DEVELOPMENT AND CALIBRATION OF AN AUTOMATIC RUNOFF-METER

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ABSTRACT

An automatic Runoff-meter using tipping bucket arrangement consisting of a pair of water level sensor that sends signal to the control circuit through the sensitive micro-switch (P166, N123, P26) was designed and constructed. The design was based on soil and water engineering principles. The instrument operation was calibrated to tip 0.14 litre of runoff water at every tipping operation with an accuracy of ±0.001 litre. Electromechanical principle was used to establish the tipping mechanism. Calibration tests were carried out on the instrument at different gradients. The effect of runoff intensity on functional efficiency and speed of the instrument was statistically significant at 5% and 1% confidence levels. Results show a peak average total functional efficiency of (95.9%) with least speed of (37.4 rpm) at gradient 3° and least functional efficiency (85.2%) and highest speed of 45.7 (rpm) at gradient 7^0. The results obtained can be used to formulate physics-based deterministic models useful in designing hydraulic structures and for recommending appropriate land management systems.

Keywords: runoff meter, instrument, tipping mechanism, calibration, sensitive micro-switch, discharge, gradient.

1. INTRODUCTION

Automatic Runoff-meter is an instrument used in measuring and evaluating runoff water in terms of volume and intensity with high level of precision. This instrument is designed and constructed based on soil and water engineering principles. In order to develop a permanent solution to the measurement inaccuracies of runoff volume and intensity and also to generate reliable hydrological data, sensitive and environmental friendly instrument is needed to perform the intended function. The instrument is expected to bring a reduction in drudgery involved with evaluation of surface runoff from farmland.

The main problem facing agricultural practices in Nigeria and the developing nations is the rate at which agricultural soil is gradually being lost as a result of soil erosion (Olotu, 2006). Based on this, food and other agricultural products have substantially reduced and this has resulted to serious inflation. It is also reported in some parts of the world that soil erosion has caused serious economic hardship. On the Indonesian Island of Java, erosion continues to threaten agriculture in the uplands and the many already economically destitute farmers that rely on it (Purwanto *et al*., 1999).

Rainfall intensity and raindrop energy impact on soil assist in the erodibility of the soil (Armsfstrong, 1995). The problem is further compounded because of the failure to accurately measure surface runoff and sediment loss using direct or conventional system of runoff measurement. Without accurate and precise data on runoff and sediment loss, land management decisions cannot be effectively reached (Okoli, 2000). Farmlands will still continue to be cultivated by farmers without knowing the extent of damage caused annually by surface runoff and erosion (Bhaduri *et al*., 2001).

Having linked the failure to accurately measure surface runoff to the conventional measurement method, the concept of designing and developing an automatic instrument which will be used to measure surface runoff and sediment yield was initiated. The instrument is expected to be user friendly, reliable and affordable in terms of procurement and maintenance. The output of the instrument can be used to derive physics-based deterministic model useful in making land management decision, designing flow control structures and calculating sedimentation in the reservoir area of a dam.

1.1 Description of an automatic runoff-meter

The developed instrument consists of soil tray, pair of tipping bucket, diverting funnel, water level sensors, sensitive micro-switch, geared electric motor, electronic timer, storage tank of 200 litres capacity which serves to store tipped runoff water for further laboratory assessment and analysis. The isometric view of the machine components are as shown in Figure-1. Tipping bucket receives the runoff water from the soil tray and tips it to the storage tank through the cylindrical collector. Diverting funnel guides the runoff water into the buckets repeatedly with little or no loss of runoff water. Connecting pipe conveys the runoff water from the soil tray to the collecting chamber and the runoff water flows from the collecting chamber to the diverting funnel and down to the buckets. Water level sensor was strategically positioned in each of the tipping buckets to sense the level of runoff water in the bucket. The sensitive micro-switch receives signal from the water sensor in response to the volume of runoff water in the tipping bucket and relays it to the control circuit of the instrument. Electronic timer and electromechanical counter are connected to the tipping buckets to record the time to complete each tipping operation and total number of tipping operation respectively. The instrument is powered with 60AH, 12V battery.

