac{\sum_{i}^{n} abs(x_i - x_m)}{n x_m}]] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

Where; CU = Coefficient of uniformity; i = 1, 2, 3, …, n= individual gauge; x_m = Average depth of water; n = No of rain gauge

Figure 6: Grid of rain gauges on the plot

3.5.4 Rainfall Kinetic Energy

Eqn. 6 was used estimate the kinetic energy (K.E) of the rainfall according to Wischmeier (Guo *et al.*, 2013).

$$KE = 11.897 + 8.73\ logI \ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

Where KE is the kinetic energy per unit area (J/m^2 mm^{-1}); I is average rainfall intensity (mm/hr)

3.5.5 Drop size Estimation

Flour pellet method was used. Sample of well sieved flour was collected in a bow. As rainfall simulation was in progress, the bow of flour sample was passed under it (see Plate 7a) where pellets were formed. The formed pellets were gently removed from the bow and oven dried at 110 ^{0}C for one hour which was later removed to remove the moisture in the pellets. Each of the pellets were weighed (Figure 7b). Equation 7 (Horne, 2017) was used to estimate rain drop diameter.

$$D_r = \sqrt[3]{\frac{6}{\pi} W} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

Where; D_r is the rain drop diameter (mm), W is average pellet weight (mg)

(a) Bow of wet pellets (b) Weighing of oven-dried flour pellets

Plate 7: Flour pellet method

3.5.6 Determination of Velocity

The drop velocity is an important characteristic in the design of rainfall simulator. In this design the Drop velocity was determined using Eqn. 8 (Warude *et al.*, 2015)

$$V = \frac{\sqrt{(\pi * d^3 * \rho_{water} * g)}}{6 * \rho_{air} * A * Cd} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

Where; ρ is density, g is acceleration due to gravity, Cd is drag coefficient and A is the cross-sectional area of drop size. The drag coefficient was estimated using Eqn. 8a as proposed by Hills and Gu (Sobrinho *et al.*, 2008).

$$C_n = 0.4671 d^{-0.9859} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 8b$$

Where d is diameter of the drop size (mm)

3.5.7 Runoff

Runoff at the foot of the slope was accumulated and measured using a vertically placed metre rule to record the depth of water. In a 7 minutes' rainfall, runoff from the plot were observed and recorded after every 1 minute 30 seconds for a sum period of 25 minute 30 seconds.

4. RESULTS AND DISCUSSION

4.1 Rainfall Intensity

The intensity of rainfall produced by the system ranged between 56.9 mm/hr and 91.1 mm/hr with an average of 74.45 mm/hr above an intensity of 45.4 mm/hr and 20 mm/hr produced by Zemke (2017) and Keya and Karim (2020) respectively. However, the obtained value here tallied with that of Yusuf *et al.*, (2017) and Ricks, et al., (2019) possibly due to the similarity in the materials used. Furthermore, prediction by regression analysis showed that between rainfall intensity and drop size, there is a strong relationship which has proportion of variance explained as R^2 = 0.8856.

4.2.2 Rainfall Drop diameter

The system simulated drop diameters ranging from 0.96 mm to 2.0 mm with an average of 1.62 mm. This result was similar to 1.5 mm result obtained by other researchers (Abudi *et al.*, 2012; Keya and Karim, 2020) but was less compared to 4.5 mm obtained by (Regmi and Thompson, 2001) obtained from drop forming simulator at a height of 14 m. The less obtained value from the design was as result of the shower-rose aperture diameter which is common in pressurized simulators as the pressurized flow are conveyed through small aperture (Horne, 2017). The height of fall of the simulator was approximately 1.8 m from the plot due to the height of the laboratory; this challenge can be mitigated potentially by using a shower-rose with larger aperture with a concurrent reduction in pressure which may tend to affect the velocity consequentially by reducing it. The regression model with R^2 = 0.8856 indicates that there is a close relationship between drop diameter and rainfall intensity.

