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Soil Resistance to Overland Flow at Ibiekuma Watershed in South Central Nigeria

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Abstract: Understanding and proper modeling of overland flow hydraulic parameters is essential in the development of process-based erosion models and evaluation of surface runoff under field situations. In this study, field measurement of significant overland flow parameters was conducted on a 3×7 m twin-runoff plots within Ibiekuma watershed in south-central Nigeria. Parameterization of the resistance model involved: a detailed topographic survey of the plots using a 1×1 m cell grid and evaluation of the median particle size; small plot experiments to determine parameters of the Green and Ampt infiltration model and small plot experiments to determine parameter estimate for the dynamic friction factor. With the friction factor varying between 0.0006 and 0.0016 depending on the median particle size, the soil resistance to surface flow at Ibiekuma catchment is considerably low. The rate of runoff produced after the ensuing infiltration and attainment of rainfall-infiltration excess is high with an attendant high level of erodibility of the superficial soil. A neurosolution in a spread sheet environment of the data collected established the relationship between the friction factor and median particle size of the soil in the area as $f = 3E-06\,Gm^2 - 0.0002\,Gm + 0.0039$ where, f and Gm are the friction factor and the median particle size, respectively.

Key words: Hydraulic properties, roughness coefficients, flow velocity, reynolds number, median particle size

INTRODUCTION

Analysis of surface runoff in a field situation requires identification of hydraulic roughness coefficients, vital for the estimation of flow velocity and routing of runoff hydrographs. These coefficients are derived essentially from runoff data obtained from erosion studies on experimental plots (Eugman, 1968).

Flow resistance may be estimated by the dimensionless Darcy-Weisbach friction factor

$$f = 8gds/v \quad (1)$$

where:

- g = The acceleration of gravity.
- d = The mean depth of flow.
- s = The energy slope.
- v = The mean flow velocity.

Resistance to flow generally varies with the rate of flow, which is represented by the dimensionless Reynolds number

$$Re = 4vd/v \quad (2)$$

where, μ is the kinematic viscosity. Laboratory experiments and theoretical analysis since, the 1930s have established that the relation between f and Re for shallow flow is a power relation whose exponent depends on the state of flow. The relation has a slope of -1.0 where, the flow is laminar and a slope of approximately -0.25 where, it is turbulent. Virtually all models of hillslope runoff have employed this relation between f and Re (or surrogates thereof).

While, a number of individual parameters influencing hydraulic geometry may vary at a given site (Hey, 1979) there are basically four ways an increase or decrease in imposed flow can be accommodated, i.e. by increasing or decreasing velocity, depth (hydraulics radius), frictional resistance or energy grade slope. Each of these fundamental hydraulic variables is accounted for in the Darcy-Weisbach equation for uniform, turbulent, kinematic sheet or rill flow. Written to solve for discharge, this equation is

$$Q = wd\left(\frac{8gRs}{f}\right)^{0.5} \quad (3)$$

where:

- Q = Discharge.
- w = Width of the slope element.
- d = Mean depth.
- g = The gravity constant.
- R = Hydraulic radius.
- s = The energy grade slope.
- f = The Darcy-Weisbach friction factor.

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Where, flows are wide relative to their depth, R=d. this is the case for sheet flow and for composite or aggregate rill flow.

The mutual interdependencies of the fundamental hydraulic variables can be illustrated by rewriting the Darcy-Weisbach equation to solve for V, s, R and f in the following form so that positive and negative influences are quickly seen from the exponents:

$$V = R^{0.5} s^{0.5} f^{-0.5} (8g)^{0.5} \quad (4)$$

$$s = V^2 R^{-1} f^1 (8g)^{-1} \quad (5)$$

$$R = V^2 s^{-1} f^1 (8g)^{-1} \quad (6)$$

$$f = V^{-2} R^1 s^1 (8g)^1 \quad (7)$$

The qualitative relationships between the variables would be identical for equations describing a laminar flow regime, though in some cases laminar flow resistance is accounted for by a viscosity term. The equation system above has been shown to be asymptotically unstable (Phillips, 1990) and is thus potentially chaotic.

