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Gully Growth Patterns and Soil Loss under Rainfall at Urban Underground Drainage Construction Site, Uyo

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Abstract: This study investigated, evaluated and modeled patterns of growth of gully morphometric dimension and soil loss volume under prevailing rainfall on the slopes of land graded for the construction of underground drainage at Uyo but delayed in completion. Land grading at underground (tunnel) drainage construction site rendered the exposed surface very impervious but young ephemeral gullies developed due to delays in completion. Data on gully morphometric dimension, soil loss and depth of rainfall were analyzed using SPSS ver. 17 statistical package. Mean gully growth in length, width and depth were different at 2.54±0.86, 0.923±0.29 and 0.41±0.11 m, respectively, yielding 3.87±0.08 m^3 as mean volume of soil loss at full stage. Cubic polynomial was best-fit model for growth in length (R^2 = 79%) and width (R^2 = 69%) using weekly rainfall for an annual season. All gully sites had constant depth change, better predicted by quadratic (R^2 = 13%) than linear (R^2 = 9%) functions. Mean volume of soil loss per unit rainfall amount varied with low, medium and high rainfall amount and was highest at slope bottom (33 cm^3/cm) and least at the crest (6.99 cm^3/cm) with R^2 = 38-34%. Land grading to impervious sublayer produced constant depth change in all gullies at the sites. The models for morphometric incremental growth and soil loss volume under the rainfall effect was significantly improved ($p<0.05$) by bifurcating the lumped annual curve into two growth periods in a year: the periods for increasing rainfall (from week 10-30) and for receding rainfall (from week 31-43) in a year and applying quadratic regressing functions on each (R^2 = 91-99%). Rainfall was the principal gully factor and construction delays should be avoided.

Keywords: Geometric increment, growth pattern, gully, Land grading, rainfall, soil loss volume, underground drainage

INTRODUCTION

Soil erosion is a natural degradation process that occurs when the agency of wind and water washes the superficial layer of soil from the area of land but it may not reach a damaging stage if the soil erosion does not exceed the creation limits (howany.com, 2011).

The case of land grading for the construction of underground (tunnel) drainage at Uyo presents a completely disturbed (removed) topsoil and cut subsoil with resistance to erosion highly affected The land grading operation especially at the rough grading stage, removes the sod or vegetation cover and the abrupt irregularities such as mounds and ridges and fills pits or depressions (Michael, 1978). However, the land leveling reshapes the land surface to a planned grade but, in the process, leaves an irregular surface due to the dumping and pushing of loads of cut soils and debris, which may need land smoothening to remove them. Before this could be done at a construction site under the impact of rainfall and runoff flow, the exposed surface becomes vulnerable to the vagaries of runoff erosion, especially in the case when construction spans many rainy seasons before completion with or without planation. This is akin to having a bare soil before canopy closure in periods of increasing rainfall, which renders the bare soil highly vulnerable to water erosion (PennState Cooperative Extension, 2011). The minute, irregular marks of the implement blade left on the land-graded surface by the cut or grub and drag operations become micro-furrows or rivulets for hydraulic movement of surface runoff streams, thereby expanding and perfecting the irregular marks into rills and initiating ephemeral gully formation from the expansion/grubbing of the advancing rill erosion (Michael, 1978; Cao *et al*., 2009).

The graded surface reduces the topsoil down to the lateritic sub layers. This presents a flow bed from which the loosened soil particles wash along the irregular micro channels, saltating, abrasing and under-cutting the hanging side walls of the rivulets or rills. The lateritic sub-layer has different particles orientation, texture, structure and porosity from topsoil. The lateritic subsoil,

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being firmer and of more uniform particle size than the topsoil, may change the natural pattern of soil erodibility together with the slight grade of the surface and may reduce infiltration and concentrate the upland runoff at the down slope and side slope of the graded surfaces, there by accelerating rill advance and gully initiation and morphometric deterioration at rates which depend on the soil properties and rainfall parameters.

