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Hydraulics of slope erosion by overland flow A case study: Nnobi-Onitsha hillslope site, Anambra state S.E. Nigeria

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Abstract. The erosion problem at Nnobi was investigated with a view to determine the types and major factors responsible for accelerated erosion in the area, in order to develop a simple prediction model for the erosion rate. The severe erosion of ground surfaces, such as unpaved road shoulders and bare soil surfaces, in high density areas of South Eastern Nigeria is a common feature. For many years, hydrologist and engineers have been faced with the challenge of producing adequate drainage programs to check the menace of erosion by overland flow. Six flume experiments were conducted where erosion rates were measured. The rainfall data for the past ten years were obtained and analyzed, a survey of the catchment area for each of the gully sites was carried out and soil samples were obtained from the eroding layers of the gullies. Analysis of the results show that the area experiences rainfall of high intensity, with intensities of up to 80 mm/hr being recorded for a duration of 30 minutes. The slope of the land is generally steep, with slope gradient varying from 15% to 22%, and soil particles with very low organic and clay content, ranging between 0.2 to 0.4 to 1 and 6%, respectively. A mathematical model of hill slope overland flow for the Nnobi experimental watershed, obtained using the Saburo [1] equation, to predict the erosion rate, is presented as:

$$E = \frac{0.0158}{D} C._A C_E (fI)^{15/8}.L^{3/8}.S^{3/2}.$$

1. Introduction

In Nigeria, major ecological disasters, such as flooding, soil erosion and desertification, have an adverse impact on the nation. The wearing away of the earth's surface by running water and wind is called erosion. Soil has strength, which implies that for any soil particle to be dislodged from the soil mass, it will require some force, and, therefore the internal resistance of the soil must be overcome. Erosion is influenced by a combination of soil topography, soil type, climate and vegetation. There are three types of erosion: (i) water or ice erosion; (ii) wind erosion; and (iii) desertification. For many years, hydrologist and engineers have been faced with the challenge of producing adequate drainage programs to check the menace of erosion by overload flows. Generation of sediment via hill slope erosion is a major environmental problem in several regions of Nigeria, causing decreased soil fertility and the transportation of particulate nutrients to waterways, which has a detrimental impact upon aquatic and estuarine biota. In the south east part of the country, the problem is acute due to steep slopes, erodible soils

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and a seasonally high rainfall, including short duration events of high intensity. Erosion prediction is the most widely used and effective tool for soil conservation planning and design in the United States [2]. Water erosion is often predicted by using the factor based Universal Soil Loss Equation (USLE) [3]. The USDA-Water Erosion Prediction Project (WEPP) is a new technology based on the fundamentals of hydrology, soil physics, plant science, hydraulics, and erosion mechanics [4].

Hillslope form and structure are directly related to vegetation composition and patterns, soil and soil surface characteristics and the interactive process affecting them. A key process affecting hillslope structure and stability is soil erosion by water, which causes the detachment, transportation and deposition soil particles. Because erosion processes and their interactions vary by scale, the "scale" problem has become a central focus of the erosion modelling of hillslopes. The interaction of soil erosion processes with soil, vegetation, surface cover and topography on hillslopes varies with time, space and intensity to produce the hillslope features we see at any given time [5].

When soil particles are eroded, they are transported as sediment by flowing water. The sediment yield is the net result of sediment detachment by impacting raindrops and flowing water, sediment transportation by raindrop splash and flowing water, and sediment deposition.

Flow rates and amounts change over time during a runoff event and with its position along the hillslope in the direction of flow. Soil detachment, transportation and deposition thus change with time and space. The sediment concentration in the flowing water must be known in order to determine the sediment discharge rate [6]. The product of sediment concentration (mass per unit volume of water) and flow rate (volume of water per unit time) gives the sediment discharge rate per unit time. By integrating sediment discharge rates through the period of flow, sediment yield is obtained from the contributing area above the point of interest. These erosion processes are also dependent upon the intensity scale of driving forces [7].

1.1. Erosion processes and modelling

Erosion processes appropriate at hillslope scale were described as early as the 1940's [8] and by the 1960's were being represented in the form of equations [9]. By the early 1970's, closed-form solutions to steady-state forms of sediment continuity equations resulted in mathematical models of erosion [10]. During the 1970's, the impact of agricultural practices on off-site water quality became a major concern. Chemical, Runoff and Erosion, from the Agricultural Management System (CREAMS) model by Kinsel [11], was developed as a tool to evaluate the relative effects of agricultural practices on pollutants in surface runoff and soil water below the root zone. Because sediment is a major pollutant and carrier of contaminants, the CREAMS model includes an erosion component. The main equation governing overland flow is the steady-state continuing equation for sediment transport [12].

Various studies have investigated the hydraulics of hillslope erosion by overland flow. In field studies, Guy et al. [13] measured the velocities of flow in rills for 10 types of soil. For each soil, the slope was constant and flow rates were varied. For Reynolds number ($N_r = \mathrm{UR}/v$), ranging from 300 to 10,000, the Darcy-Weisbash friction factor ($f = 8$ grs$/v$) was found to be a negative exponential function of N_r for each soil. Thus, for constant slope, Das [14] found that roughness decreases in the rill as flow rate increases.

