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DERIVATION OF EQUATIONS TO PREDICT SHEAR STRESS AND EROSION RATE OF GULLY EROSION SITE IN OGUN STATE, SOUTH WESTERN, NIGERIA

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ABSTRACT

The serious effects of erosion constitute a real environmental challenge that should not be underestimated. This study investigated the functional relationships of shear stress, discharge, channel characteristics and erosion rate estimation models. The length, depth and width of the channel were measured and other hydraulic parameters were derived from the measurements. The shear stress **τ** is taken as the important factor measuring the power of the flow to discharge the sediment. Simple regression analysis was applied to the three computed values of shear stress, **τ**, discharge **Q** and erosion rate **E** according to their functional relationships. The predicted values were subjected to scatter plot and various trend lines and equations were obtained. The results of this study indicate that there was an explanatory independent variable for discharge in predicting shear stress with a coefficient of determination r^2=85% and also the results of erosion rate prediction of r^2 of 97% and 99% respectively. The equations established for shear stress and erosion rate prediction are power and 3rd degree polynomial equation that can be useful and essential to the development of sound sediment management plans and formulation of policies.

Keywords: Erosion, Shear-Stress, Discharge, Coefficient of determination, 3rd degree polynomial, Power equation

INTRODUCTION

Soil erosion is essentially the result of water in motion over cohesive and non-cohesive soils in the laminar and turbulent range. The environment has constantly been subjected to critical stress resulting from both natural and anthropogenic sources of erosion. Uncertainty over the extent of the effects cannot serve as reasons for complacency or delay in facing the threats posed to life and properties by erosion activities in Nigeria. Erosion occurring between soil and water boundary can be classified into sheet, rill and gully. Theoretically, there are multitudes of possible routes that trigger the initiation of gullies and determine their rate of advance. Reality demands immediate answers to provide suitable methods of conservation to ameliorate and alleviate these pressing human problems.

However, the formation of gully erosion occurs due to widening and deepening of the rill erosion due to increase in concentration of runoff. Soil erosion is caused by the interaction of several factors, among which surface water runoff and human activities certainly play a significant role. This phenomenon is a serious problem since it determines the removal of the most useful portions of soil or the vegetation, of fine organic substances and materials, as well as diminishing the capacity of the soil to retain water and nutrients. The serious effects of erosion constitute a real environmental challenge that should not be underestimated.

The ability to estimate the rate of surface erosion is essential to the development of sound sediment management plans and policies. Yang *et. al.* (2004) proposed a procedure to compute lateral shear stress on a compound channel in a depth averaged mathematical model using a modified log-law applied to the normal direction to the bank surface by dividing the channel area into sub-zones.

Mikos *et al.* (2006) noted that rainfall erosivity is one of the most important factors in the process of soil erosion, especially on bare ground or with sparse vegetation cover. The rainfall detaches soil from the ground by impact of drops. Soil can also be detached and transported down slope by shear force caused by the overland flow generated from precipitation. Habersack and Schober, (2005), observed that under natural conditions, the sediment budget is commonly characterized by erosion in the upper parts of a catchment and deposition in the lower parts, so that any retention of sediment upstream causes a lack of material for downstream transport. Walling *et. al.* (2003) concluded that the sediment budget of a catchment is the key tool for understanding its sediment dynamics and for developing effective sediment management and control strategies. There are few, if any, reliable procedures for predicting the sediment budget of an ungauged catchment. In the absence of such prediction procedures, recourse must be made to direct measurements to provide the necessary information to synthesize the sediment budget. Several models describing detachment, transport and delivery of sediments and solutes exist, but most of them require detailed information on rainfall and distributed information about soil parameters, such information is very rare if it exists at all in developing nations. It is worthy to note that these models are developed primarily for agricultural areas in temperate climates. Hasholt (2003) showed that simple hydrological models could provide fair estimates of annual runoff. Papanicolaou and Elhakim (2007) pointed out the necessity of realistic riverbank shear stress modeling and applied an analytical model for computation of riverbank shear stress using field measurements.

Although great achievements have been made in the field of hydrological research during the past several decades, the issue of how to reliably predict the erosion and deposition of sediment in ungauged river basins is still a great challenge. This study investigated the functional relationships of shear stress, discharge and channel characteristics and erosion rate estimation models in ungauged location.

Simulating erosion and sedimentation usually requires prediction of spatially variable hydrological processes. Yang and McCorquodale (2004) proposed an analytical method for determination of wall shear stress in a smooth rectangular channel. Yang and Lee (2007) proposed an analytical method for computation of Reynolds shear stress distribution and bed shear stress in a gradually varied flow in a roughened channel. In view of this the accurate assessment of the spatial and temporal variation of erosion and ultimately sedimentation rates is of great importance, in order that effective soil conservation measures may be adopted. This study investigated the functional relationships of shear stress, discharge and channel characteristics and erosion rate estimation models in ungauged location.