Both intense rainfall and low flow under prolonged wet soil may trigger problems of gully development that may create damage to drainage lines if not protected (Carey, 2006). The case of tunnel drainage if not protected may expose lateritic subsoil to cracks and increase water seepage and further cracks, hence it may manifest different levels of vulnerability or resistance to erosion (Carey, 2006; Department of Environmental and Resources management, 2011). Therefore, although erosion is a natural soil surface washing process, the land grading and the marks of the land grading machines, the imposed surface grades and surface grains orientation amongst others, constitute anthropogenic creation which excercebates runoff erosion which may result in gully ephemeral growth with attendant soil loss before recovery or preventive measures are applied.

Gully growth metamorphoses from morphometric degradation of gullies under the agencies of erosion while soil loss is the accumulated mass wasting of the gullied soil volume at the field rate. Therefore, the biometric scale measurement of gully dimensions as morphometric degradation progresses will quantitatively define gully soil loss volume, which, with its unit weight, will yield the weight of soil loss (Cheng *et al*., 2007). The area of field investigation is treated as a micro catchments being the actual area under the land grading operation.

Objectives: The objectives of the research are:

- To establish and evaluate morphometric growth patterns of developing gullies with rainfall amount at underground drainage reclamation site.
- To examine the relationship of gully morphometric growth and soil loss with rainfall under mechanically graded (disturbed) soil condition.

Review of important gully sites in Uyo: Gully erosion occupies significant land mass of Uyo as shown in Table 1. The five major gullies reported at various zones are presented in Table 1. Gully No.5 had the least eroded area (2400 m^2) followed by gully No.4 with 3000 m^2 while the others had the highest area of 4500 m^2. The five gullies occupy 18900 m^2 of land (1.89 ha).

Which large land area could otherwise have contributed significantly to agricultural production and food security in the area. The gullies widened by 20 to 35 m between the onset of rain and October. The widening of the gully sides could be as a result of sloughing action, mass wasting in gravity accelerated erosion, which removed a great deal of soil sediment and rocks (since sediment transport accompanies rainfall/runoff erosion on moderate slopes (Valentin *et al.*, 2005). Side walls sloughing was a major erosion component in freshly tilled soils, with low cohesion and high capillary pressure that produce rills caused by scouring and headcut erosion (Bagarello and Ferro, 1999). Gully depth ranged from 10-20cm, with No. 2 being the deepest gully with 20 cm while No. 4 gully had the least depth (5 cm). The linear pattern of their morphometric growth followed the order: length > width > depth in the ratio 11.2:2:1. It implies that gullies in Uyo grow faster in length than in width at different rates and expand wider than grow deeper, which is a very important guideline in modeling gully morphometric pattern (Aksoy and Kavvas, 2005).

MATERIALS AND METHODS

The study area: The study area lies between Latitudes 05º 02′ and 05º 32′ North and Longitudes 07º 30′ and 07º 36′ East, (measured using GPS by the drainage contracting firm) and is within the tropical rainforest belt in Uyo, capital city of Akwa Ibom State, Nigeria. The geological formation in Uyo is the Coastal Plain Sands; more than 75% of Akwa Ibom State soils are coastal plain sands where rivers are very few and in between (Udo, 1999). The soils are derived from the sandy parent materials and are highly weathered and dominated by low activity of clays. The dominant soils are of inter-fluvial type with a pattern of increase in clay content down the profile and are generally of low organic matter content, low water storage capacity, low CEC and highly susceptible to erosion (Ogban and Ekerette, 2001; Ibia, 1995). The rains are high in intensity and the pattern is bimodal with two peaks in July and September and a period of 2-3 weeks of dry spell, which is called the August break. The annual rainfall amount ranges from 2,000 mm on the north-easterly fringe to over 3,000mm along the coast. The mean relative humidity is 75% while solar radiation ranges from 6-15 KJ per day. The study lasted from March, 2009 to May, 2011.