Okoli [15] used an energy principles approach to obtain a surface erosion rate equation for a hillslope. Lane and Nearing [16] developed the Water Erosion Prediction Project (WEPP) model. This is a daily time step simulation model, which uses the rill-interill concept of soil eroding. The WEPP profile version computes the detachment, transport and deposition of by flowing water and is applied to hillslopes where rill and sheet erosion can occur.

Hairsine and Rose [17] proposed a model for water erosion using its principles for both sheet and rill flows. The fundamental theory of Hairsine and Rose is the concept of stream power, which is the rate of overland flow causing shear stress at the soil/water interface. Iscareno-Lopez [18] suggested the use of a Bayesian Monte Carlos approach to assess uncertainties in process based continuous simulation models. Ahmadi et al. [19] developed a general approach for comparing different models used in gully erosion and gully head advancement. They used a technique to study different gully sites in the Hableh Rood basin in the Dahmek region of Iran. Ahmadi went further to calibrate four erosion models: (i) Thompson model; (ii) models of American conservation service SCS (I); (iii) SCS (II); and (iv) the FAO model. All factors have been measured and studied. Statistics studies such as relative error percent, absolute error percent and change variable percent were used. The results of the mathematical studies show that SCS (II) and FAO models are best applicable to gully erosion in arid and semi arid regions of Iran.

The most recent and commonly used erosion model in the United States of America was developed by Lane et al. [20], while working at USDA-ARS Southwest Watershed Research Centre in Tuscon, Arizona. Initially, a closed-form soil erosion equation was suggested by Foster and Meyer in [12]. Following the development of a solution in time and space for the coupled kinematic wave and erosion equation, the next step was to use a solution to derive a sediment yield model for a plane. The solution to the sediment continuity equation for the case of constant rainfall excess was integrated through time [21] to produce a sediment yield equation for a runoff event as follows:

$$Q_b(x) = QC_b = Q\,(B/k) + (K_i - B/K)\left[1 - \exp(-K_n x)\right]/K_r x,$$

where Q_b is total sediment yield for the entire amount of runoff per unit width of plane (kg/m), Q is the total storm runoff volume per unit width (m^3/m), C_b is mean sediment concentration over the entire hydrograph (kg/m^3), x is the distance in the direction of flow (m), k_i is the interill coefficient (kg/m^3), K_r is the rill coefficient (kg/s/$\mathrm{m}^{2.5}$), the discharge coefficient $K = CS^{\frac{1}{2}}$, C is the Chezy hydraulics resistance coefficient for turbulent flow ($\mathrm{m}^{\frac{1}{2}}/S$), S is the dimensionless slope of the land surface, and r is the rainfall excess rate (m/s). The sediment yield equation for a single plane was extended by Liu and Singh [22] to include irregular slopes and cascades of planes.

The conventional approach to study the rainfall run-off relationship of a watershed uses natural historical data to fit a mathematical model simulating the watershed hydrologic behavior. The time variable of watersheds, and uncertainty with respect to the space and time distribution of hydrologic variables, however, makes the analysis of natural data extremely difficult. Amorocho and Orlob [23] stated this in their article on hydraulics and erosion in eroding rills, by fitting the mathematical model to simulate watershed behavior. Liu and Singh [22] introduced a method, using the effect of microtopography, slope length and gradient, and vegetation cover on overland flow, through a simulation technique. Furthermore, the available data do not cover a sufficient range of events to provide a thorough test of the mathematical model. For these reasons, there has been growing interest in the study of the rainfall-runoff relationship under controlled conditions, by means of laboratory catchment [1,22,24-30]. The most recent advances in the modeling of hillslope include the work of Dusseillant [31], Shufang Wu et al. [32], Kim et al. [33] and Jonna [34].

However, it is observed that most available values of parameters in erosion rate equations are derivable from studies conducted in small flumes and backed by mathematical analysis. Of all hillslope erosion rate concepts so far presented, such as the turbulence boundary concept, the critical tractive force concept, and the stream power concept, for the purpose of this study, the Saburo [1] equation for the hillslope erosion rate seems to be favoured, because it takes into consideration the concepts of turbulence and boundary layer and does not depend on the value of critical tractive force or stream power to initiate motion. Rather, once a suitable value of the erodibility coefficient of the soil is known and relevant hydrological data are available, an accurate expression for erosion is obtainable. For these reasons, it has been used for the calibration of the proposed model.

The objective of this study is to adapt the existing model for prediction of hillslope erosion rates at the Nnobi hillslope site. This will be achieved by comparing measured erosion rate with values obtained using the Saburo [1] Eq. (2) after obtaining the relevant parameters in the experiment and after substitution into the formula. We focus modelling the influence of spatial variability on the processes, and interpret the results on application of a particular hillslope model with respect to hillslope stability. The study is used to show how lack of adequate technology to enable measurement of erosion processes in time and space, limits our ability to parametize, evaluate and, thus, validate a process-based erosion model.