Study Area

Ogun State can be divided geographically into three major zones, considering the susceptibility of the rock sequences to erosion. According to information obtained from an undated map compiled from a 1:2,000,000 map GNS2215, Fig.1 about 37% of the area is moderately susceptible to erosion, zone 1.This consists of rocks of crystalline Precambrian to Paleozoic age and its associated younger intrusive of generally high relief. Approximately 28% of the area marked as Zone 2A is highly susceptible to erosion, this is sediments of Cretaceous to Tertiary age. In Zone 2B, 35% of the area is very highly susceptible, this area coincides with the unconsolidated sediments of the Quarternary Coastal Plain Sands.

The study site falls within Zones 2A and 2B. Jones and Hockey (1964) described coastal plain sands as consisting soft, very poorly sorted, clayey sands, pebbly sands, sandy clays and rare, thin lignite's. They are indistinguishable in the field from much of the Ilaro formation and from the basal continental beds of the Abeokuta formation, which is similar lithologically, also unfossiliferous, and weather to the same, familiar, red and brown sandy earths and clayey grits.

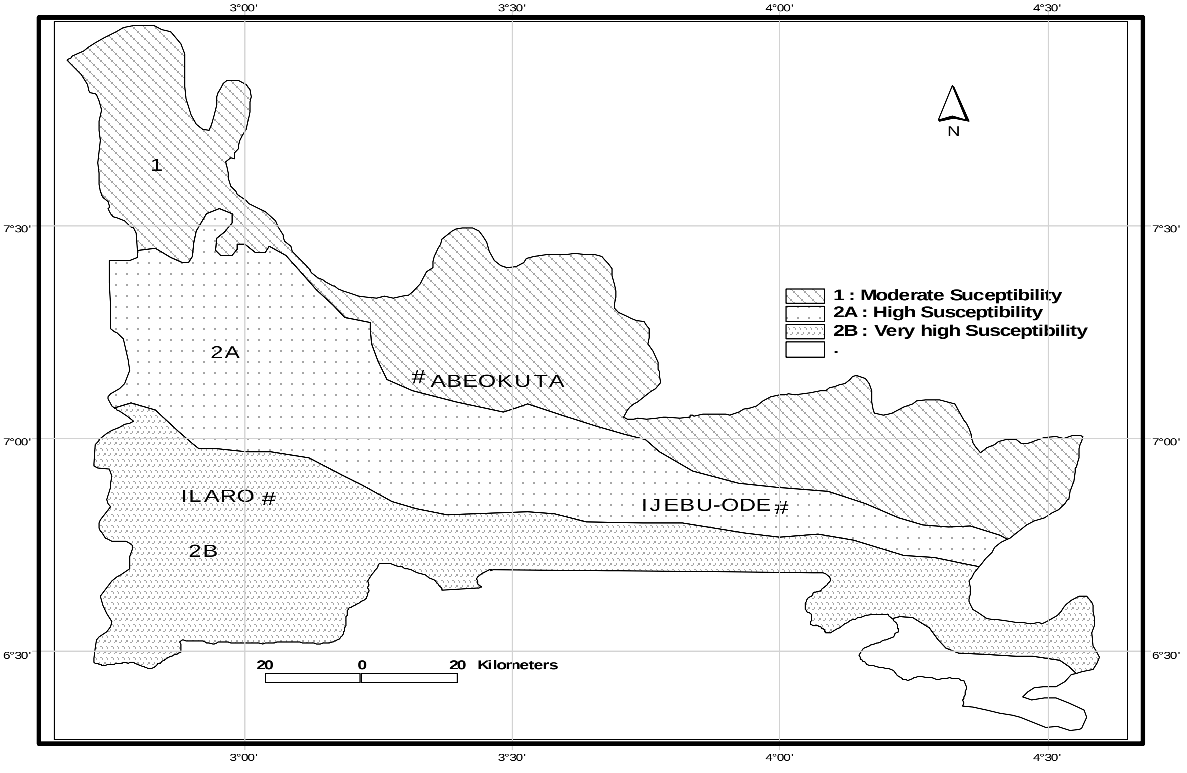

Fig. 1: Map of Ogun State showing the study areas and erosion susceptibility, modified from undated map compiled from a 1: 2,000,000 map GNS2215

MATERIALS AND METHODS

The gully erosion channel in the study area was surveyed using Dumpy Level, Theodolite, Tape and Staff. The measurements were carried out during the dry season in 1994-1996 and between 2002 and 2005. The length, depth and width of the channel were measured and other parameters derived are detailed in Table 1.

The shear stress τ is taken as the important factor measuring the power of the flow to discharge the sediment. This phenomenon is called scour or erosion and the force causing it is known as the tractive force. The equation commonly used to describe the tractive force is the Du-Boys Equation, (Henderson, 1966 and Kinori, 1970)

$$\tau = \gamma RS \cdots\cdots\cdots\cdots\cdots 1$$

Where τ = the shear stress, N/m^2,
γ =unit weight of water, N/m^3,
R= hydraulic radius, m,
S= the longitudinal slope of stream bed or hydraulic gradient, m/m.

