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Automated Measurement for Sensitivity Analysis of Runoff-Sediment Load at Varying Surface Gradients

Direct measurement of surface runoff is often associated with errors and inaccuracies which results to unreliable hydrological data. An automatic Runoff-meter using tipping buckets arrangement calibrated to tip 0.14 liter of runoff water per tip with an accuracy of ± 0.001 litre was used to measure surface runoff from a steel bounded soil tray of dimension (1200 mm X 900 mm X 260 mm) filled with sand loamy to the depth of 130 mm and inclined at angle (0^0, 5^0 ,12^0 and 15^0) horizontal to the instrument. The effect of varying angles of inclination on runoff intensity, sediment loss rate and sediment loss is significant at 5 % confidence level, while surface runoff is not significant at 5 % confidence level. Total highest sediment loss of 458.2 g and 313.4 g were observed at angle 15^0 and 12^0 respectively. Total surface runoff of 361.5 mm and 445.8 mm were generated at inclined angle of 0^0 and 5^0, while at angle 12^0 and 15^0, 564.3 mm and 590.0 mm of surface runoff were generated. In addition, runoff intensity and sediment loss rate were highest at angle 15^0, while the lowest values of 1.5mm/min and 5.43 g/min were obtained at angle of inclination 5^0. The results showed that strong relationship existed among the hydrological variables as a result of subjecting the steel bounded soil tray to different angles of inclination. Such results would provide useful data for the running of physics-based deterministic model of surface runoff and erosion which will be useful for the design of hydrological structures, land use planning and management.

Keywords: *Surface runoff, Sediment yield, Runoff-meter Slopes/Angle Hydrological variables, Soil tray, Rainfall*

1. Introduction

Continuous surface runoff and sediment loss concentration can be linked with land degradation and environmental deterioration in most parts of the world

(Bruijnzeel, 1999). This situation is reported to be worsened by poor land use and agricultural practices. Soil detachment and transport by impacting raindrop is an important first step in soil erosion. Unconcentrated (sheet) runoff usually does not have enough power to actively detach and entrain soil particles (Booth, 1993), but particles detached by rain splash may subsequently be transported by the flow (Armfstrong, 1995). Soil erosion, downstream flooding and siltation pose a major challenge to watershed mangers, particularly in the humid tropics with their high rates of deforestation and intense rainfall. (SCS, 1984).

The major problem facing agricultural practices in Nigeria and other developing nations is the rate at which the agricultural soil is gradually being lost to soil erosion initiated by surface flow. In order to correct soil erosion and wisely manage land resources, erosion processes and mechanism must well be studied and understood and appropriate land management must be assessed (Olotu, 2007). In formulating a distributed hydrologic runoff and sediment models that will be veritable in solving the problem of surface flow, loss of agricultural soil and sedimentation of lakes, reservoirs, ponds e.t.c, surface runoff and sediment yield need to be accurately measured and determined (Bruijnzeel,2000). It has been reported that conventional measurement of surface runoff and sediment yield is inadequate to produce reliable results because of the inaccuracies often associated with the method. Having linked the failure of inaccurate measurement of surface runoff to the conventional or manual method, a sophisticated and sensitive instrument (automatic Runoff-meter) is expected to be used in measuring surface runoff in terms of volume and intensity with high precision (Olotu, 2007).

It is very important to obtain a reliable hydrological data because studies of this nature are useful to improve our understanding of rainfall-runoff and sediment yield relationship (Bruijnzeel, 2000). To further understand the dynamics between rainfall, surface runoff and sediment yield, accurate and precise data of these interrelated hydrological variables are required (Fury, 2002). This paper outlines the simulation of rainfall, determination of generated surface runoff and sediment yield, while exploring the dynamics that existed within these factors on bare soil at different angles of inclination using automatic Runoff-meter.

2. Automatic Runoff-meter

Automatic Runoff-meter is an automated instrument developed and used to measure surface runoff in terms of volume and intensity with high precision. The instrument was calibrated to meet the required standard. Its operations was based on tipping buckets arrangement. Instrumentation and control systems were well incorporated into the equipment to enhance its performance. Details of the description and operational mechanism of this instrument is not available in this paper.

Figure 1. Automatic Runoff-meter during operation at gradient 0^{o}.