2. Geography of the stydy area

The study site is found at latitude $6^0 21^1$ and $6^0 30^1$ N and longitude $7^0 15^1$ and $7^0 3^1$ E, and lies within the rainforest belt of Nigeria. Figure 1 shows the map of the Anambra state and the erosion sites. Two main seasons exist in Nigeria, namely, the dry season that runs through the months of October to March and the rainy season that begins in March and ends in October. The average monthly rainfall for a 30 year period ranges from less than 1 mm in the dry season to 300 mm

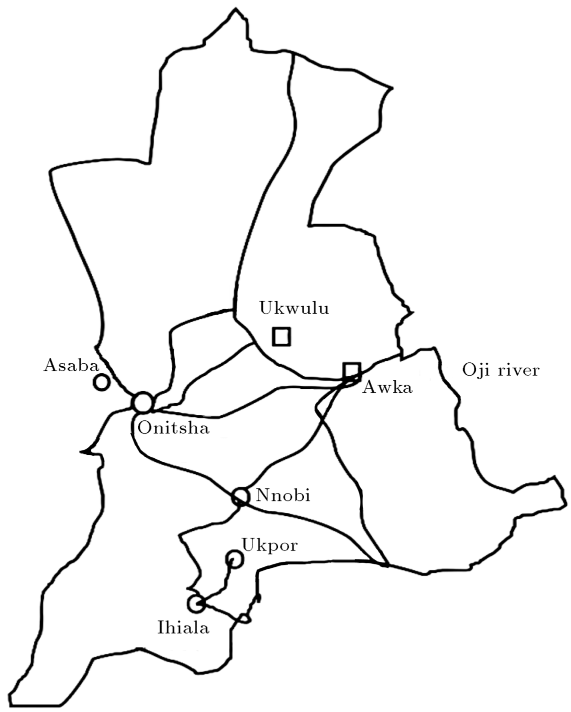

Figure 1. Map of anambra state Nigeria showing the study sites.

Table 1. Erodibility coefficients C_E for various types of soil (extracted from Saburo [1]).

Erosion type (1)	Value of C_E (2)
Sheet erosion and sheet erossing and erosion with small rills	1.0
Sheet erosion with rills	5.0
Sheet erosion but gullies	10.0

in the rainy season. The wet season is characterized by moderate temperature and high relative humidity, while the dry periods have high temperature and low relative humidity.

The distribution of geological units and consideration of rainfall drainage patterns, land use topography and vegetation characteristics, bare soil ratio, runoff coefficient for the rate of overland flow per unit area of slope, and erodibility coefficient for various types of soil, were used to obtain the erosion rate Eq. (10) for Nnobi hillslope sites. Table 1 contains erodibility coefficients, C_E, for various types of soil.

2.1. Site description and test flume

A simple field flume, designed in accordance with Ogbonna [35], was used in this investigation. A natural slope at the back of the Community Secondary School Nnobi-Onitsha in Anambra State was selected as the site for the experimental station. The reason is that the area is located at the heart of the erosion site of south-eastern Nigeria. The erodible stretch of the flume is 3.9 m long, 23 cm wide, and was designed such that its bed was the natural bed slope of the nearby erosion gullies, with the natural bare-soil surfaces of that slope. In order to maintain the banks, the sides of the flume were lined with one course of mortared concrete to form kerbs 15 cm deep. At the end of the slope, a structure-type-bed load sampler with a grate was installed. Downstream of the sampler is a constriction 2.03 m long, the cross section of the waterway being 3.75 cm. The constriction served to provide a faster flow than over bare soil to make for greater velocity and, hence, a tangible head difference in the pitot tube; the latter being mounted, together with a pitot gauge, on a carriage. The total length of the watercourse from the upper end of the flume to the outfall in a farm was, altogether, 10.30 m. Rainwater producing overland flow on the slope was let in through a funnel and a 10 cm diameter pipe leading from the roof gutter; the area of catchment was 6.8 m^2.

3. Experiments and methods

Prior to each rainfall event, the flume slope was established via a land survey involving, mainly, leveling. Levels were taken of two ends of the flume and of an intermediate station in order to compute the slope of the flume. The topsoil of the slope of the flume, outside the flume kerbs (and of the same composition as that of the flume) had previously been collected for particle size analysis and specific gravity determination.

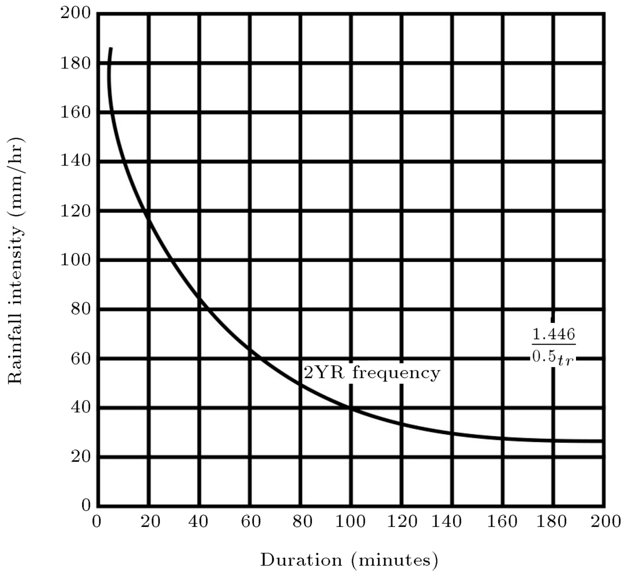

Figure 2. Rainfall intensity duration curve for Nnobi.