The shear stress (tractive force) τ, could be seen approximately as a function of the hydraulic radius R, and the slope S, i.e. τ = f(R,S).
From the dynamic equation of flow in open channels given as

$$Q = \frac{A}{n} R^{2/3} S^{1/2} \cdots\cdots\cdots\cdots\cdots 2$$

Where Q = discharge (m^3/s),
A = cross-sectional area (m^2),
n = the roughness coefficient,
R = hydraulic radius (m)
S = slope (m/m).

Manning's roughness coefficient, n is obtained from grain size distribution patterns through different approaches (Awokola and Martins 1996). The discharge Q is also a function of the Hydraulic Radius R and Slope S i.e. Q =f(R,S). Hence Shear stress is a function of discharge i.e. τ = f (Q) and also a function of erosion rate i.e. τ = f (E). The following functional relationships were computed and compared in this study i.e.
τ = f (Q), τ = f (E), to develop appropriate equations for prediction of shear stress and erosion rate for the study area.

RESULTS AND DISCUSSION

Awokola and Martins (1996) concluded that given the mean sediment size of the slope material of Manning's roughness coefficient n=0.012 for the bare land without vegetation and for gully type erosion, the rate of erosion can be computed from hydraulic parameters.

$$E = 0.025(1.022Q)^{15/8} L^{3/8} S_o^{\ 3/2} \ldots Kg/m^2/hr \cdots\cdots\cdots\cdots 3$$

The equation 3 above was the derived predictive model for erosion rate estimation with hydraulic parameters only for the study area (Awokola and Martins 1996); the predictive model was used to estimate the erosion rate for the study area with the calculated discharge from equation 2, the results are as detailed in Table 2. The shear stress, τ was estimated using equation 1, the computed values of τ**, Q and E** are as shown in Table 3. Simple regression analysis was applied to the three computed values according to their functional relationships. The predicted values were subjected to scatter plot and various trend lines, the trend lines were used to graphically display trends in data to obtain appropriate models for each functional relationship (Figures 2-7). The derived equations are of the 3rd degree polynomial, power, exponential and linear types. The coefficient of determination (R^2) obtained from the various analysis ranges from 0.547 to 0.9911. The coefficient of determination (R^2) of 0.99 is close to unity and is the highest theoretically possible thus indicating that whenever the values of the independent variables or assigned variables are known exactly, the corresponding values of the dependent or derived variables can be evaluated with a high degree of accuracy. The coefficients of determination (R^2) can also be described as the ratio of the explained variation to the total variation that gives an indication of how well the regression line fits the observed data. From the summary detailed in Table 4 the three different relationships were summarized and the coefficient of correlation was used to categorize the equations in order of higher value of coefficient of correlation. In the relationship of Shear Stress versus Discharge a power equation Eq. 5 from Table 4 is the best for prediction of shear stress with the discharge measurement as independent variable.

$$\tau = 5.5146Q^{0.8658} \cdots\cdots\cdots r^2 = 0.8546 \cdots\cdots 5$$

The erosion rate versus shear stress relationship resulted in two different types of equations which are 3rd degree polynomial and power equations of the form in Eq. 8 and 9 below,

$$E = 3x10^{-08}\tau^3 + 1x10^{-05}\tau^2 + 0.0052\tau - 0.1903 \cdots\cdots r^2 = 0.9911 \cdots\cdots .8$$

$$E = 6x10^{-08}\tau^{3.0451} \cdots\cdots\cdots r^2 = 0.9704 \cdots\cdots\cdots 9$$

The Figures 2, 5 and 6 demonstrated theoretical abnormality by indicating negative shear stress and erosion rates. It is not theoretically possible to obtain negative shear stress but it could be logical for a negative erosion rate to be interpreted as no erosion or sedimentation this will need to be further investigated. It could be observed that the only two equations of 3rd degree polynomial order and the only linear equation gave the negative indication for the shear stress and erosion rate estimation.

The power equation seems to be consistent in the predictability of shear stress and erosion rate and the higher values of coefficient of correlation is an indication of superiority of the equations. The results of this study indicate that there was an explanatory independent variable for discharge in predicting shear stress with a coefficient of determination r^2=85% and also the results of erosion rate prediction of r^2 of 97% and 99% respectively. Despite the fact that the results are derived from a small sample size, the strength of the correlations provides evidence that there is a link between the erosion rate, the discharge and the shear stress parameters and their functional relationship established.