Instability and deterministic chaos in this context require the existence of multiple modes of adjustment, i.e., qualitatively different ways in which the system can respond to a given change in imposed flow (Phillips, 1990, 1991). A mode of adjustment in hydraulic geometry is defined as a particular combination of increases, decreases or relative constancy of hydraulic variables in response to changes in Q theoretically, one would expect V, s and R to change in the same direction as Q and f to change in the opposite direction. Existence of qualitatively different modes of adjustment thus depends on the possibility of opposite direction from discharge and f in the same direction

The Darcy-Weisbach equation is used in this study to model hydraulic characteristics of overland flow. Under uniform flow conditions, the Darcy-Weisbach roughness coefficient, f, may be expressed as:

$$f = 8g\, Rs/v^2 \quad (8)$$

and

$$R = by/(b+2y) \quad (9)$$

where:

R = The hydraulic radius.
b = Flow width.
y = Flow depth.

For a rectangular channel, following continuity equation with Q as flow rate, water depth is given as:

$$y = Q/vb \quad (10)$$

Reynolds number, used to express the ratio of inertial force to viscous force is given as:

$$Re = vR/v \quad (11)$$

v is kinematic viscosity (a function of temperature).

Investigation of the correlation between roughness coefficient and Reynolds number requires the determination of shallow flow depths existing under field conditions. Since, it may be difficult to identify the soil-water interface for eroding situations, direct measurement of flow depth may not be possible (Gilley *et al*., 1992). Consequently, water depth is determined indirectly using Eq. 10 and its value is then substituted into Eq. 9 to obtain the hydraulic radius. Finally, roughness coefficient and Reynolds number values are obtained from Eq. 8 and 11.

MATERIALS AND METHODS

The model is applied to a twin 3 m wide by 7 m long runoff plots at Ibiekuma watershed. Located on a hillslope with gradient ranging from 1.25-8.8%, the site (Fig.1) is underlain by gravelly loam developed on a well-cemented laterite.

The study area is a geographical conglomeration of areas contributing to the runoff accumulating in a stream of natural origin situated at the south-western end of Ambrose Alli University Ekpoma. The stream with an encompassing area of 2894.4 ha flows south wards into River Ethiope, a headwater of Ossimo river system.

After moldboard ploughing about 3 months before the test was conducted, the site was lightly disked and maintained free of cultivation by tillage. Each study area was disked and raked for uniform surface conformed (Gilley *et al*., 1990), immediately proceeding testing.

A detailed topographic survey of the site was carried out using a 1.0 by 1.0 m grid (Fig. 2). For each cell in the