The experiment consists of letting the overload flow run over the flume bed; the duration of rainfall being recorded. At the cessation of rain, the eroded material partly deposited along the flume bed and concentrated in the sampler was excavated, its compacted volume determined from a standard cylindrical container and then dry weighed in a laboratory. As for rainfall gauging, rainfall intensities were obtained via test flume experiments, as shown in Figure 2. The values of rainfall thus obtained were used to compute the run off rate using the rational formula, and the results obtained were compared with those calculated using the pitot-tube and point gauge, to measure runoff velocity and depth, respectively. This serves to cross check the runoff data corresponding to a given eroded amount of soil. In this manner, a number of experiments were conducted during a number of storm days.

3.1. Experimental results and analysis

Three soil Ssmples, A, B and C, were collected from the hillslope sites and examined. The following are the test results obtained.

Soil Data

(i) Sample A: The result shows a particle size analysis of 99.5% material passing sieve no. 7, 55% of material passing sieve no. 36 and 41.5% material passing sieve no. 200.

However, a liquid limit of 40% was obtained, while the plasticity index was 16.4%. Also, the natural moisture content of the sample was 13.9%, while the optimum moisture content was 13.9%. The California bearing ratio was 65%. From the above, the soil is fine laterite with loose properties.

According to Smith [36], any soil with liquid limit (35%-50%) has medium compressibility and, therefore, cannot retain water.

(ii) Sample B: The results gave particle size analysis of 99.7% passing sieve no 7, 55.2% passing sieve no 36 and nothing passing sieve no 200. The liquid limit value was 23.5%, while the plastic limit was 175 with a plasticity index of 6.2%. The value of the natural moisture content was 26%, and the optimum moisture content and California bearing ratio were 12% and 28%, respectively.

It was observed that the materials have poor gravelly interlocution, which is susceptible to erosion. It also has very low compressibility strength.

(iii) Sample C: The value of the results gave a particle size analysis of 89.1% passing sieve no.7, 2.84% passing sieve no.36, and 1.6% passing sieve no.200. The liquid limit was 12.5%, with a plasticity index of 13.5%. The value of the natural moisture content was 20.91%, while the optimum moisture content and California bearing ratio were 14.5% and 22.65%, respectively.

The sample with a liquid limit less than 35% has low compressibility strength. Therefore, with the prevailing high rainfall intensity, an erosion process is expected. Figure 3 shows the result of the particle size analysis of soil Sample A.

3.2. Hydrological data

Rainfall intensities and depths are responsible for soil particle detachment and surface run-off [15].

Figure 4 illustrates the relationship between rainfall intensity and duration frequency for the study site using Gumble distribution. It contains frequency factors, K, and time duration (t) from 2 hours to 24 hours. Intensity is the falling rate of rainwater over the ground surface. Commonly expressed as mm/hr., it is determined from the mass curve obtained from the rain-gauge.

Gumbel is a probability distribution commonly employed for determining the frequencies of continuous random variables. The probability density function of this distribution is given as:

$$F(x) = \exp.\left[-e^{-y}\right] = \frac{1}{0.77976^0}\left[x - \overline{x} + 0.4506^0\right],$$

where 6^0 is the variance of the sample data, and $\overline{x}$ is the mean of the sample data. The frequency factor of Gumbel distribution is given as:

$$K = \frac{(Y_T - 0.577)}{1.2825},$$

where Y_T is the reduced variant of a given return period, T. it is given by:

$$Y_T = -\left[\ln.\ln\left(\frac{T}{T-1}\right)\right]$$
$$= -\left[0.834 + 2.303\log.\log\left(\frac{T}{T-1}\right)\right].$$

Figure 5 shows the rainfall depth-frequency factor for Nnobi. The depth-area relationship is very important for determining the changes in rainfall depth, with respect to the variations in the area of watershed during a given storm. In this regard, Horton developed a mathematical model for predicting the average rainfall depth, based on the highest amount of rainfall and the area of watershed. The model is given as:

$$\overline{p} = p_0 e^{-KA^n},$$

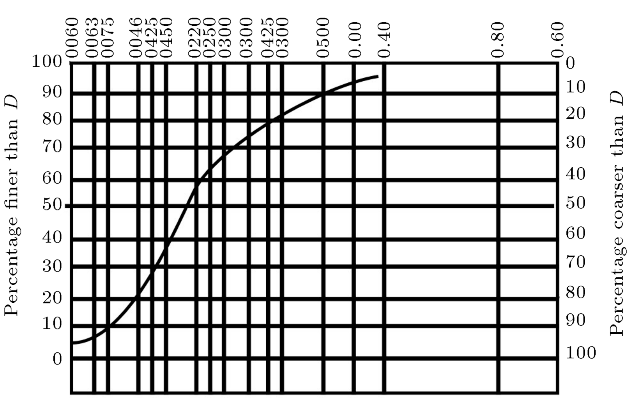

Figure 3. Sieve curve showing particle size analysis of the soil .