1.2 Mechanism of operation

The instrument works on principle of tipping mechanism. Full views of mechanical steel fabricated component of the instrument in Plates 1 and 2 show the instrument when it has been assembled and positioned for operation. Rainfall is simulated on the prepared impervious materials in the soil tray and runoff water flows through the connecting pipe down to the collecting chamber and to the tipping bucket through the diverting funnel and finally to the storage tank. As runoff water flows into the bucket, which is positioned at 45^0 to the diverting funnel, the water level sensor positioned inside the bucket starts to be displaced. The displacement of the water level sensor increases with increase in the volume of runoff water inside the tipping bucket, gradual displacement is signaled to the sensitive micro-switch through the connected knob Olotu (2006). Once the tipping bucket has collected a certain volume of runoff water, the displacement of water level sensor stops and the signal is relayed to the connected micro-switch (SW_1, or SW_3) depending on the position of the tipping bucket. The signal is finally sent to the control circuit, which is sensed as preset in the variable resistor. If the instrument is connected to the main power source of 60AH, 12V battery, current flows through the power source to the circuit, the transistor will energize the relays to trigger on the geared electric motor that controls the tipping buckets. The electric motor rotation turns the motion converter and the motion is transferred to the mechanical arm of the buckets, with this process tipping is initiated and the runoff water is tipped into the cylindrical collector and finally to the storage tank. The process continues till the edge of the tipping bucket in operation touches a sensitive micro-switch positioned on the trapezoidal shaped panel (SW_2, or SW_4). The process is triggered off, water level sensor returns to its initial position inside the bucket. Immediately the first bucket tips, the second tipping bucket automatically positions itself in position of the tipped one. Tips are recorded with electro-mechanical countering device and time of each tip is recorded to the nearest second with the electronic timer. Fig. 2 shows the tipping bucket operational circuit diagram illustrating the tipping mechanism of the buckets.

2. CALIBRATION TEST

Calibration test was carried out on the developed instrument in order to determine:

- speed or tipping rate of the instrument;
- volume tipped of each of the tipping bucket; and
- functional efficiency of the instrument.

The component parts of the instrument were coupled as shown in Plate 1 and connected to power source 60AH, 12V battery as shown in Plate 2. The instrument was allowed to run for an hour before the commencement of the experiment in order to rectify any form of malfunctioning. The soil tray was supported by adjustable wooden table of 1.4 m height, fed with impervious materials to the depth of 130 mm and arranged horizontally to the instrument. The design aspect of the instrument was started in June, 2004. Also, the mechanical fabrication of the component parts and selection of appropriate instrument and control arrangement was carried out in April, 2005. Coupling and testing of the assembled components parts was done at Agricultural Engineering Workshop, Federal University of Technology, Akure, Nigeria in (2005). Calibration tests at different gradients were carried out on the instrument at the experimental plots within the Teaching and Research farm of the Department of Agricultural Engineering, Federal University of Technology, Akure, Nigeria, in 2006. The instrument was calibrated at gradient 3^0, 5^0 and 7^0 respectively. Rainfall was applied to the soil tray which contains impervious material. Applied rainfall was completely lost to runoff which flowed from the soil tray down to the tipping buckets through the diverting funnel and finally to the storage tank. Applied rainfall was recorded as Expected discharge (E_d) in litres and the recovered runoff was recorded as Actual discharge (A_d) also in litres. The experiment was carried out by applying water at 10 liters interval up to 100 litres as rainfall on the impervious surface. Time of each successful operation was registered on the electronic timers and the total number of tipping operations was recorded on electro-mechanical device.

2.1 Function efficiency (E_f)

This is a measure of the effectiveness with which the instrument (automatic Runoff-meter) performs its intended function. It is the ratio of complete volume of water recovered (actual discharge) to the volume of water applied (expected discharge) at each operation and expressed as percentage. This is calculated as follows:

$$E_f = \frac{A_d}{E_d} x100 \quad (1)$$

E_f = functional efficiency (%)
E_d = volume of water applied (expected discharge in litres)
A_d = volume of water recovered (actual discharge in litres)

2.2 Volume per tip (Vp)

This can be expressed as the ratio of volume of runoff water recovered from the storage tank (actual discharge) to the total number of tipping operation (Np) recorded by the electro-mechanical device. It is calculated as follows:

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$$V_p = \frac{A_d}{N_p} \qquad (2)$$

V_p = Volume of water tipped per each bucket (litres)
A_d = Actual discharge (litres)
N_p = Total number of tipping operation

2.3 Modified volume per tip (MV_p)

The volume of water tipped per bucket is modified with calibration factor as follows:

$$MV_p = \frac{CA_d}{N_p} \qquad (3)$$

MV_p = Modified volume per tip
C = Calibration factor (= 0.98)
Equation (3) is the calibration equation.