Table 1: Channels measured and derived hydraulics parameters

Measured			Derived		
Distance L (m)	Depth Y (m)	Width B (m)	Area A (m^2)	Hydraulic radius $R = A/P (m)$	Mean slope $Sx10^{-2}$
0	*4.21	0.8			
20	4.12	2.07	13.08	1.25	0.9
40	2.92	0.88	10.71	1.14	3.0
55	2.70	2.05	7.32	0.91	4.4
75	2.60	0.76	6.19	0.87	11.11
96	1.50	1.10	3.73	0.67	5.25
105	1.36	0.74	2.19	0.54	0.7
110	*1.22	0.47	1.81	0.5	0.9
150	1.23	0.9	1.89	0.51	0.19
180	1.41	0.72	2.2	0.56	0.9

*Indicates location of maximum and minimum depth

Table 2: Estimated and predicted values of discharge and erosion rates

Distance L (m)	Discharge Q (m^3/s)	Erosion Rate E ($kg/m^2/hr$)
		Equation 3
0	-	-
20	120.12	0.5422
40	168.62	6.2328
55	124.95	5.6657
75	156.93	38.821
96	54.75	1.782
105	10.11	0.0027
110	8.97	0.0025
150	2.26	$5.36X10^{-5}$
180	11.75	0.0081

Table 3: Estimated value of τ, Q, and E

Shear stress τ $\left(N/m^2\right)$	Discharge Q (m^3/s)	Erosion rate E($Kg/m^2/hr$)
Equation 1	Equation 2	Equation 3
110.54	120.12	0.5422
335.50	168.62	6.2328
390.63	124.95	5.665
950.38	156.93	38.821
347.13	54.75	1.783
37.15	10.11	0.0027
43.79	8.97	0.0025
9.01	2.26	0.0000536
49.00	11.26	0.0081

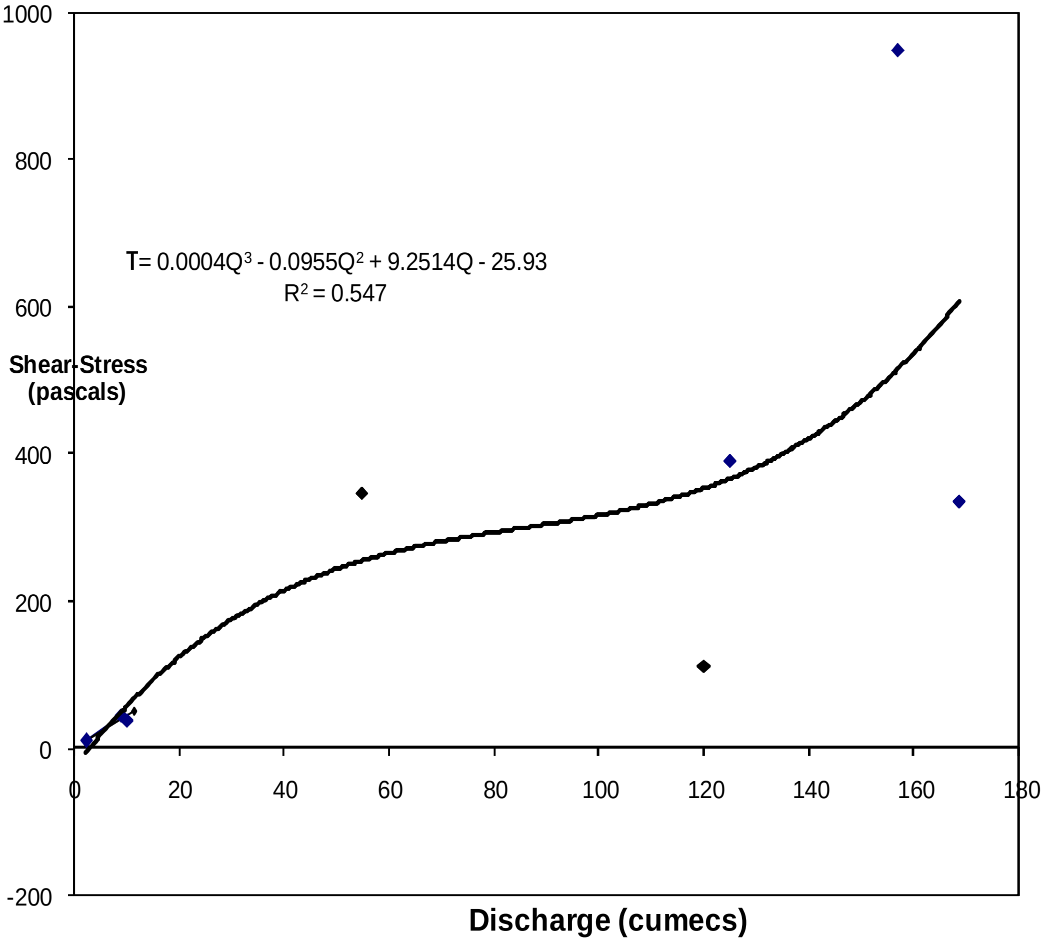

Fig. 2: Scatter plot comparing shear-stress and discharge (3rd degree polynomial equation)