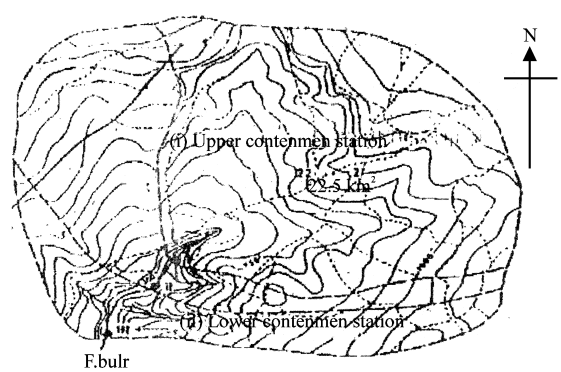

Fig. 1: Ibiekuma watershed

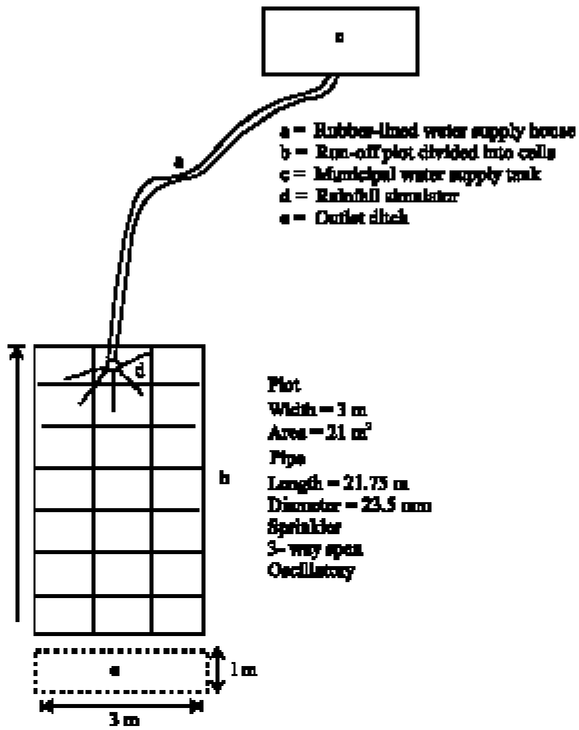

Fig. 2: Semi portable rainfall simulation system on the runoff plot

grid, measurement was made of the percentage desert pavement relating it to median particle size in order to determine the relationship between the Darcy-Weisbach friction factor and plot characteristics. Overland was simulated by trickling water onto each plot at different rates using flexible hose of approximately 22 m length attached to a portable simulator (Plate 1) with a drop height of 0.66 m. The outflow rate for each run was measured volumetrically at the lower of the plot. Discharges at different established cross sections were computed by assuming that infiltration and evaporation losses were uniformly distributed over the plot. Once equilibrium discharge was obtained, flow depth was measured with a thin scale of 5 cm across each cross section and these measurements were averaged to yield mean flow depth (d), the mean velocity (v), was calculated by dividing discharge Q by wd, where w is the width of the cross section. The energy slope was approximated by the local ground slope, kinematic viscosity, μ, was estimated from water temperature while, f and Re were determined using Eq. 8 and 11. In these experiments runoff response to increasing input values was determined, imitating flow conditions on the plot through a consideration of both onsite and inflow contribution to run off hydraulics. Soil particle size distribution was

Plate 1: Sprinkler system on the runoff plot

determined by wet sieve to separate gravel and sand fractions followed by pipette analysis for the silt and clay fraction, according to the method of Gee and Bauder (1986).

The oven-drying or gravimetric sampling method conformed (BS 1377, 1990) was used to determine the amount of water present between grains and within pore space. The predicted infiltration time parameter was estimated using the Green and Ampt (1911) equation:

$$t_p = \frac{\beta}{I - \alpha} \tag{12}$$

where:

t_p = Predicted time.
β = Infiltration in mm.
α = Infiltration rate (mm min^{-1}).
I = Rainfall intensity.

The data was analyzed in a spreadsheet using Neurosolution to establish the relationships between the various input parameters.

The portable rainfall simulator with oscillating nozzles sprinkles downwards in a 3-way span with dropheight of 0.66 m. The average discharge rate and approach velocity were 3.2 m^{3}s^{-1} and 1.3 ms^{-1}, respectively.

RESULTS AND DISCUSSION

The results of the site investigation, field work and laboratory tests were processed into various forms as presented in Fig. 3-6 and Table 1-3. Figure 3 represents the variation of the maximum dry weight of the soil with the initial moisture content. The micro-plots of 21 m^2 each within Ibiekuma watershed yielded a moisture content of 11% of the total soil mass of 819.62 g tested. The friction

Table 1: Soil type in watershed

Plot	Temperature (°C)	Density (g cm^{-3})	Clay (%)	Silt (%)	Sand (%)
I	23-24	24	24.08	1.3	74.62
II	23	15-23	25.08	0.3	74.62

Table 2: The Soil median particle size distribution and measured hydraulic properties

Cell No.	Time to run off t_o (min)	Infiltration rate (mm h^{-1})	Median particle size (mm)	Weightof soil (g)	Initialmoisture content (%)
1	4.36	27.0	28.40	817.00	11.38
2	5.72	12.0	25.48	814.00	11.72
3	5.49	28.2	22.48	824.20	10.41
4	4.00	22.8	21.31	816.80	11.41
5	8.34	42.0	30.04	821.00	10.84
6	5.04	27.6	23.50	822.00	10.71
7	3.20	19.8	29.10	818.00	11.25
8	2.30	48.0	23.14	816.50	11.45
9	4.00	26.0	17.08	820.80	10.87
10	7.30	28.2	20.59	821.50	10.77
11	7.18	29.0	16.29	818.40	11.19
12	6.05	27.0	16.43	822.53	10.63
13	7.33	23.4	24.77	812.00	12.07
14	9.82	18.0	29.20	827.00	10.04
15	9.07	25.2	26.98	817.21	11.35
16	2.30	29.4	32.30	811.82	12.09
17	2.30	26.2	22.01	815.60	11.57
18	5.42	20.8	25.52	821.12	10.82
19	7.00	12.0	22.48	821.16	10.82
20	4.30	29.9	23.15	821.73	10.74
21		25.8	22.98	831.23	9.48