2.4 Speed of the instrument

The speed or the tipping rates of automatic Runoff-meter was calculated from this relationship:

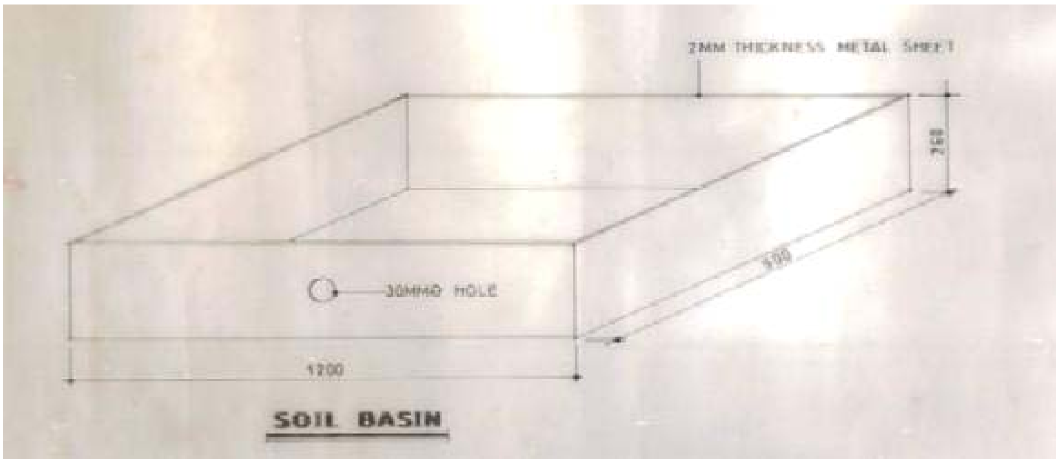
$$S_p = \frac{T_p}{N_p} \qquad (4)$$

S_p = speed or the tipping rate (rpm)
T_p = total time of tipping operation in seconds
N_p = total number of tipping operation
NOTE: r.p.m = tipping rate of the bucket per minute.

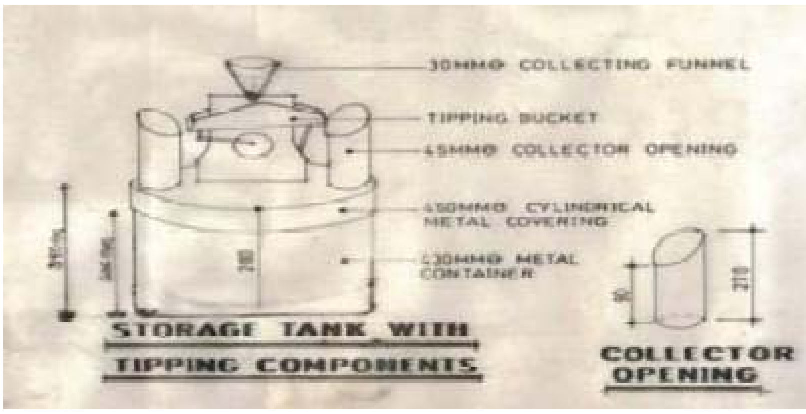
2.5 Dimension of steel bounded soil tray
= (900mm x 1200mm x 260mm)

(i) Soil tray
Area of soil tray (900mm by 1200mm) = $1.08m^2$
Volume of soil tray = $0.28m^3$

(ii) Tipping bucket
Area of tipping bucket = $0.007m^2$
Volume of the tipping bucket = $0.001m^3$



(a)



(b)