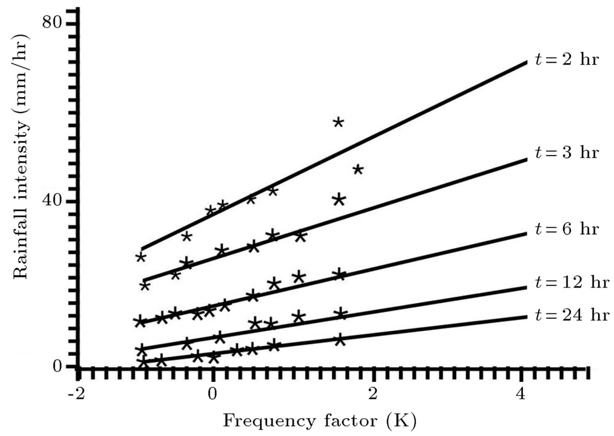

Figure 4. Intensity-duration frequency curve for Nnobi using Gumbel distribution.

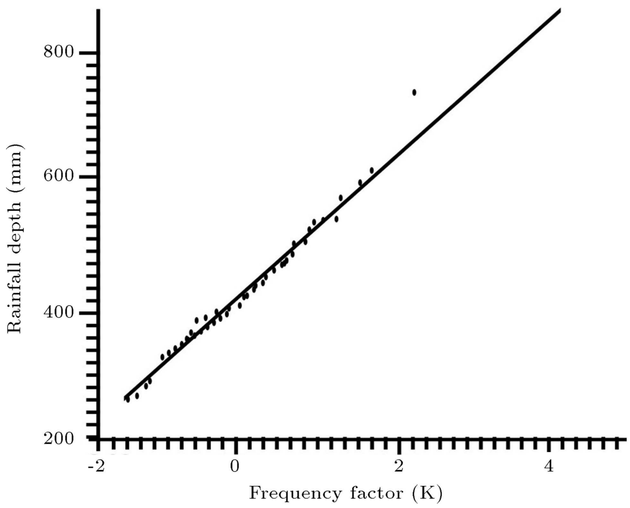

Figure 5. Rainfall depth-frequency factors for Nnobi.

where:

$\overline{p}=$	Average rainfall depth, cm;
$P_0=$	Highest rainfall depth occurred at the storm centre, cm;
$A=$	Area of the watershed, km^2;
K and $n=$	Constants for a given region;
$k=$	Frequency factor for a given location.

From the experiments it is observed that:

1. Sediment concentration is dependent on runoff depth.
2. Sediment detachment and transport are dependent on rainfall intensity, and higher rainfall rates increase soil surface concentration.

4. Analysis of data

A simple erosion rate equation is proposed based on the Saburo model [1]. It was shown by Saburo Kamuro in 1976 that slope erosion rate, E, is of the following functional form:

$$E=F(C_A,C_E,D,I,f,L,S_0), \tag{1}$$

in which C_A is bare soil area ratio (ratio of bare-soil area to total slope area); C_E is the erodibility coefficient; D is the mean sediment size of the slope material; f is the runoff coefficient for the soil; I is intensity of rainfall; L is slope length; and S_o is the slope gradient. In this experiment, the mean diameter of sediment materials is obtained as 0.3 mm.

From the further analysis by Saburo [1], Eq. (2) is demonstrated:

$$E=\frac{N}{D}C_AC_Eq*^{15/3}\,L^{3/8}S_o^{3/2}, \tag{2}$$

in which D is in millimeters, L is in metres, and q^* is the lateral inflow rate of overland flow per unit area of slope, in cubic meters per second, per square meter. Parameter q^* is related to f and I as:

$$q*=\frac{fI}{3.6\times10^6}=2.778\,fI\times10^{-7}, \tag{3}$$

and:

$$\frac{N}{D}=\frac{3(1+2_P)a_s\mu^{b/12}(K+0.012)^{b/3}}{(7b+6)(8g)^{b/3}\left(\frac{\ell_s}{\ell}-1\right)D^{p-1}}\left[\frac{2\beta}{(S-1)s}\right]^{1/2}. \tag{4}$$

In Eq. (4), p is a dimensionless parameter in the Saburo Komura [1] equation, a_s and b are constants, μ is the kinematic viscosity of water, ℓ is the density of water, ℓ_s is the density of the sediment, β is momentum coefficient, and s is the ratio of natural slope gradient to mean frictional slope. K is a constant described as the Darcy-Weisbach friction factor, without rainfall.

Figure 3 depicts particle size distribution for the test soil of specific gravity 2.72 and unit weight 1312 kg/m^3 (determined in an air experiment). Substituting $p=2.0$ (for erodibile open channels according to Saburo [1]), $b=3/2$, $a_s=30$, $s=1.2$, $\beta=1.1$, $k=0.60$ and $g=9.81$ m/s^2 into Eq. (4) and taking $\mu=0.996\times10^{-6}$ m^2/s [37] (because the temperature of water remained at or near 26°C throughout the tests), the value of N in Eq. (4) becomes as in equation shown in Box I.

Therefore, taking the unit weight of the eroded soil as 1300 kg/m^3 (actual value found experimentally was 1312 m^3), the slope erosion rate becomes:

$$E=\frac{439C_AC_E}{D}q*^{15/8}\,L^{3/8}S_o^{3/2}, \tag{5}$$

in which, E is in meters per second per *sq* meter. The bare soil area to the total slope area is C_A. In this experiment, $C_A=1.0$ as there was no vegetation on the test slope (see Table 1).