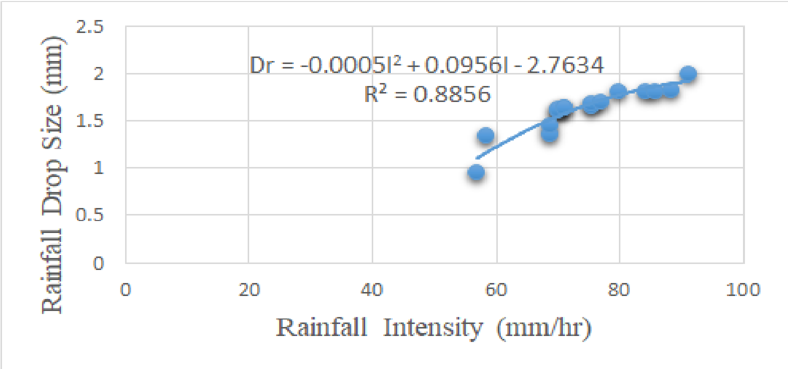


Figure 8: Graph of Rainfall intensity Vs. Rainfall drop size

4.4.3 Distribution Uniformity

The system gave coefficient of uniformity (CU) of 81.2 % to 88.5%. The upper limit result was within the acceptable range given by and was more higher than 84.4%, the value obtained by Yusuf *et al.*, (2017). However, the lower CU obtained was higher than that of other researchers (Nielsen *et al.*, 2019; Zemke, 2017). Therefore, the coefficient produced by the demonstration system is within the accepted range.

4.4.4 Fall Velocity of Raindrop

Using model to compute the fall velocity, it confirmed that the system mimicked high rainfall velocity ranging from 63.56 to 86.47 m/s with an average of 77.93 m/s (see Table 9) This was very high compared to the 8.16 m/s value obtained by Yusuf *et al.*, (2017) but similar to 78 m/s result obtained by Persakhoo *et al.*, (2012). This higher value was as a result of the height of the simulator at the period of the experiment (1.8 m). The result of the velocity obtained from the simulator confirmed the effect of the height on the drop diameter and velocity as reported by (Van Boxel, 1997). A regression analysis indicated that raindrop size had effect on the rainfall velocity with proportion of variance of R^2 = 0.9961% as indicated in Fig 9.

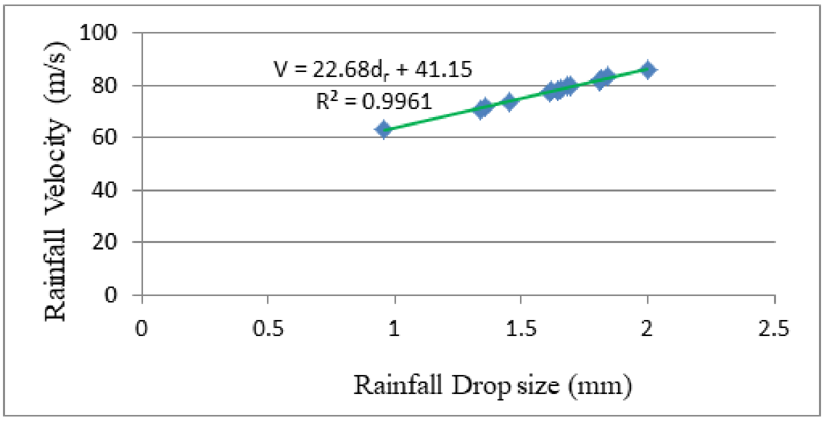


Figure 9: Relationship between velocity and Raindrop size

4.4.5 Kinetic Energy of Raindrop

The kinetic energy (KE) resulting from the impact of the raindrop ranged between 27.22 and 29.00 $Jm^{-2}mm^{-1}$ with an average value 28.20 $Jm^{-2}mm^{-1}$. This is similar the findings of Abudi *et al.*, (2012) which was obtained from a height ranging from 2 to 2.4 m. It is however, different and above 4.6 $Jm^{-2}mm^{-1}$ the value (Zemke, 2017) but approximately 98% of the natural rainfall (Chouksey, *et al.*, 2017). Correlation analysis between the kinetic energy and the intensity of the rain showed R^2=0.997 of proportion of variance; this indicates that there is strong relationship between the two variables. An increase in the rainfall velocity resulted in increase in the rainfall kinetic energy (Szabó *et al.*, 2020) (see Figure 10).