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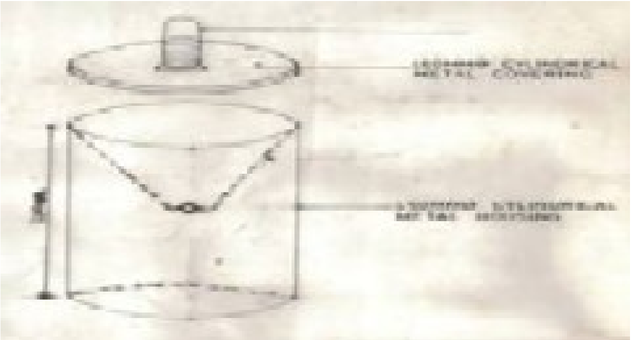

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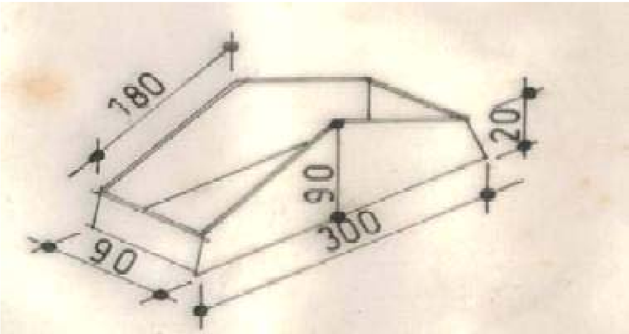

(d)

Figure-1. Isometric view of the machine components (runoff-meter): (a) soil basin (b) storage tank and tipping components (c) cylindrical housing (d) Tipping bucket. All dimensions are in mm.

Full view of the component parts of the instrument

Plate-1. Full view of fabricated component parts of the instrument before assembled for operation and experimentation.

Full view of the instrument during Experimentation

Plate-2. Full view of the assembled instrument during testing and experimentation.

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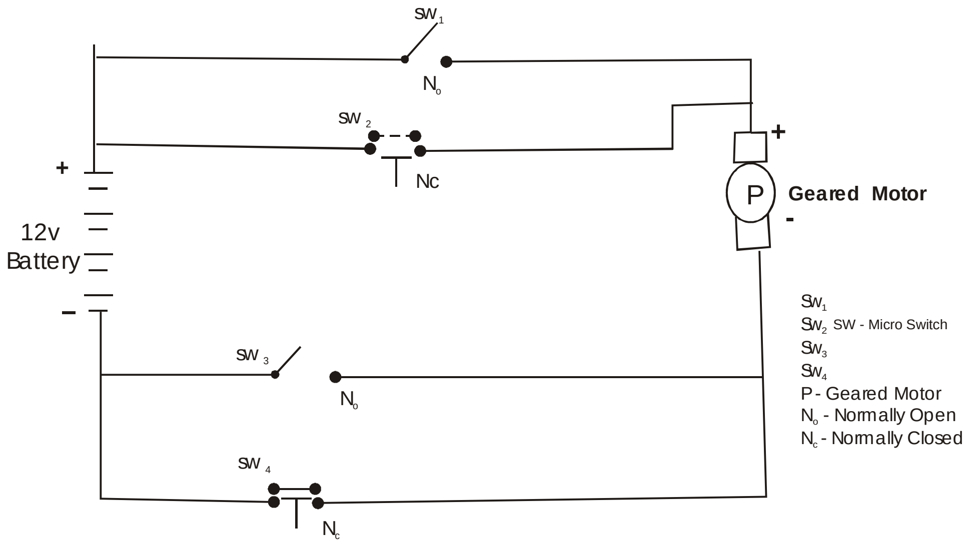

Figure-2. Tipping bucket operational circuit system diagram.

3. RESULTS AND DISCUSSIONS

The results of calibration test are shown in Table 1, 2 and 3. Table-4 shows the average volume of applied water or expected discharge (*l*) as rainfall, recovered water or actual discharge as runoff all measured to nearest millimeter. Runoff intensity (*l*/s), Speed or tipping rate (rpm) and Functional efficiency (%) at various gradients were obtained. Result of calibration in Table 1, 2 and 3 showed that the volume of water tipped by each of the tipping buckets varied between 0.141 to 0.142*l*. Introduction of calibration factor C = 0.98 modified the volume of runoff water per tip to the nearest 0.14*l*. Based on this, each of the tipping buckets was calibrated to tip 0.14 litre of runoff water.