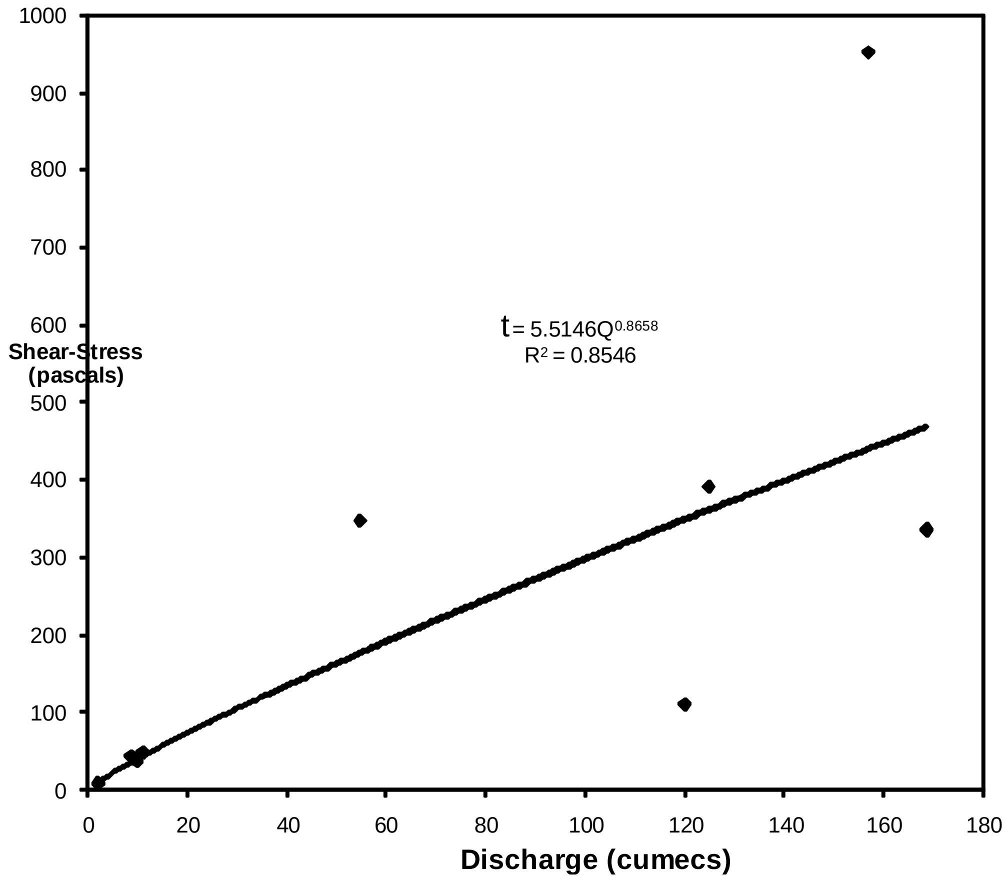

Fig. 3: Scatter Plot comparing shear-stress and discharge (power equation)