In deriving Eqs. (2) and (3), Saburo [1] used the Kalinske bed-load equation as a basis, i.e.:

$$\frac{q_s}{U_*D}=a_s\left[\frac{U_*^2}{(\rho_s/\rho-1)\,D}\right]^p. \tag{6}$$

In Eq. (6), p is the dimensionless parameter, q_s is the rate of sediment transport, including the suspended sediment in the volume of material per unit time and unit width. U^* is the frictional velocity. g is the acceleration due to gravity, ρ is the density of water and ρ_s is the density of sediment particles.

In Eqs. (2) and (3), values of the natural slope gradient, S_o, are readily computable from land surveying, while those of the parameters, f, and mean size (D) may be determined from the hydrology of the study site and the particle size distribution curve, respectively.

As for the bare-soil area ratio, C_A, its value is readily obtained from field measurements. If, for

$$\frac{N}{D}=\frac{30(1+2\times 2)30\times(0.996\times 10^{-6})^{1.5/12}\times(0.6+0.012)^{1.5/3}}{(7(1-5)+6)\times(8\times 9.81)^{1.5/3}\left(\frac{2.72}{1}-1\right)D^{2-1}}\left[\frac{2\times 1.1}{(0.0437-1)1.2}\right]^{1/2}$$

$$:.\ N=\frac{4500\times(0.996\times 10^{-6})^{1..5/12}\times(0.6+0.012)^{1..5/3}}{(16.5)\times(78.48)^{1..5/3}\times(1.72)0.30}\left[\frac{2.2}{0.6}\right]^{1/2}\times D$$

$$=\frac{4500\times(0.996\times 10^{-6})^{1..5/12}\times(0.612)^{1..5/3}}{(16.5)\times(78.48)^{1..5/3}\times(1.72)(0.30)}\left[\frac{2.2}{0.6}\right]^{1/2}\times 0.30=439.$$

Box I

example, the above data are available, Eq. (2) may be evaluated. If the erodibility coefficient is properly chosen from Table 1, with due regard being paid to the type of soil erosion under consideration, Eq. (7) becomes:

$$E=\frac{439C_AC_E}{D}q_*^{15/8}L^{3/8}S_o^{3/2}. \quad (7)$$

Converting Eq. (7) into kilograms per square meter (multiplying by 1300 kg/m^3), we obtain:

$$E=\frac{5.7\times 10^5}{D}C_AC_E\,q*^{15/8}\,L^{3/8}S_o^{3/2}. \quad (8)$$

To obtain the erosion rate equation, E, for the Nnobi hillslope sites, substituting for dimensionless discharge, q^*, in Eq. (4) into Eq. (8), gives Eq. (9):

$$E=\frac{5.7\times 10^5}{3.6\times 10^6}C_AC_E(fI)^{15/8}L^{3/8}S_o^{3/2}. \quad (9)$$

Therefore, Eq. (9) becomes:

$$E=\frac{0.0158}{D}C_AC_E\,q*^{15/8}\,L^{3/8}S_o^{3/2}. \quad (10)$$

In Eq. (10), E is in kilograms per hour per square meter; D is in millimeters; I is in millimeters per hour; L is in meters; and S_o, the natural slope gradient, is a real number.

4.1. Experimental results and discussion

Choosing the value of $C_A=1$, i.e. no vegetation at the test site. $C_E=10$ (see Table 1), and $D=0.178$ mm, obtained from the particle size distribution curve, Figure 3. $f=0.47$ (obtained from experiments; Komura [1]. Table 2 contains flume readings obtained from field experiments. Table 2 shows column 1 rainfall duration in minutes, and column 2 shows the date of the experiment. Column 3 shows the length of the flume covered by eroded material, and column 4 is the rainfall intensity curve shown in Figure 2. Column 5 is the volume of eroded material for a given duration of rainfall. Column 6 is the weight of the volume of soil in kg/hr/m^2. Column 7 is the weight of that volume of computed material obtained from Eq. (9), and column 8 is the percentage error (difference between computed and calculated eroded material). Column 9 shows the slope gradient measured prior to each rainfall event.

Table 2. Results obtained with test flume on site.

Rainfall duration T_R min (1)	**Date in 2005 (2)**	**Eroded length of flume L (m) (3)**	**Rainfall intensity I mm/hr (4)**	**Volume of material eroded in t_R minutes (m)^3 $\times 10^{-4}$ (5)**	**Weight of material eroded in 1 hr in kg per m^2 (6)**	**Computed weight of material eroded in 1 hr.kg per m^2 (7)**	**Percent error (8)**	**Slope gradient prior to rainfall (9)**
22	24 July	3.9	95	2.030	0.840	0.820	4.0	0.0440
31	30 July	3.9	80	1.950	0.590	0.610	3.8	0.0435
25	10 Aug	3.9	89	1.990	0.740	0.736	0.58	0.0437
45	16 Aug	3.2	66	1.550	0.435	0.446	2.85	0.0440
28	15 Sept.	3.9	84	1.992	0.660	0.669	1.15	0.0438
18	10 Oct.	3.9	105	2.036	1.010	0.980	3.16	0.0438
	*col.5 $\times\frac{60}{t_R}\times\frac{1}{\mathrm{BL}}\times 1300$; B=width eroded=0.23 m					Mean error	2.59	

Table 3. Runoff data based on rational formula and runoff rates measured using point guage and pitot tube readings.