Figure 2. Automatic Runoff-meter during operation at gradient 5^{o}

Figure 3. Automatic Runoff-meter disassembled after operation

3. Research methodology

An automatic Runoff-meter with tipping bucket arrangement was designed, constructed and calibrated to deliver 0.14 litre of runoff water per tip operation with an accuracy of ± 0.001 litre. The instrument was set up and used to measure surface volume and intensity from steel bounded soil tray of dimension (120 X 900 X 260) mm. The experiment was carried out at Department of Agricultural Engineering, Federal University of Technology, Akure, Nigeria in July, 2008. The tray was filled with sand loamy soil to the depth of 130 mm and placed on adjustable wooden frame of 1.4m height as shown in Fig. 1, 2, 3 and 4. Rain simulator was positioned above the supported soil tray and the simulator height was 1.0 m throughout the experimentation. Before the simulation began, all the components of the instrument were coupled and connected to the power source (60 AH, 12 V battery). Four series of experiments were conducted with the soil tray inclined at varying angles (0^0, 5^0, 12^0 and 15^0) horizontal to the instrument (see Fig. 1, 2, and 3). Rainfall was simulated uniformly over the prepared soil tray and to establish uniform antecedent moisture conditions, the same amount of rainfall was simulated for all the experiments. Surface runoff was automatically measured with the aid of calibrated tipping bucket logger system of the instrument. Tips from the calibrated buckets were recorded on the electro-mechanical timer in seconds. Measured runoff was recovered from the storage compartment of the instrument after each simulation attempt. Dissolved coagulating agent, $AIS0_4(_{aq})$ was added to the recovered water sample, and after the sediment had settled, the water was carefully decanted and the remaining water was passed through paper filter placed within a vacuum filtration funnel. Deposited sediment retained by the filter paper was oven dried at 105^0C for 24-hour and then weighed to the nearest 0.1 g. Suspended sediment obtained was oven dried to 105^oC for 24-hour and weighed. Summation of suspended and dissolved sediment resulted to the total sediment loss. Simulated rainfall and measured runoffs were converted to the nearest (mm). The automatic runoff meter was dismantled after operation as shown in Fig. 4.

4. Results and discussion

The results of the experiments at different gradients are shown in Table 1, 2, 3 and 4 respectively. Table (5) and (6) show the sediment loss rate (g/min) and Runoff intensity (mm/min) at different angles of inclination. The same amount of rainfall (mm) was simulated for each of the experiments. The effect of varying angles of inclination on runoff intensity, sediment loss rate and sediment loss is significant at 5 % confidence level, while surface runoff is not significant at 5 % confidence level. Total highest sediment loss of 458.2 g followed by 313.4 g were observed at angle 15^0 (Table 4) and 12^0 (Table 3) respectively. Results also show total surface runoff of 361.5 mm and 445.8 mm were generated at inclined angle of 0^0 (Table 1) and 5^0 (Table 2). At slope 0^0 and 5^0, maximum infiltration rate was reached before surface runoff could be generated and this was due to the position at which the soil tray was inclined which allowed enough infiltration and percolation of simulated rainwater. At angle 12^0 (Table 3) and 15^0 (Table 4), 564.3 mm and 590.0 mm of surface runoff were generated. Hence, infiltration capacity was not attained before surface runoff was generated at slope angle 12^0 and 15^0. All simulated rainfall was lost to surface flow and this was due to angles at which the soil tray was subjected during experimentation.

Table 5 shows sediment loss rate (g/min) for each of the experiment. Sediment loss rate were highest with 189.6 g/min at slope 15^o followed by angle 12^o with a value of 98.6 g/min. Least value for sediment loss rate was observed at slope 5^o with 68.9 g/min and 48.9 g/min at slope (0^o) respectively. The increment in sediment loss rate was not generally proportional to increase in the amount of simulated rainfall. At slope 12^o, second simulation attempt produced sediment rate loss of 12.8 g/min followed by 17.6 g/min at the third simulation attempt; the fourth simulation produced lower sediment rate loss of 9.8 g/min (Table 5). This development in sediment loss rate was observed to vary in all the treatments and this complexity can be best described with the process of detachability and entrainment of soil particle whereby, the fine soil particles were easily transported in large quantity by surface flow velocity of running water during the earlier simulation attempts, while coarse soil particle were not easily transported because its body mass.