At calibration 3^0, least runoff intensity of 0.04*l*/s, speed of 11.4r.m.p corresponded with highest functional efficiency of 98%, while least functional efficiency of 93.8% at maximum operating speed of 48 rpm and runoff intensity of 0.11*l*/s were obtained (Table-1). In addition, at calibration 5^0, minimum functional efficiency of 87.6% corresponded with the least operating speed of 51.3 rpm and constant runoff intensity of 0.03*l*/s (Table-2). The overall least functional efficiency of 81.6%, highest speed of 53.9 rpm and runoff intensity of 0.11*l*/s were recorded at calibration of 7^0 (Table-3). Table-5 presents the Analysis of Variance (ANOVA). It could be observed that the treatments having effects on the functional efficiency of the instrument are speed and runoff intensity. The effect of runoff intensity and speed of the instrument on functional efficiency are highly significant at 5% and 1% confidence interval and hence, exert great effect on the results obtained during the experimentation.

Calibration was carried out at different gradients; runoff intensity was observed to increase with increase in the volume of expected discharge(E_d) and angle of inclination of the soil tray horizontal to the measuring instrument. At calibration 3^0, maximum runoff intensity of 0.11*l*/s was recorded at expected discharge(E_d) of 80.0*l*, 90.0*l* and 100*l*, while least runoff intensity of 0.04*l*/s was obtained at expected discharge(E_d) of 10.0*l* (Table-1). However, at calibration $5^{0,}$ runoff intensity of 0.03*l*/s was constant throughout the simulation experiments. Finally, highest runoff intensity of 0.11*l*/s was recorded for the expected discharge(E_d) from 40*l* to 100*l*, while least runoff intensity of 0.07*l*/s was recorded at expected discharge(E_d) of 10.0*l* at calibration of 7^0 (Table-3). Since the angles at which the soil tray was placed horizontal to the measuring instrument influenced runoff intensity, operating speeds and functional efficiency, therefore angle of inclination should be carefully selected during the running of the instrument in order to obtain higher functional efficiency.

Figure 3, 4 and 5 show the linear relationship (calibration curves) between expected and actual discharge at gradients 30, 5^0 and 7^0. The difference between the variables (Expected and Actual discharge) recorded as loss in discharge (L_D) in litres with less values at calibration of 3^0 (Table-1), while high values were obtained at calibration of 5^0 and 7^0 (Tables 2 and 3), respectively. This occurred as a result of leakage in the diverting funnel, runoff collecting chamber and splash of runoff water during the tipping operation. The coefficient of determination (R^2) in Figures 3, 4 and 5 shown there is high correlation between expected and actual discharge at all calibrations. Figures 6, 7 and 8 also show the relationship between functional efficiency and the speed of the instrument at different gradients of calibration. The result of calibration experiments also gave an indication that each bucket tipped a modified volume of 0.14 litre of runoff water. Total average highest functional efficiency (95.9%), least total average operating speed of 37.4 rpm and total average runoff intensity of 0.86*l*/s were obtained at calibration 3^0, while highest total average speed and runoff intensity of 45.7 rpm, 1.0*l*/s and least total average functional efficiency of 85.8% were obtained at calibration 7^0. Total average runoff intensity, operating speed and functional efficiency of 0.30*l*/s, 40.5 rpm and 92% were obtained at calibration 5^0. A variation in total runoff intensity at calibration of 5^0 was as a result of intensity of expected discharge of 0.2*l*/s during the calibration experiment. Expected discharge was applied at 0.1*l*/s for calibration at 3^0 and 7^0 respectively. This was done in order to evaluate the sensitivity of the instrument in response to expected discharge/ applied rainfall, actual discharge/ runoff water, runoff intensity and also to the alternation of calibration gradients.