Rainfall duration T_R min (1)	Rainfall intensity I (mm/hr) (2)	Runoff velocity V (m/s) (3)	Runoff depth Y (mm) (4)	Runoff at upper end of bare-slope in m^3 per m^2 of slope. $Q \times 10^{-4} = \frac{fr \times I \times A_r}{\text{s.m}^2} s$ (5)	Runoff measured in the constriction in m^3 per m^2 of slope $Q \times 10^{-4} = \frac{\text{Col } 3 \times \text{Col } 4 \times B_c}{\text{m}^2 s}$ (6)	Rainfall inflow rate $q_* \left(\frac{\text{m}^3}{S\text{m}^2}\right) \times 10^{-5}$ Col 6-Col 5 (7)	Eq. (3) (8)
22	95	0.52	8.30	1.680	1.800	1.20	1.24
31	80	0.48	7.50	1.410	1.500	0.90	1.04
25	89	0.50	7.90	1.570	1.670	1.05	1.16
45	6	Rise in tube above water level negligible	5.60	1.430	–	–	0.86
28	84	0.49	7.70	1.480	1.577	0.97	1.1
18	105	0.55	8.71	1.860	2.000	1.40	1.37

Table 3 shows runoff rates based on rainfall duration (according to Figure 2) and runoff rates based on velocity using the pitot tube and on depth using the point gauge. Table 3 may be discussed as follows: Column 1 shows rainfall duration, column 2 shows rainfall rates, column 3 shows runoff velocity using the pitot tube, column 4 shows runoff depth using the pitot gauge, column 5 shows the runoff coming from the upper end of the bare slope, column 6 shows the runoff on the bare slope, column 7 equals column 6, and column 5 represents the rainfall inflow rate on the bare soil. Column 8 is the rainfall inflow rate computed as Eq. (9).

Regression analysis was performed on the data obtained from experiments, and the following results were obtained (Figure 6) for measured eroded material versus rainfall intensity, to obtain a curve with linear relationship, $y = 0.014x - 0.578$, with a coefficient of determination ($R^2 = 0.988$). This shows a high level of correlation between rainfall intensity and eroded material. This result confirms the work of several authors, such as Foster et al. [38], Laften et al. [2], Saburo [1], Lane et al. [20], Rose et al. [39], Schmidt [40], Okoli [15], Ahmadi et al. [19], and Wainwright [41]. The coefficient, 0.014, is very close to the derived model equation, 0.0158. Figure 7 shows the computed eroded material versus rainfall intensity. Figure 8 shows the relationship between the measured material and computed material to be very high. The accuracy of the model equation is very high. Figure 9 shows the retest model used for various parameters to confirm the experiment, with a high coefficient of determination ($R^2 = 0.976$).

The retest of the equation, $y = 0.010 + 0.024$, is very significant. Finally, the retest results were compared with experimental results. Therefore, from the result obtained from various tests, the accuracy of the present model is confirmed.

4.2. Retest of the model for various parameters

Table 4 shows the effect of arbitrary increase in the length of the flume, with the runoff coefficient =

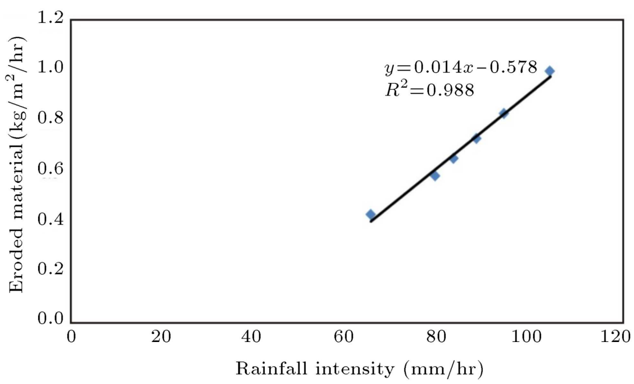

Figure 6. Correlation model for the measured erosion rate.

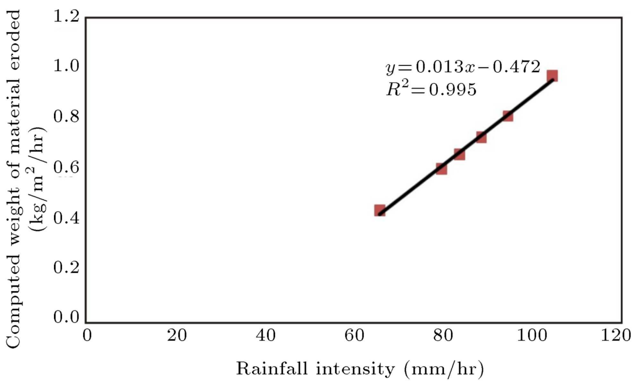

Figure 7. Correlation model for the computed erosion rate.

Table 4. Retest of the model for various parameters.