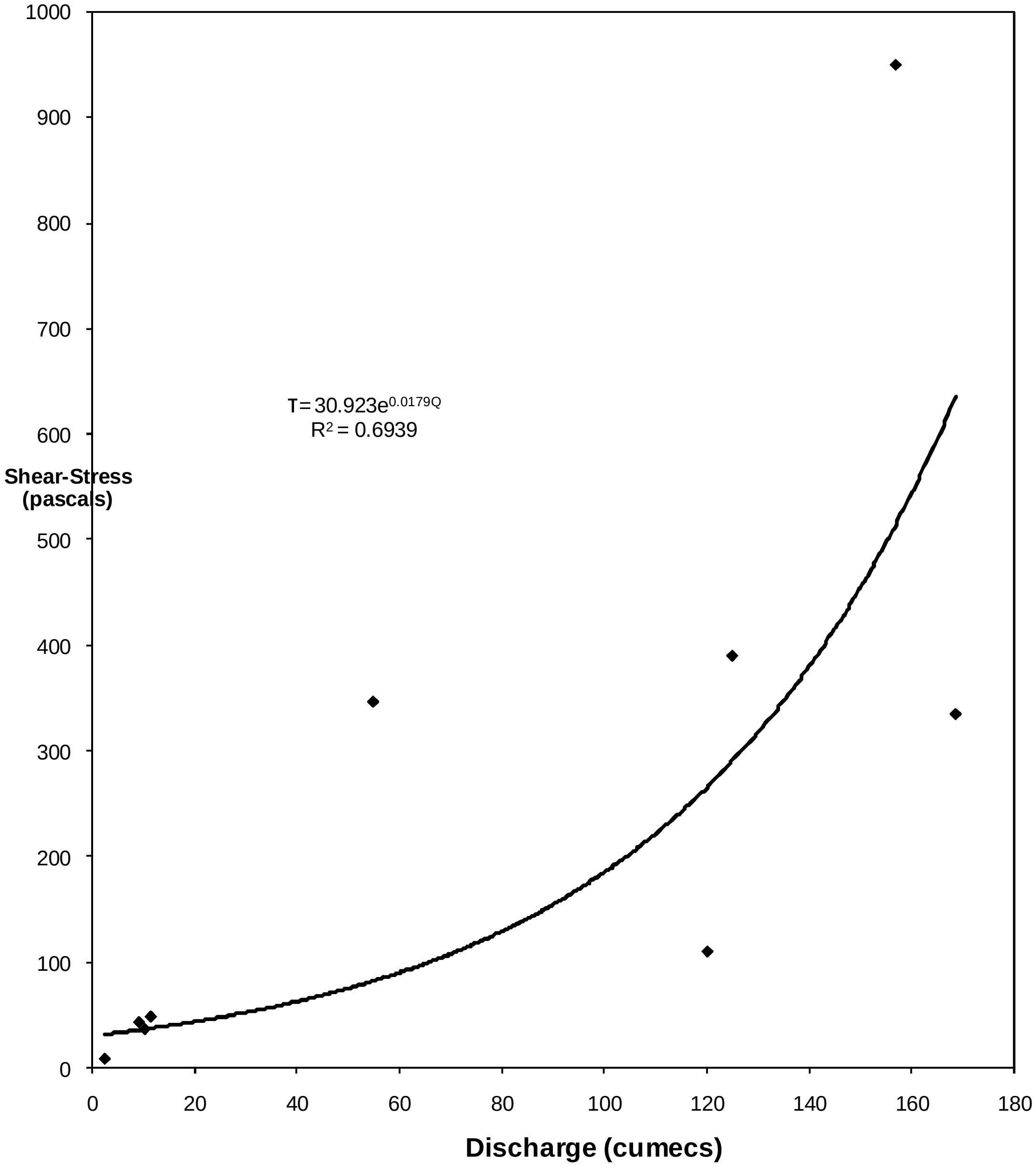

Fig. 4: Scatter plot comparing shear-stress and discharge (exponential equation)