4. CONCLUSIONS

Generally, precise results obtained during the calibration of the instrument will enable hydrologist, meteorologist, and engineer to use the instrument effectively in evaluating surface runoff volume and intensity on both bare and cropped soil at different gradients with reliable results. Obtained hydrological data using the automatic Runoff-meter is expected to be used in formulating physics-based deterministic models which will be useful in land planning for agricultural purpose and also in designing hydrological structures like dams, drainages, culvert, storm sewer etc. Since all the component parts of the instrument were locally-sourced, this will go a long way to boost indigenous technology and reduce the total reliance on foreign instrument which perhaps may be too expensive and environmental unfriendly.

5. RECOMMENDATIONS

The instrument is prone to electrical and mechanical problems. All the sensors, sensitive micro-switch, connecting wire, and control circuit must be checked and satisfied that they are in order before the instrument is positioned to be used.

There is need to modify the design of the instrument so that each of the tipping buckets is calibrated to tip larger volume of runoff water. Digital remote sensing mechanism should be incorporated in the instrument in order to increase the sensitivity and efficiency of the instrument. Values of runoff intensity and volume should be permanently recorded and kept in form of sinusoidal pattern in the computer database packages. Such results will be useful in flood analysis and in flood routines prediction.

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Table-1. Result of calibration at 3^0.

S. No.	$\mathbf{E_d}$(1)	$\mathbf{A_d}$ (1)	$\mathbf{L_d}$(1)	**Ri** (l/s)	$\mathbf{E_f}$ (%)	$\mathbf{N_p}$	$\mathbf{T_p}$ (s)	$\mathbf{V_p}$ (*l*)	$\mathbf{C_f}$	$\mathbf{MV_p}$ (l)	$\mathbf{S_p}$ (rpm)
1	10.0	9.8	0.2	0.04	98.0	69	245	0.142	0.98	0.14	11.4
2	20.0	19.6	0.4	0.06	98.0	138	320	0.142	0.98	0.14	25.6
3	30.0	29.3	0.7	0.07	98.0	207	400	0.142	0.98	0.14	31.1
4	40.0	33.7	13	0.07	97.5	276	460	0.141	0.98	0.14	36.4
5	50.0	47.5	2.5	0.09	95.0	337	525	0.141	0.98	0.14	38.7
6	60.0	57.4	2.5	0.10	95.0	404	595	0.142	0.98	0.14	40.8
7	70.0	66.8	3.2	0.10	95.0	474	658	0.141	0.98	0.14	43.4
8	80.0	75.8	4.2	0.11	95.0	541	713	0.142	0.98	0.14	45.6
9	90.0	85.2	4.8	0.11	94.0	600	770	0.141	0.98	0.14	46.9
10	100.0	94.4	5.6	0.11	93.8	661	832	0.142	0.98	0.14	48.0

Table-2. Result of calibration at 5^0.

S. No.	$\mathbf{E_d}$(1)	$\mathbf{A_d}$ (1)	$\mathbf{L_d}$(1)	**Ri** (l/s)	$\mathbf{E_f}$ (%)	$\mathbf{N_p}$	$\mathbf{T_p}$ (s)	$\mathbf{V_p}$ (*l*)	$\mathbf{C_f}$	$\mathbf{MV_p}$ (l)	$\mathbf{S_p}$ (rpm)
1	10.0	9.3	0.4	0.03	96.0	66	161	0.141	0.98	0.14	19.4
2	20.0	19.0	1.0	0.03	95.0	361	759	0.142	0.98	0.14	28.8
3	30.0	28.5	1.5	0.03	95.0	561	900	0.142	0.98	0.14	36.4
4	40.0	37.6	2.4	0.03	94.0	261	1100	0.142	0.98	0.14	38.2
5	50.0	46.7	3.3	0.03	93.4	331	1520	0.141	0.98	0.14	42.0
6	60.0	54.2	5.8	0.03	90.4	382	1897	0.142	0.98	0.14	44.1
7	70.0	62.0	7.0	0.03	89.3	440	2340	0.142	0.98	0.14	46.6
8	80.0	70.1	9.1	0.03	88.6	499	2660	0.142	0.98	0.14	48.8
9	90.0	80.2	10.8	0.03	88.0	562	2690	0.141	0.98	0.14	49.6
10	100.0	82.6	17.4	0.03	87.6	617	2720	0.141	0.98	0.14	51.3

Table-3. Result of calibration at 7^0.