Figure 4 also shows the relationship between the sediment loss rate (g/min) and time of its delivery in seconds. Peak sediment loss rate of 17.6g/min was observed at slope 12^o at 130 secs., and the least sediment rate of 4.1 g/min at 1340 secs., the delivery picked up from 4.1 g/min to 7.3 g/min at 2800 secs. At slope 15^o, the peak sediment delivery rate was 16.2 g/min at 100 secs, and the least sediment loss rate of 13.4 g/min was recorded at 1900 sec., the recession of sediment delivery rate at this level is not sharp. At slope 0^o, highest sediment loss rate (6.9g/min) was obtained at 2000 secs. and least sediment loss rate of 2.1 g/min was recorded at 284secs. (Fig.4). Mathematical model can be derived from precise analysis of sediment delivery rate, which will be very useful in arresting sedimentation in dams and some other hydrological structures, also in soil erosion control.

Fig.5 show average sediment yield and rainfall for all the experiments at different slopes. Sediment yield was proportional to increase in slope of the horizontal inclined soil tray to the instrument during the experiments with simulation of the same amount of rainfall at different slopes.

Linear relationship between generated surface runoff and simulated rainfall is shown in Fig. 6. The graphs showed that as rainfall increases, the amount of water that runs off increases. This result could be used to generate mathematical models which could be used to build predictive models. Statistical Analysis of Variance (ANOVA) in Table (8) indicated that changes in slopes of soil tray during the evaluation of runoff volume intensity using automatic Runoff-meter had significant effect on runoff intensity at 5% level of significant. At gradients 0^0 and 5^0, surface runoff volume and intensity was low with less sediment yield. However, earlier generation of surface runoff at slope angle 15^0 and 12^0 was based on the position of the catchments plot (soil tray). Generally, the slope at which the soil tray was positioned during the experimentation influenced the runoff volume, intensity and sediment yield.

It was also observed that increase in slopes of the soil tray had effect on simulated raindrop impact energy, and this force broke up the soil aggregates and detached soil particles, which was eventually transported down the slope by the surface flow. Statistical Analysis of Variance in Table (10) indicated that angles at which the soil trays were inclined had a significant effect on sediment yield at 5% level of significance. Fig. 5 shows the linear relationship between total sediment (g) and simulated rainfall (mm). Mathematical expressions can be developed from the sediment loss curves to formulate deterministic predictive model that can be used to solve the problem of soil erosion and land degradation. Such models may be useful in arresting sedimentation in dams and other hydrological structures. Table 12 shows the relationship between total average sediment yield and surface runoff generated. The increment in surface runoff resulted to increase in sediment loss, both sediment loss and surface runoff were functions of angles at which the soil tray were positioned to the instrument and also to the volume and intensity of simulated rainfall.

Table 1. Simulation result for angle 0°

S/No	Rainfall (mm)	Runoff (mm)	No of Tips	Time of tips (s)	*TSS (g)	**TDS (g)	*** TS (g)
1	9.3	0.0	0	0	0.0	0.0	0.0
2	18.5	0.0	0	0	0.0	0.0	0.0
3	27.5	0.0	0	0	0.0	0.0	0.0
4	37.0	0.0	0	0	0.0	0.0	0.0
5	46.3	1.0	8	284	3.1	9.9	6.8
6	56.0	6.6	50	746	4.8	45.1	40.3
7	65.0	14.0	107	1040	6.2	72.3	66.1
8	74.0	23.2	186	1340	0.0	90.5	90.5
9	83.3	33.0	251	1640	0.0	137.5	137.5
10	93.0	41.0	351	1900	0.0	220.3	220.3
11	102.0	48.2	372	2000	0.0	230.6	230.6
12	111.0	60.2	430	2400	0.0	238.1	238.1
13	120.4	63.3	489	2505	0.0	250.4	250.4
14	130.0	71.0	595	2800	0.0	253.3	253.3

T.S.S = Total Suspended Sediment (g)

T.D.S = Dissolved Sediment(g)

T.S = Total Sediment(g)

Table 2. Simulation result for angle 5°

S/No	Rainfall (mm)	Runoff (mm)	No of Tips	Time of tips (s)	*TSS (g)	**TDS (g)	*** TS (g)
1	9.3	1.1	0	0	0.0	0.0	0.0
2	18.5	9.0	0	0	0.0	0.0	0.0
3	27.5	0.0	0	0	0.0	0.0	0.0
4	37.0	0.0	9	150	1.1	10.9	12.0
5	46.3	0.0	69	500	4.9	46.3	51.2
6	56.0	16.7	129	712	5.2	78.1	83.3
7	65.0	24.1	186	950	0.0	97.6	97.4
8	74.0	32.4	250	1300	0.0	122.2	122.2
9	83.3	40.3	311	1800	0.0	157.1	157.1
10	93.0	48.6	375	2000	0.0	243.4	243.4
11	102.0	56.9	439	2150	0.0	250.3	250.3
12	111.0	65.5	505	2250	0.0	253.2	253.2
13	120.4	73.2	565	2450	0.0	259.4	259.4
14	130.0	83.0	636	2600	0.0	284.2	284.2