Selection of gully study sites: Rills developing into gullies were inspected at the reclamation site along Itam ravine, off Uyo-Itu road for the study. The choice of Itam ravine was informed by the nature of the area. The area was graded in 2010 for the construction of urban underground tunnel drainage and part of the site has been reclaimed but some gullies have developed on the reclaimed soils and was growing in the rains.

Determination of gully growth: Gully erosion is due to the action of running water or concentration of run off and it begins with rill. Hence, the measurement was carried out during the onset period of rain in the region (March) until the retreat period (October). The geomorphometric

Table 1: Gully size at various zones of Uyo

Gully site ID	Gully length (cm)	Gully width (cm)	Gully depth (cm)	Area eroded m^2
Eka street (01)	150	30	15	4,500
Behind prison (02)	130	35	20	4,500
Old stadium road (03)	150	30	10	4,500
Brooks street (04)	150	20	5	3,000
Effiong akpan, off Bassey street (05)	120	20	15	2,400
Mean	140	22	13	3780
Total	700	135	65	18900

Akwa Ibom State Ministry of Environment, Udo (1999). Personal communication

Table 2: Growth in gully dimensions at reclamation site for underground drainage, Uyo

Gully ID	Variable	Length, m	Width, m	Depth, m	LWD ratio	Volume loss, m^3
GU 01	Initial, I	1.51	0.56	0.42	3.6:1.3:1	2.49
	Final, F	1.90	0.84	0.45	4.2:1.9:1	3.19
	Increment	0.39	0.28	0.03		0.70
	F/I ratio	1.23:1	1.5:1	1:1		1:1
GU 02	Initial	2.26	0.94	0.49	4.6:1.9:1	3.69
	Fina	l2.71	1.18	0.52	5.2:2.3:1	4.41
	Increment	0.45	0.25	0.03		0.72
	F/I ratio	1.2:1	1.26:1	1:1		1.2:1
GU 03	Initial	1.48	0.48	0.37	4:1.3:1	2.33
	Final	1.97	0.75	0.49	4:1.5:1	3.21
	Increment	0.49	0.27	0.03		0.88
	F/I ratio	1.33:1	1.56:1	1.3:1		1.4:1
GU 04	Initial	3.40	0.84	0.45	7.6:1.9:1	4.69
	Final	3.96	1.12	0.47	8.4:2.4:1	5.55
	Increment	0.56	0.28	0.02		0.86
	F/I ratio	1.16:1	1.3:1	1:1		1:2
GU 0	5Initial	2.84	1.10	0.21	13.5:5.2:1	4.15
	Final	3.41	1.42	0.24	14.2:5.9:1	5.07
	Increment	1.07	0.32	0.03		0.92
	F/I ratio	1.2:1	1.3:1	1:1		1.2:1
	Min G.I.V	2.30±0.84	0.78±0.26	0.39±0.11		3.47±1.03
	M.G.G.V.	2.54±0.86	0.923±0.29	0.41±0.11		3.878±1.08
Mean	Max.G.G.V.	2.79±0.90	1.06±0.27	0.43±0.11		4.29±1.07

Min. G.I.V: minimum gully initiation variable in L (length), W(width), D (depth); M.G.G.V: mean gully growth variable; Max.G.G.V: Maximum gully growth variable; F/I: final/Initial variable ratio; LWD: length-to-width-to-depth ratio; L, W, D: Length, Width and Depth dimension, m