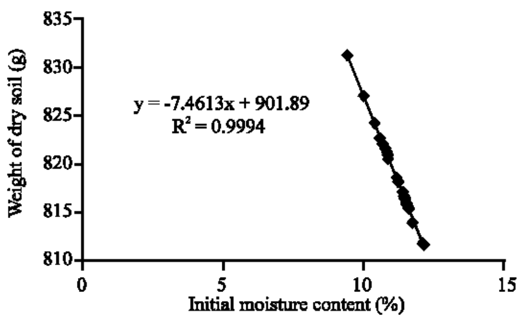

Fig. 3: Weight of dry soil and initial moisture content

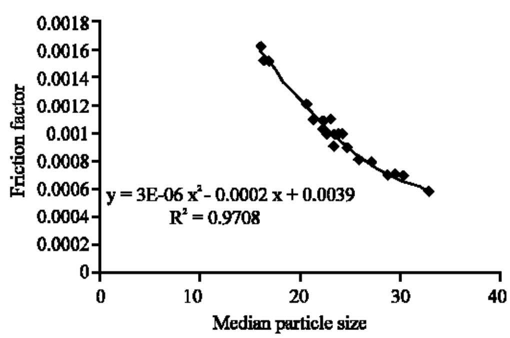

Fig. 4: Friction factor and median particle size

factor varied between 0.0006 and 0.0016 depending on the median particle size distribution (Fig. 4).

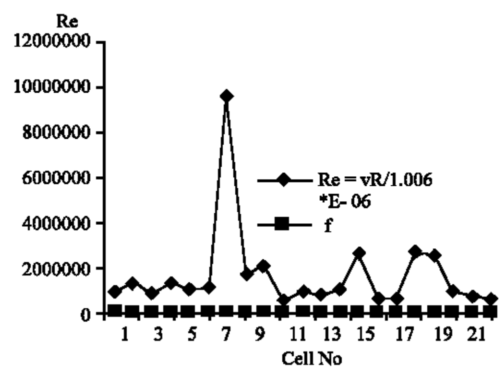

Fig. 5: Spatial variation of reynolds number

Analysis of the soil samples (Table 1) revealed that the area is sandy loam, reddish in colour with a coefficient of uniformity ($C_u = D_{60}/D_{10}$) of approximately 0.18. The implication of the latter is that the soil is a uniform and well-graded regime. The variation of Reynolds number within the micro-plot is highlighted in Fig. 5, the values ranging from 4.96E + 05 - 2.74E + 06. This indicates clearly that the friction factor is extremely low with an attendant weak grain resistance to surface runoff in the watershed. In general, hydraulic roughness coefficients can be seen to decrease with greater Reynolds number. The largest hydraulic roughness coefficients occurred on those cells with the greatest

Table 3: Estimates of small-plot infiltration parameters using Green and Ampt formulation for Ibiekuma watershed

Cell No.	α (mm min⁻¹)	β (mm)	P (%)	Slope	Rain intensity	tp (mm)
1	0.45	9.00	99.34	3.05	120.72	5.760
2	0.20	8.00	99.22	2.05	120.72	4.420
3	0.47	10.00	99.23	3.05	120.72	6.490
4	0.38	7.22	99.14	3.00	120.72	4.420
5	0.70	7.00	99.44	3.02	120.72	5.340
6	0.46	7.82	99.41	3.12	120.72	5.040
7	0.33	1.00	98.78	2.97	120.72	0.590
8	0.80	4.00	98.78	2.974	120.72	3.300
9	0.43	4.30	99.28	2.974	120.72	2.720
10	0.47	14.00	99.25	2.936	102.20	11.35
11	0.48	7.60	99.19	2.912	102.20	6.160
12	0.45	9.00	99.05	2.906	102.20	7.180
13	0.39	7.00	99.01	2.898	102.20	5.330
14	0.30	3.00	99.17	2.850	102.20	2.140
15	0.42	12.60	99.25	2.898	102.20	9.820
16	0.49	11.00	98.85	2.840	102.20	9.070
17	0.44	2.64	99.27	2.860	103.80	2.050
18	0.35	3.15	98.95	2.860	103.80	2.280
19	0.20	9.00	98.69	2.784	103.80	5.880
20	0.49	9.80	99.26	2.800	103.80	7.900
21	0.43	13.00	99.23	2.800	103.80	10.00