T.S.S = Total Suspended Sediment (g)

T.D.S = Dissolved Sediment(g)

T.S = Total Sediment(g)

Table 3. Simulation result for angle 12°

S/No	Rainfall (mm)	Runoff (mm)	No of Tips	Time of tips (s)	*TSS (g)	**TDS (g)	*** TS (g)
1	9.3	0.0	0	0	0.0	0.0	0.0
2	18.5	1.2	9	100	2.2	19.2	21.4
3	27.5	4.0	31	228	3.1	63.7	66.8
4	37.0	12.3	95	492	5.9	94.2	80.1
5	46.3	20.6	159	758	9.3	98.1	107.4
6	56.0	29.9	231	1408	0.0	115.2	115.2
7	65.0	29.2	296	1945	0.0	133.8	133.8
8	74.0	46.2	356	2128	0.0	150.6	150.6
9	83.3	54.8	423	2204	0.0	171.3	171.3
10	93.0	58.2	485	2274	0.0	200.7	200.7
11	102.0	70.4	543	2352	0.0	231.3	231.3
12	111.0	78.5	606	2428	0.0	261.1	261.1
13	120.4	86.2	665	2498	0.0	290.4	290.4
14	130.0	95.4	735	2569	0.0	313.4	313.4

*T.S.S = Total Suspended Sediment (g)

**T.D.S = Dissolved Sediment(g)

***T.S = Total Sediment(g)

Table 4. Simulation result for angle 15°

S/No	Rainfall (mm)	Runoff (mm)	No of Tips	Time of tips (s)	*TSS (g)	**TDS (g)	*** TS (g)
1	9.3	0	0	0	0.0	0.0	0.0
2	18.5	3.7	3.7	214	5.3	52.6	57.9
3	27.5	8.4	8.4	368	8.1	83.2	91.3
4	37.0	15.1	15.1	523	12.2	123.1	135.3
5	46.3	23.9	23.9	727	0.0	194.6	194.6
6	56.0	32.2	32.2	938	0.0	236.1	236.1
7	65.0	41.6	41.6	1149	0.0	274.3	274.3
8	74.0	49.9	49.9	1241	0.0	305.1	305.1
9	83.3	56.1	56.1	1499	0.0	333.6	333.6
10	93.0	63.8	63.8	1603	0.0	364.3	364.3
11	102.0	71.7	71.7	1693	0.0	392.2	392.2
12	111.0	79.1	79.1	1777	0.0	416.3	416.3
13	120.4	87.4	87.4	1856	0.0	436.2	436.2
14	130.0	95.4	95.4	1938	0.0	458.2	458.2

*T.S.S = Total Suspended Sediment (g)

**T.D.S = Dissolved Sediment(g)

***T.S = Total Sediment(g)

Table 5. Sediment loss rate (g/min) at different slope angles (°)

S/No	Rainfall (mm)	0^o	5^o	12^o	15^o
1	9.3	0.00	0.00	0.00	0.00
2	18.5	0.00	0.00	12.84	16.23
3	27.5	0.00	0.00	17.58	14.88
4	37.0	0.00	4.80	9.77	15.52
5	46.3	2.10	6.14	8.50	16.01
6	56.0	3.62	7.02	4.91	15.01
7	65.0	4.17	6.15	4.13	14.32
8	74.0	4.05	5.64	4.25	14.75
9	83.3	5.08	5.24	4.66	13.35
10	93.0	6.96	7.30	5.30	13.64
11	102.0	6.92	7.00	5.90	13.40
12	111.0	5.95	6.75	6.45	14.10
13	120.4	5.80	6.35	6.96	14.10
14	130.0	5.43	6.56	7.32	14.19

Table 6. Sediment loss (g) at different angles of inclination (°)

S/No	Rainfall (mm)	Sediment loss (g)			
		0^o	5^o	12^o	15^o
1	9.3	0.0	0.0	0.0	0.0
2	18.5	0.0	0.0	21.4	57.9
3	27.5	0.0	0.0	66.8	91.3
4	37.0	0.0	12.0	80.1	135.3
5	46.3	9.9	51.2	107.4	194.6
6	56.0	45.1	83.3	115.2	236.1
7	65.0	72.3	97.4	133.8	274.3
8	74.0	90.5	122.2	150.6	305.1
9	83.3	137.5	157.1	171.3	333.6
10	93.0	220.3	243.4	200.7	364.3
11	102.0	230.6	250.3	231.3	392.2
12	111.0	238.1	253.2	261.1	416.3
13	120.4	250.4	259.2	290.4	436.2
14	130.0	253.3	284.2	313.4	458.2