extent which these gullies could grow would help to estimate when the maximum damage on the reclaimed site will occur under the rainfall pattern of the area so that reliable control measures could, therefore, be adopted. Five gullies were randomly selected from many developed rills (in terms of their length, width and depth) for the study. A gully was selected at the crest; three gullies at the middle slope and the other at the foot of the slope tunnel side. The sampling pattern was obtained from frequency of gullies along the three slope positions. The initial length, width and depth of respective gullies were noted and subsequent incremental changes in these basic morphometric properties were measured and used to determine the geometric growth of the gully dimensions and soil loss. The properties were measured at weekly intervals yearly for 2010 and 2011 using a 30 m linen tape. Locally constructed ranging poles and 1cm × 4cm ×1m pegs were used in measuring the length, bed width and depth of the gullies (Michael, 1978; Michael and Ojha, 2006). The gully top width, depths and bed width were measured at the gully mouth, gully head and at carefully selected points, usually at regularly spaced intervals of between 1m and 2 m, along the incised length of the gully. A tape was stretched out across it to determine the top width at each interval of length measurement. Gully depth was measured vertically from the taut tape to the gully bed with the aid of the ranging pole. Dimensions of the sample gullies were noted from initial to final stages.

Statistical analysis: The descriptive statistics of the gully parameters were processed and the profile of growth was modeled by regression analysis using SPSS ver. 17 package and charts.

RESULTS AND DISCUSSION

Growth pattern of new gullies at underground drainage construction site: Plate1 and 2 show typical gully growth from initiation to developed features following soil disturbance by land grading machinery at study site. Five representative gullies (GU 01, GU 02, GU 03, GU 04 and GU 05) at the study sites were selected for analysis and evaluation. Table 2 shows growth in dimensions of the five sample gullies. All the gullies grew faster in length (L) than in width (W) and depth (D) (Fig. 1). At mean ratios of 2.70: 1 for L: W and 6.05:1 for L: D. However, the morphometric incremental rate was not the same. Considering the gully length, GU 05 at the

Plate 1: Initiation stage of the gullies

Plate 2: Final stage of the gullies

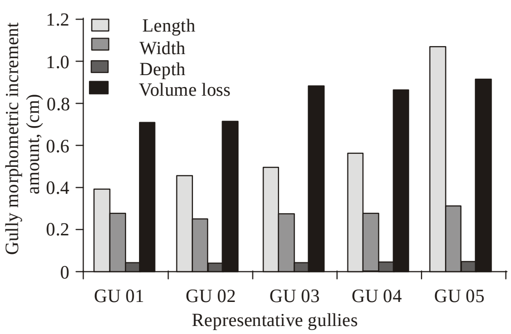


Fig. 1: Increment in representative gully properties

bottom had the highest length increment followed by those of GU 04, GU 03 and GU 02 at mid slope in decreasing order while GU 01 had the least (Table 2). The length-width-depth ratio also varied widely (Table 2) showing spatial differentiation in gully growth even within the same micro-catchments.

Change in gully depth was almost similar in the five sample gullies except in GU 04 which had slightly lower depth increment (Table 2), unlike the profiles observed in Table 1. The overall growth increment shows that gullies at the reclaimed drainage site grew faster in length followed by width and least in depth. This is similar to observations obtained from gullies growth in other zones in Uyo (Table 1). GU 05 also had the highest increment in soil loss volume (0.92 m^3) followed by GU 03 with 0.88 m^3, GU 04 with 0.86 m^3 and GU 02 with 0.72 m^3 while GU 01 located at the crest had the least being 0.70 m^3. Final/Initial (F/I) ratio for the depth was nearly the same (1:1) in all gullies except GU 04, showing that depth changed proportionately at constant rate in all the gullies undergoing morphometric degradation at the drainage reclamation site. This may be attributed to the structure of the subsoil becoming more impervious after the loss of topsoil, following the grading (cut and excavation) of the soil for underground drainage construction.

Generally, F/I volume loss = 1. 2 for initial (soil loss) volume $\geq$ 3.5 m^3 while F/I > 1.2 for initial gully volume < 3.5 m^3.

Thus, F/I volume ratio could be used to estimate final volume loss from the gully dimensions at gully initiation. This shows that the reclaimed soil at drainage construction site produced very low growth in depth under nearly the same subsoil structure.

Slope effect: Volume increment of soil loss increased with lower slope position of the gully. GU 01 at the crest of the site had the least volume loss while gullies at the middle slope and the foot or bottom had the highest increment of volume loss over time (in the rainy months of the year). The impervious surface of the reclaimed soil may concentrate runoff on the slope, initiating rill erosion which may progress to gully initiation.