P (%) = Percentage of desert pavement (surface stone cover) within a cell; The infiltration parameters could be expressed as functions of P (%) i.e., α (x) = function [(%P(x)]; β (x) = function [(% P(x)]

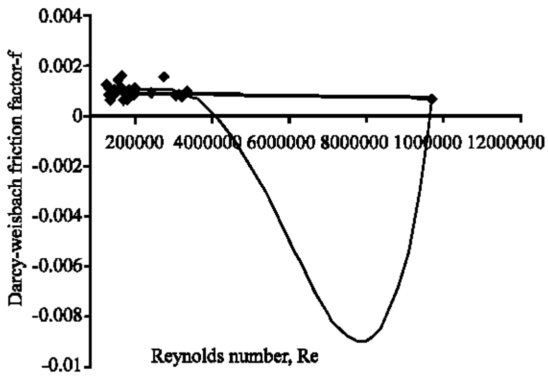

Fig. 6: Darcy-weisbach friction factor,f number

random roughness. Also, as Reynolds number increased, differences in flow pattern sometimes occurred. A parabola (Eq. 13) best expressed the relationship between the Darcy-Weisbach friction factor and the median particle size.

$$f = 3E - 06\,Gm^2 - 0.0002\,Gm + 0.0039 \qquad (13)$$

where, f and Gm are the friction factor and the median particle size, respectively.

CONCLUSION

In this study, a significant correlation was established between Reynolds number Re and roughness coefficient f as well as between the roughness coefficient and surface material properties of the soil at Ibiekuma watershed.

Owing to the dependence of f on surface form, the shape of the f-Re relation changes markedly over short distances across a hillslope as surface form changes. As a result, there is unlikely to be any single f-Re relation that applies to an entire hillslope. Consequently, field and laboratory experiments which improve physical understanding of overland flow parameters should precede and guide model design. To be most effective, the results of such experiments need to be presented in such a manner that they are readily assimilated into mathematical models. Field testing is particularly important where surface material properties are a significant determinant of the behaviour of the system being modeled. Laboratory testing is especially useful for isolating multiple system controls and testing the sensitivity of the model to each of them.

REFERENCES

British Standard Institution BS 1377, 1990. Methods of test for soils for Civil Engineering purposes. Part 2 London.

Eugman, E.T., 1968. Roughness coefficients for routing surface runoff. J. Irrigation Drainage Engin. Am. Soc. Civil Engin., 112: 39-53.

Gee, G.W. and J.W. Bauder, 1986. Particle-size Analysis. In: Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. 2nd Edn. Klute A. Am. Soc. Agron. Madison, pp: 383-411.

Gilley, J.E., E.R. Kottwiz and J.R. Simanton, 1990. Hydraulic characteristics of rills. Transac. Am. Soc. Agric. Engin., 33: 1900-1906.

Gilley, J.E., D.C. Flanagan, E.R. Kottwitz and M.A. Weltz, 1992. Darcy-Weisbach Roughness Coefficients for Overland Flow. In: Anthony, J.P. and D.A. Athol (Eds.). Overland flow Hydraulics and erosion mechanics, UCL Press Limited, London, pp: 25-52.

Green, W.H. and G.A. Ampt, 1911. Studies on soil physics -1. The flow of air and water through soils. J. Agric. Sci., 4: 1-24.

Hey, R.D., 1979. Dynamic Process-response model of river channel development. Earth Surface Processes and Landforms, 4: 59-72.

Phillips, J. D., 1990. The instability of hydraulic geometry. Water Resour. Res., 26: 333-342.

Phillips, J.D., 1991. Multiple modes of adjustment at unstable river channel cross-sections. J. Hydro., 123: 39-49.