Length of slope L (m)	Rain-fall intensity, I (mm/hr)	Runoff coeff. F	Slope gradient S_o	Mean sediment size D_{mm}	Erosion rate in (kg/hr/m^2)
	95				1.19
	80				0.90
	89	0.5	0.05	0.3	1.05
8	66				0.70
	85				0.96
	109				1.38

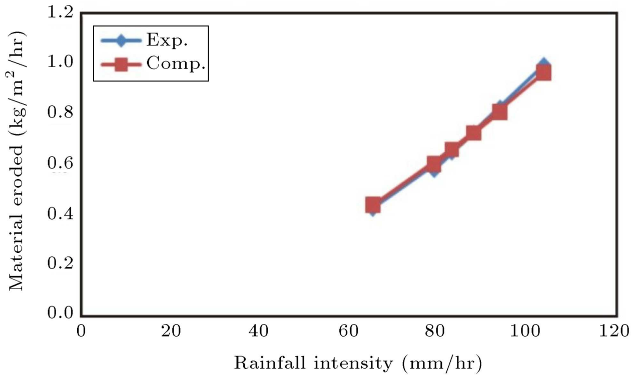

Figure 8. Relationship between measured and computed erosion rate.

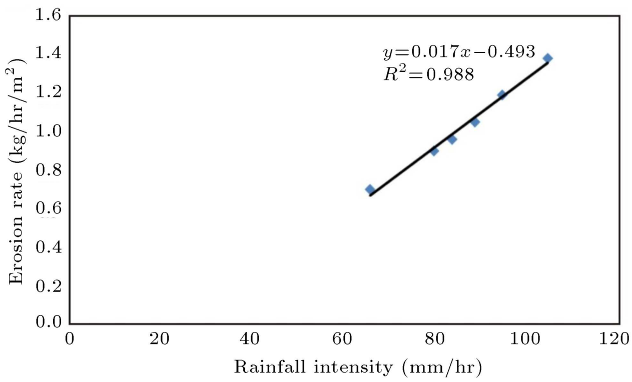

Figure 9. Retest model for various parameters.

0.5, the sediment size= 0.3 mm and the flume slope = 0.05, for the same range of rainfall rate used in the experiment. The data in Table 4 is plotted in Figure 8. To validate the model further, it is necessary to compare the experimental data with field data. This result presented in Figure 6 shows the measured slope erosion rate compared with different rainfall intensities. Figure 9 shows the relationship between measured and computed results. Using a regression analysis method to fix the straight lines to the plots, Figure 8 gives the equations: $Y = 0.013x - 0.472$ ($r^2 = 0.995$), $Y = 0.014 - 0.578$ ($r^2 = 0.988$) for computed and measured data respectively. Therefore, there is a good agreement between them. Figure 9 shows the result of the retest model for various parameters used in the experiment. There is also correlation between the measured data and the retest data with $r^2 = 0.976$.

5. Conclusion

The following conclusions can be made:

1. Given a slope composed of the top soil of specific gravity of the order of 2.70, and mean sediment size of about 0.2-0.3 mm, the rate of erosion may be computed from Eq. (10), namely:

$$E = \frac{0.0158}{D} C_A.C_E(fI)^{15/8} L^{3/8} S^{3/2},$$

in which E is the slope erosion rate in kilograms per hour per square meter, C_A is the bare soil area ratio, C_E is the erodibility coefficient, D is the mean sediment size of the slope material in millimeters, I is the rainfall intensity in millimeters per hour, f is the runoff coefficient for the slope, and S_o is the slope gradient, as a real number.

2. The value of 10 assumed for erosion C_E with C_A gullies is good, as there is close agreement between the measured and the computed erosion rate. A plot of the erosion rate versus rainfall rate is shown in Figure 6, which gives:

$$E = \frac{0.014}{D} C_A.C_E(fI)^{15/8} L^{3/8} S.^{3/2}.$$

3. Eq. (9) can be used to compute the rate of erosion on a moderate slope of any length other than the one used in the experiment. The plot of the erosion rate versus rainfall intensity for a retest in Figure 9, serves to validate this fact, which gives almost the same result as Eqs. (9) and (10), respectively.

4. The study is used to describe how the lack of adequate technology to enable the measurement

of erosion processes in time and space limits our ability to parameterize, evaluate and, thus, validate process-based erosion models.

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Nomenclature

a_s	A constant in Eq. (24)
b	A constant in Eq. (23)
B	Width of flume
B_C	Width of the constriction at the flume
C_A	Bare-soil area ratio
C_E	Erodibility coefficient
D	Mean particle size of slope material
E	Slope erosion rate
$F()$	Functional notation
F, fr	Runoff coefficients of bare-soil and roof catchment, respectively
g	Acceleration of gravity
I	Rainfall intensity
K	Darcy-Weisbach friction factor without rainfall
L	Slope length
N	A whole number in Eqs. (21) and (23)
Q_o	Runoff at upper end of bare slope
Q	Runoff measured in the constriction
P	A dimensionless parameter
q^*	Rainfall inflow rate per unit area of slope
q_s	Rate of sediment transport including suspend sediment in volume of material per unit time and unit width
S_o	Slope gradient as a real number
S	Ratio of slope gradient to mean friction slope
t_R	Duration of rainfall
μ	Kinematic viscosity of water
$U*$	Friction velocity
V	Runoff velocity
ℓ	Density of water
ℓ_s	Density of sediment
x	Abscissa in Figure 4; standing rainfall intensity
y	Ordinate in Figure 4; standing eroded material

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