Changes in steepness of slope increases the velocity of runoff and discharge rate of the sediment soil materials, hence, increasing the volume of soil loss (Table 2). However, soil properties, might also affect the variations in volume loss at gully position (Suresh, 2004; Valentin *et al.*, 2005).

Effect of rainfall amount on ephemeral gully growth: Rainfall amount constitutes water pressure on macroporous structure of the disturbed soil at the drainage construction site. The pressure of different amount of rainfall produces morphometric degradation, hence different rate of volume change, while intense rainfall produces peak flows which cause considerable gully erosion. The prolonged low flows from low rainfall-intensity, resulting from an extended wet period, can also create gully problems (Carey, 2006). In the scatter plots in Fig. 14-17, three levels of rainfall amount producing three rates of soil loss volume were identified. These were:

- The low rainfall amount (27.28 cm) with a volume change of soil loss of 0.028 cm^3/cm
- Median rainfall amount (40-60 cm rainfall) with volume change of soil loss of 0.051 cm^3/cm
- High rainfall amount ($\geq$67.78 cm) with a volume change of soil loss of 0.074 cm^3/cm of rainfall. These coefficients are summarized in Table 3

Gully growth pattern and growth rate: Using data on length, width and depth increments of the five sample

Table 3 : Rainfall amount and volume rate of soil loss at gully sites at drainage construction sites.

Gully ID		Rainfall amount, cm	Volume soil loss, cm^3	Rate, cm^3/cm
GUO1	Low	37.70	0.57	0.028
	Med			0.0511
	High	67.78	5.32	0.074
GU O2	Low	27.28	0.34	0.023
	Med			0.048
	High	63.22	4.71	0.075
GUO3	Low	37.70	0.63	0.019
	Med			0.050
	High	67.48	5.05	0.585
GUO4	Low	27.28	0.51	0.002
	Med			0.488
	High	67.48	4.89	0.049
GUO5	Low	7.10	0.08	<0.01
	Med			0.054
	High	67.48	5.52	0.075

Table 4: Summary of determination coefficient R^2 for gully dimension

Gully ID	Determination coefficient, R^2 Length	Width	Depth
GU 01	0.740	0.659	0.092
GU 02	0.744	0.750	0.064
GU 03	0.740	0.659	0.134
GU 04	0.785	0.758	0.002
GU 05	0.832	0.806	0.077

gullies, regression curves were fitted to examine the trend that could be followed in estimating the morphometric progression of young gullies over time (Handley, 2011).

The growth patterns of the gullies are presented in Fig. 2, 3, 4 and 5. The length and width of the gullies grew in a polynomial pattern but the depth however, followed a different pattern of growth with time. Length of all the gullies increased up to a maximum point corresponding to the period of maximum rainfall and dropped when the rainfall began to recede. The width also followed similar growth pattern but at a slower rate while the depth grew in almost a constant pattern and did not change significantly ($p<0.05$) during the period. Hence, the maximum growth period for gullies (particularly growth in length and width) in Uyo was during the rainy period. Therefore, growth pattern of gully length and width depended on rainfall pattern of the area, hence, ephemeral gully erosion was constituted by rainfall and runoff erosion (Valentin *et al*., 2005; Capra *et al*., 2009).

The cubic polynomial (Fig. 2, 4, 5) was the best-fit model in estimating weekly length and width increment in all the gullies under a relative rainfall amount. The quadratic functions performed better (R^2 = 0.13) (Fig. 4) than the linear (R^2 = 0.07- 0.09) (Fig. 2, 5) for estimating depth growth of the gullies over time (These polynomials are appended to their respective curves in Fig. 2, 4, 5).