Table 7. Runoff intensities at different Angles of Inclination

S/No	Rainfall (mm)	Runoff intensity (mm/min)			
		0o	5°	12 °	15 °
1	9.3	0.0	0.0	0.0	0.0
2	18.5	0.0	0.0	0.7	1.0
3	27.5	0.0	0.0	1.1	1.4
4	37	0.0	0.5	1.5	1.7
5	46.3	0.2	1.2	1.6	2.0
6	56.0	0.5	1.5	1.3	2.1
7	65.0	0.8	1.6	1.0	2.2
8	74.0	1.0	1.6	1.3	2.4
9	83.3	1.2	1.5	1.5	2.2
10	93.0	1.3	1.6	1.5	2.4
11	102.0	1.4	1.7	1.8	2.5
12	111.0	1.5	1.9	1.9	2.7
13	120.4	1.5	1.9	2.1	2.8
14	130.0	1.5	2.1	2.2	3.0

Table 8. Statistical Analysis of Variance for Surface runoff (mm)

Source	Df	Sum of Square	Mean Square	Computed F	Critical F at 5%
Treatments	3	33985	1132.8	1.71	2.84
Error	36	23819.37	661.6		
Total	39	27217.87			

Table 9. Analysis of Surface runoff (mm)

Treatment slope angle	N/S	Total Runoff (mm)	Av. Total Runoff (mm)	S.D	Variance
0°	10	361.5	36.2	23.4	548.5
5°	10	445.8	44.6	24.1	582.0
12°	10	564.3	56.4	23.6	559.5
15°	10	590.0	59.0	24.4	596.0

Table 10. Statistical Analysis of Variance for Sediment yield (mm)

Source	Df	sum of square	mean of square	computed F	Tabulated F at 5%
Treatments	3	193887.98	64629.32	5.3	2.84
Error	36	437450.33	12151.4		
Total	39	631338.31			

Table 11. Analysis of Sediment yield

Angle of Inclination	N/S	Total sediment loss (g)	Average total sediment loss (g)	Standard Deviation	Variance
0^o	10	1548.0	154.8	89.5	8008.7
5^o	10	1798.2	179.8	83.0	6902.3
12^o	10	1936.7	193.7	75.7	5736.9
15^o	10	3336.3	333.6	98.4	9673.0

Table 12. Total sediment and runoff

Slope angle (°)	Total sediment loss (g)	Total runoff (mm)
0	1548	361.5
5	1798.2	445.8
12	1936.7	564.3
15	3336.6	590

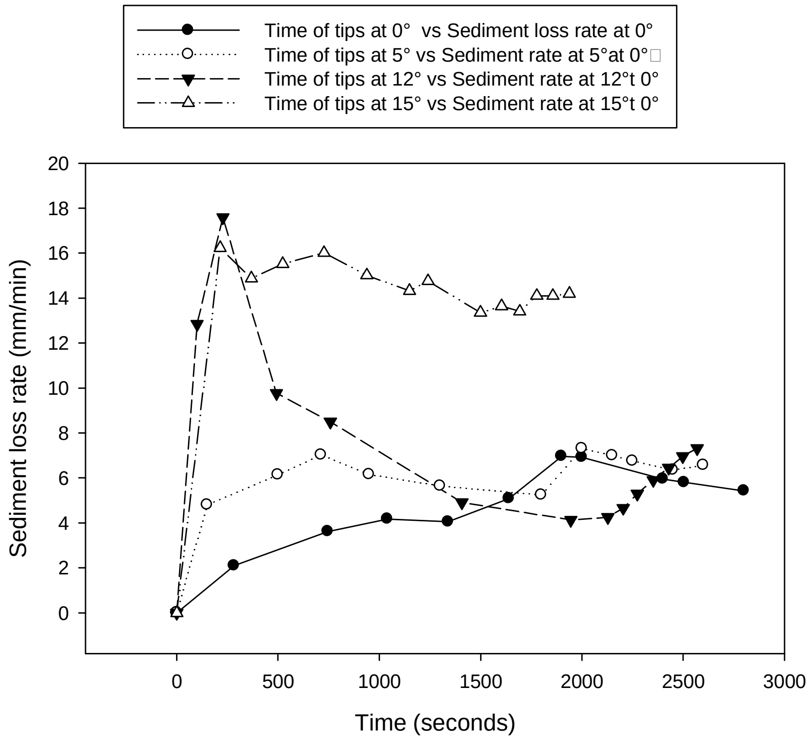

Figure 4. Sediment rate curves.