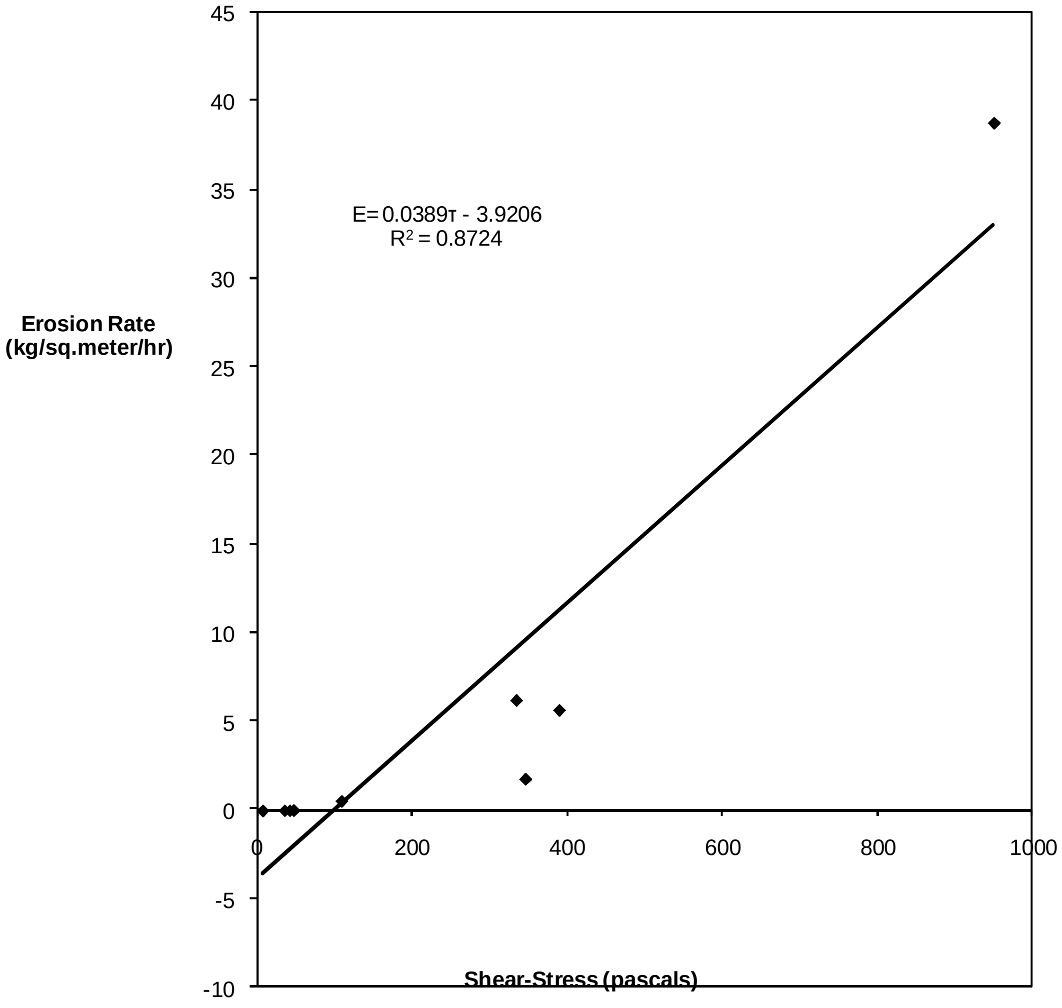

Fig. 5: Scatter plot comparing erosion rate and shear-stress (Linear equation)

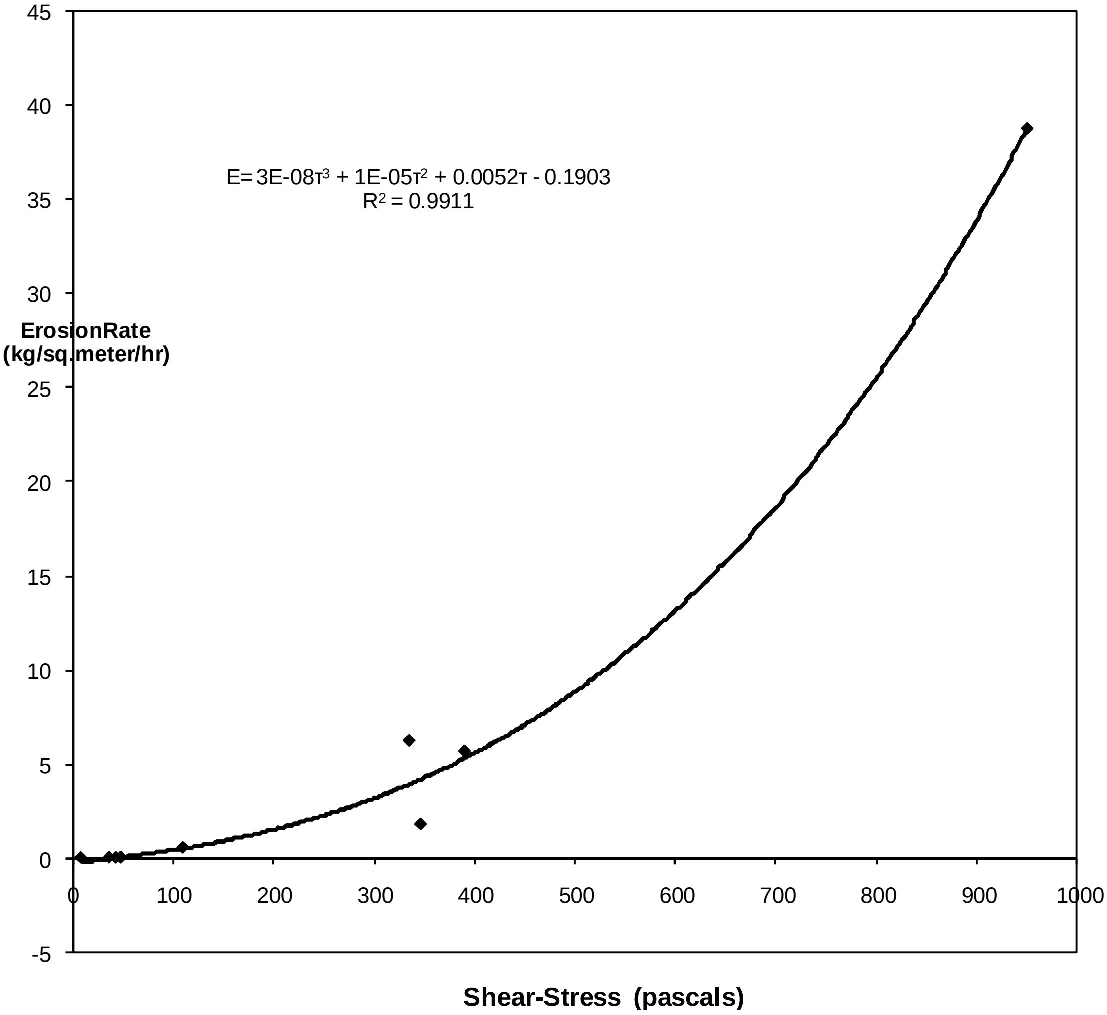

Fig. 6: Scatter plot comparing erosion rate and shear-stress (3rd degree polynomial equation)