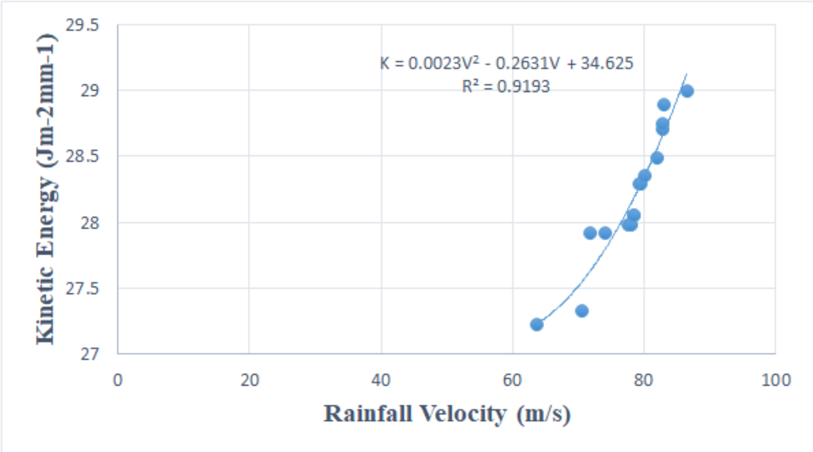


Figure 10: Graph showing the relationship between Kinetic energy and drop velocity

4.4.6 Runoff and infiltration from the plot

Studying surface runoff from the field was not possible as reason was attributed to soil type and its high porosity. Figure 11 shows the hydrograph of results of runoff discharge generated from 7 minutes' rainfall. The peak flow was observed at 10 minutes 30 seconds with a lag time of 4 minutes 30 seconds and accumulated discharge of 8.343 x 10^{-2} m^3. Recession begun at 12 minutes through 25 minutes 30 seconds before it finally retired to the based flow.

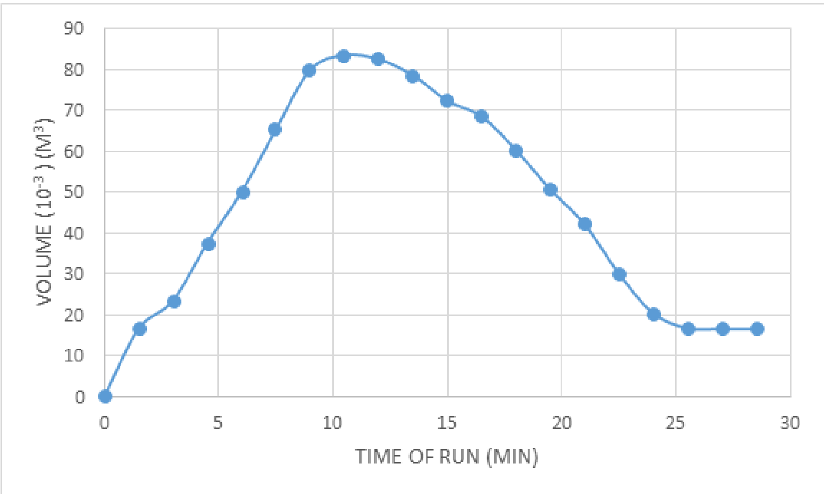


Figure 11: Hydrograph of runoff discharge for 7 minutes simulated rainfall

4.4.7 Correlation Analysis of the Rainfall parameters

The rainfall parameters were correlated. The categories of correlation adopted for this study are: perfect (R^2=1); very strong ($0.9 \leq R^2 \leq 1$); strong ($0.7 \leq R^2 \leq 0.89$); moderate ($0.4 \leq R^2 \leq 0.69$); weak ($R^2 \leq 0.39$); and negligible correlation ($0.0 \leq R^2 \leq 0.1$) (Schober *et al.*, 2018). The result of the analysis showed that the kinetic energy affect of the rainfall drop strongly affected the fall velocity with R^2=0.9401 and moderately affected the weight and raindrop with a respective R^2 value of 0.5615 and 0.5884. Moreso, the ainfall velocity moderately affects weight and raindrop size with R^2 values of 0.5615 and 0.6997 respectively, meanwhile, raindrop very strongly affected the weight of the raindrop with an R^2 value of 0.9735.

Table 2: Result of correlation analysis

	Weight (g)	*Rain drop, Dr (mm)*	*Fall velocity (m/s)*	*Kinetic Energy*
Weight (g)	1			
Rain drop, Dr (mm)	0.973478	1		
Fall velocity (m/s)	0.63653	0.699659	1	
Kinetic Energy	0.561544	0.588375	0.940165	1

CONCLUSION

This research was aimed at design, development and testing of hydrological cycle demonstration system; a laboratory scaled model using a rainfall simulator. The developed demonstration system has six basic components which are a network of nozzles, frame, reservoir, plot and water pump. Water saving showers can be employed to mimic rainfall at different intensities and at different pressures. A digital pressure gauge can be fitted to record the pressure required for an intensity of rainfall. To enable simulation of both surface and intermittent runoff, loamy soil can be used instead of sandy soil.

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