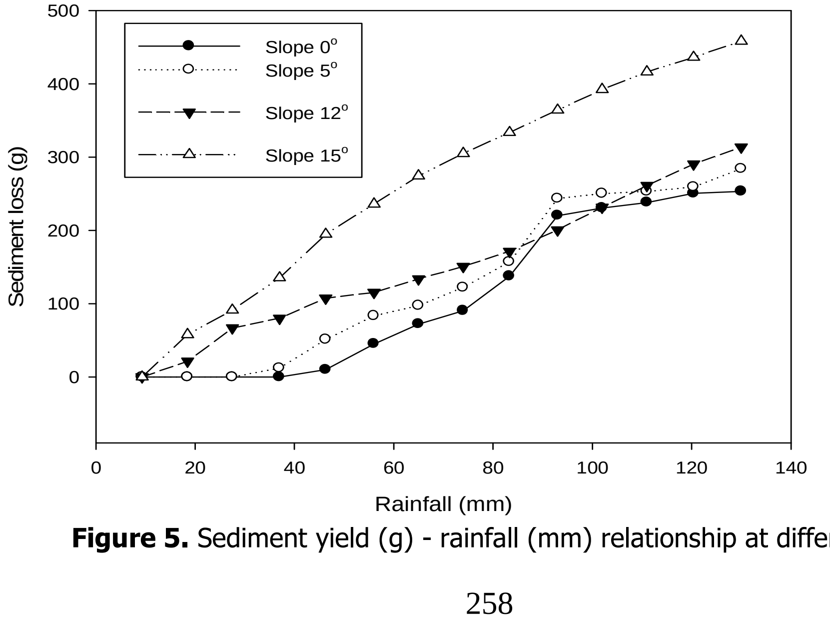

Figure 5. Sediment yield (g) - rainfall (mm) relationship at different slopes.

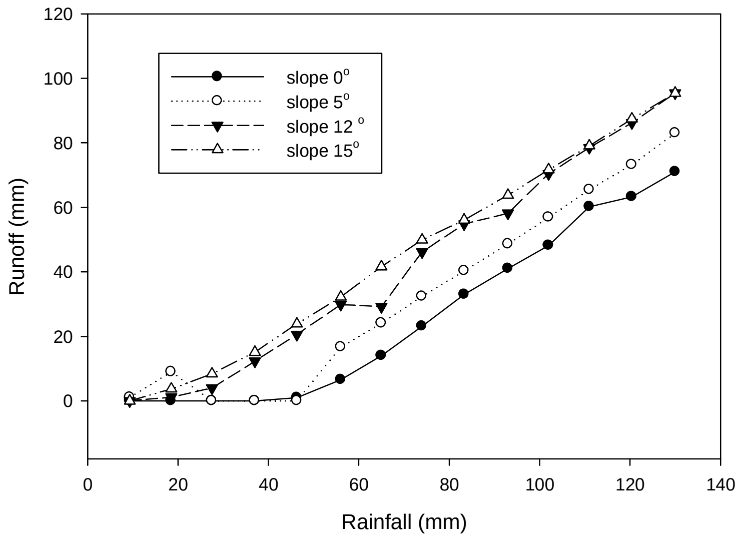

Figure 6. Runoff - rainfall relationship at different angles.

5. Conclusion

Conventional measurements of hydrological data are inadequate for the purpose of design and operation of water resource, soil erosion land degradation. This is because; these methods are always very prone to errors and inaccuracies. Based on the inaccuracy of conventional methods, an automatic Runoff-meter with tipping bucket was used to measure surface runoff at varying gradients. The conclusions that were drawn are:

- Using automatic Runoff-meter to measure surface runoff reduces the drudgery associated with conventional method.
- The instrument works with high precision and boosts the reliability of hydrological data.
- The instrument is very simple to operate and assess.
- The efficiency of the instrument is higher when used to measure surface runoff on flat or gentle slope topography to steep ones.
- Cumulative hydrological data (surface runoff in terms of volume and intensity) can be recorded and processed by the instrument.

Physics-based deterministic model can be formulated from the data obtained.

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