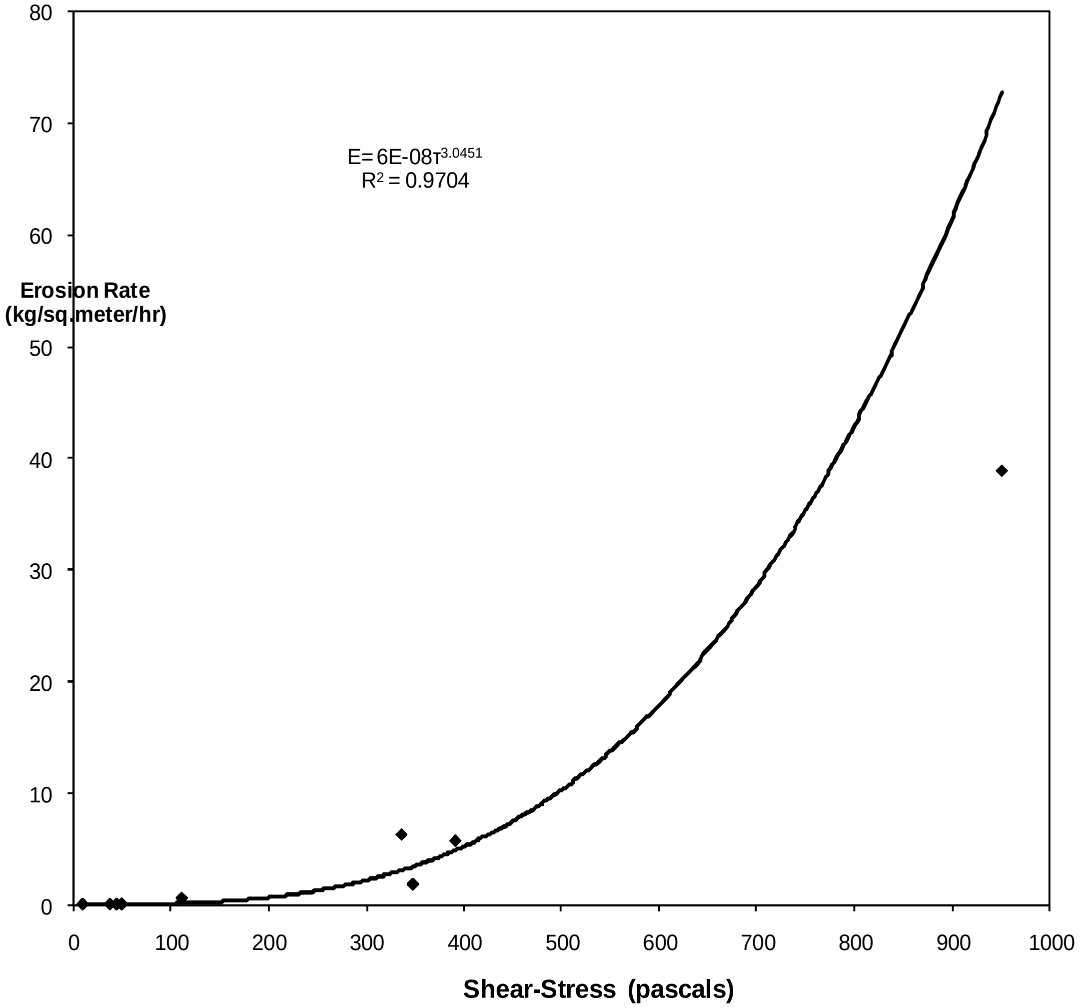

Fig. 7: Scatter Plot Comparing Erosion Rate and Shear-Stress (power equation)

Table 4: Summary of various trend line equation of Erosion rate, shear –stress

Relationship	Equations	Type of Equation	Coefficient of Determination R^2
Shear-Stress vs. Discharge	$\tau = 0.0004Q^3 - 0.0955Q^2 + 9.2514Q - 25.93$ Equation ……….4	3rd degree polynomial	0.547
	$\tau = 5.5146Q^{0.8658}$ Equation……….5	Power	0.8546
	$\tau = 30.923e^{0.0179Q}$ Equation………..6	Exponential	0.6939
Erosion Rate vs. Shear-Stress	$E = 0.0389\tau - 3.9206$ Equation……….7	Linear	0.8724
	$E = 3x10^{-08}\tau^3 + 1x10^{-05}\tau^2 + 0.0052\tau - 0.1903$ Equation ……….8	3rd degree polynomial	0.9911
	$E = 6x10^{-08}\tau^{3.0451}$ Equation………9	Power	0.9704

CONCLUSION

The results of this study indicate that there was an explanatory independent variable for discharge in predicting shear stress with a coefficient of determination r^2=85% and also the results of erosion rate prediction of r^2 of 97% and 99% respectively. The equations established for shear stress and erosion rate prediction are power and 3rd degree polynomial equation that can be useful and essential to the development of sound sediment management plans and formulation of policies. Erosion rate study are generally site specific, the range of coefficients of correlation and determination obtained for the study area are universally acceptable.

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