The regression estimates varied from one gully to another depending on the slope position. The determination coefficients (Table 4) for length and width degradation(increment) with time were significantly high and similar ($p<0.01$) at R^2 = 70-79%, for middle slope

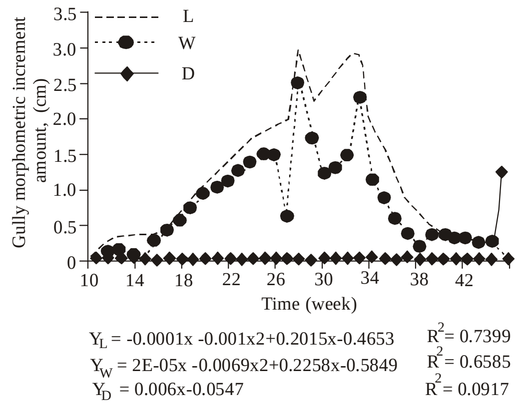


Fig. 2 : Weely gully growth pattern for GU 01 under effect of rainfall at tunnel drainage site, Uyo

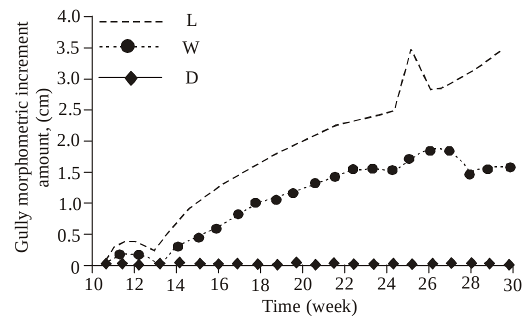


Fig. 3 : Rate of gully growth under increasing-flow rainfall on GU01 at tunnel drainage site, Uyo

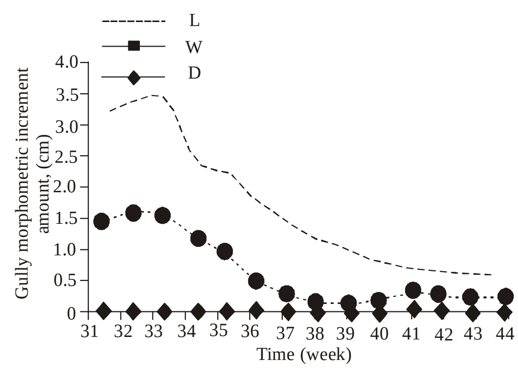


Fig. 4: Rate of gully growth under decreasing -flow rainfall on GU01 at tunnel drainage site, Uyo

gullies while ($p<0.01$) at R^2 = 70-79%, for middle slope gullies while bottom slope gully (GU 05) had the highest association (R^2 = 83) which are very good relationships. The 30-28% unexplained coefficient may be due to standard error of estimate of the curve due to lumping temporal data on dimension into one annual season whereas the rainfall has seasonal phases, hence seasonal effect was not filtered in the runoff gully erosion, also called ephemeral gully erosion (Yongguang *et al*., 2007;

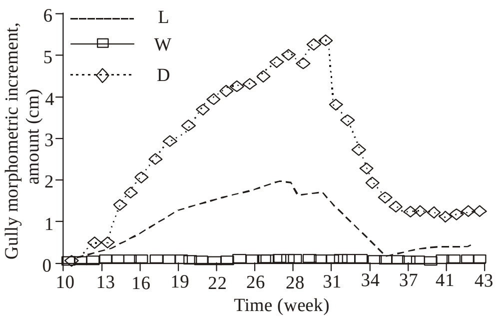


Fig. 5: Weekly gully growth pattern for GU 03 under effect of rainfall at tunnel drainage site, Uyo

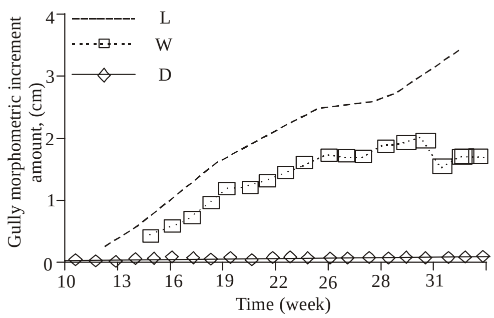


Fig. 6: Rate of gully growth under decreasing-flow rainfall on GU 03 at tunnel drainage site, Uyo