S. No.	$\mathbf{E_d}$(1)	$\mathbf{A_d}$ (1)	$\mathbf{L_d}$(1)	**Ri** (l/s)	$\mathbf{E_f}$ (%)	$\mathbf{N_p}$	$\mathbf{T_p}$ (s)	$\mathbf{V_p}$ (*l*)	$\mathbf{C_f}$	$\mathbf{MV_p}$ (l)	$\mathbf{S_p}$ (rpm)
1	10.0	9.4	0.6	0.07	94.0	67	130	0.140	0.98	0.14	35.9
2	20.0	18.6	1.4	0.09	93.0	131	200	0.142	0.98	0.14	39.2
3	30.0	26.5	3.5	0.10	88.3	187	275	0.142	0.98	0.14	40.2
4	40.0	36.0	5.4	0.11	86.3	245	330	0.140	0.98	0.14	44.4
5	50.0	42.0	8.0	0.11	84.0	296	380	0.142	0.98	0.14	46.9
6	60.0	50.2	9.8	0.11	83.7	354	440	0.142	0.98	0.14	48.4
7	70.0	52.9	12.1	0.11	52.7	408	500	0.142	0.98	0.14	49.0
8	80.0	66.0	20.0	0.11	82.5	468	550	0.141	0.98	0.14	50.8
9	90.0	73.7	16.3	0.11	81.8	523	660	0.142	0.98	0.14	52.3
10	100.0	81.6	20.4	0.11	81.6	575	720	0.142	0.98	0.14	53.9

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Table-4. Cumulative results of calibration at gradients (3^0, 5^0 and7^0).

NS	Calibration angles	E_d (*l*)	A_d (*l*)	Ri (*l*/s)	Speed (rpm)	E_f (%)
1	3^0	560.0	519.5	0.86	37.4	95.9
2	5^0	560.0	490.2	0.30	40.5	92.0
3	7^0	560.0	456.9	1.03	45.7	85.8

Table-5. Analysis of variance (ANOVA) table for the machine efficiency (%) speed (rpm) and runoff intensity (mm\min).

Source of variance	Degree of freedom	Sum of square	Square square	Computed F	Tabular 5%	Tabular 1%
E_f	29	885.56	30.5	878.8	1.61	4.052
S_p	29	608.52	20.9	600.5		
Ri	29	1.008	0.03			

E_f = Functional efficiency (%); S_p = Speed or tipping rates (rpm); Ri = Runoff intensity (l/s)
C_f = Calibration factor value (0.98); A_d = Actual discharge (*l*); E_d = Expected discharge (*l*)
L_d = Loss in discharge (*l*); N_p = Total number of tipping operations; *l* = liters
s = second; Tp, Vp, MVp as previously defined.

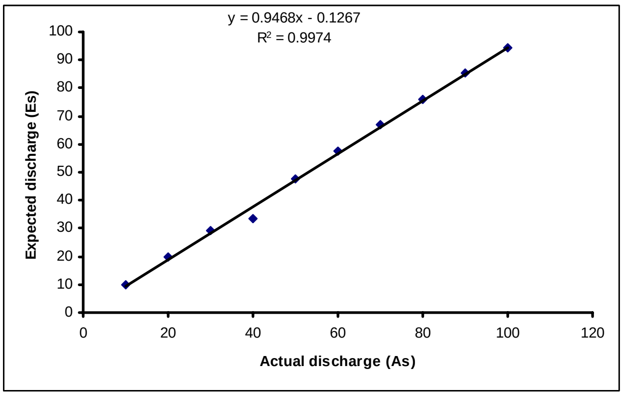

Figure-3. Linear relationship of expected discharge (Es) against actual discharge (As) in m^3/s at angle 3^0.

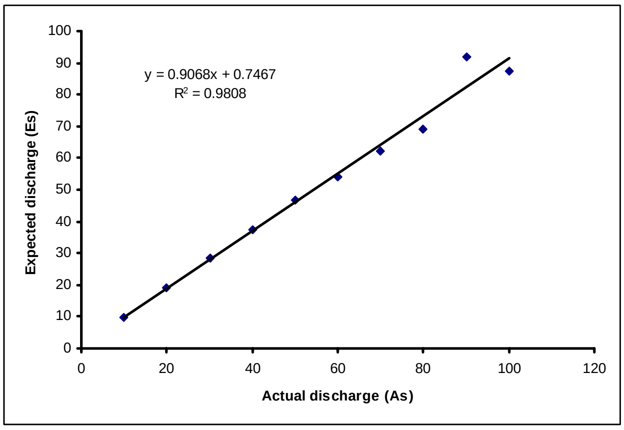

Figure-4. Linear relationship of expected discharge (Es) against actual discharge (As) in m^3/s at angle 5^0.

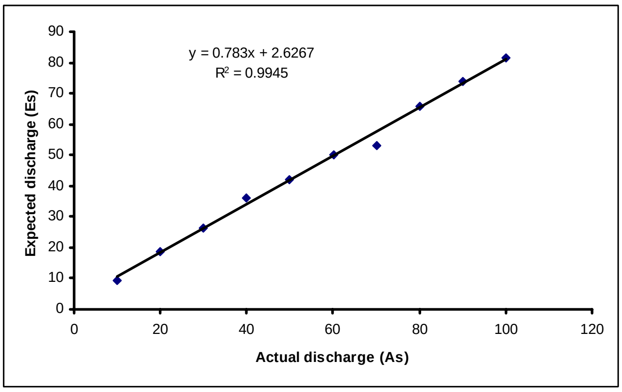

Figure-5. Linear relationship of expected discharge (Es) against actual discharge (As) in m^3/s at angle 7^0.

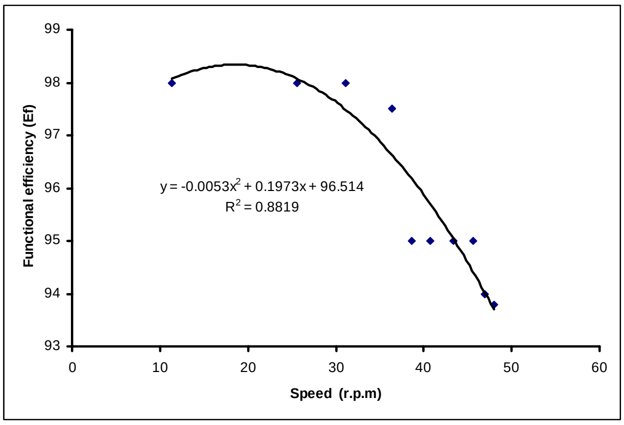

Figure-6. Functional efficiency curve at angle 3^0.

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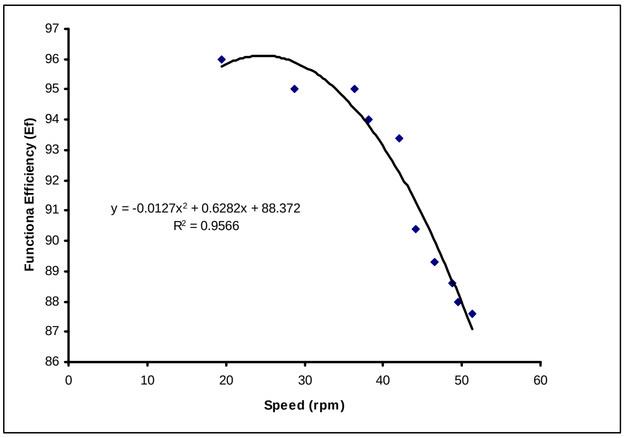

Figure-7. Functional efficiency curve at angle 5^0.

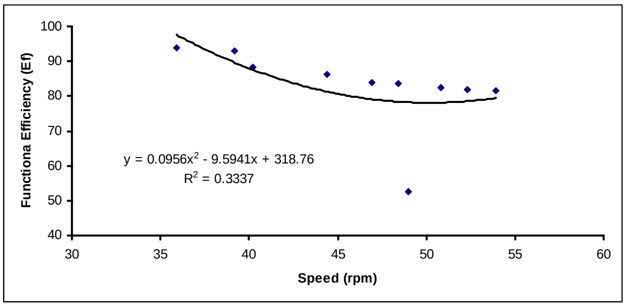

Figure-8. Functional efficiency curve at angle 7^0.