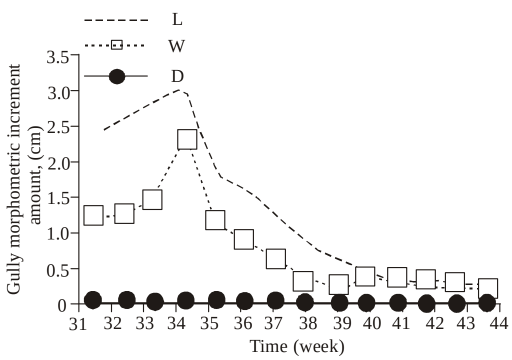
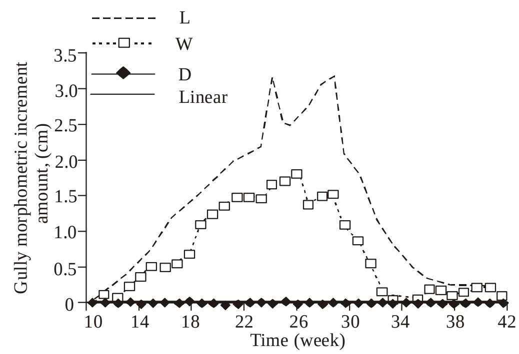


Fig. 7: Rate of gully growth under decreasing-flow rainfall on GU01 at tunnel drainage site, Uyo

Wikipedia, 2011). Therefore, annual plot was bifurcated to align with seasonal phases of the causative rainfall (Fig. 3, 4, 6, 7, 9, 10, 12, 13 (Later)). The mean growth rate for length was 0.34 m/yr and 0.18m/yr for width. The lower growth rate for width under the prevailing rainfall, soil and slope conditions implied that the growth was faster in length than in width.

The logistic regression functions fitted to the data on gully morphometric increment vs time using SPSS package are as appended to Fig. 2, 3, 4 and 5. The summary of their R^2 is given in Table 4. Approximately, 79% of length increment and 69% of width increment of



$Y = 0.0002x^3-0.0188x^2+0.4583x-0.9735$ $R^2= 0.7851$

$Y = 0.0002x^3-0.0179x^2+0.3613x-0.8209$ $R^2= 0.758$

$Y = 6E-05x+0.0281$ $R^2= 0.0023$

Fig. 8: Weekly gully growth pattern for GU 04 under rainfall effect at tunnel drainage site, Uyo

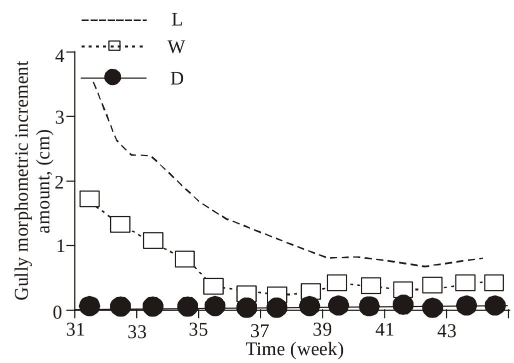


Fig. 9: Rate of gully growth under increasing-flow rainfall on GU04 at tunnel drainage site, Uyo

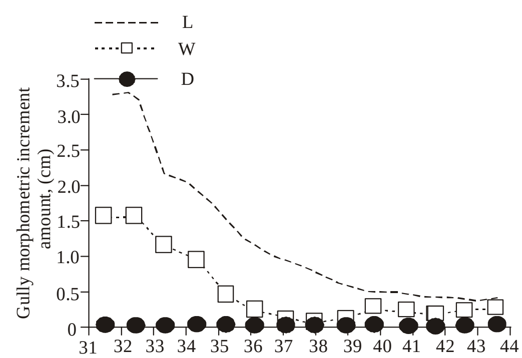
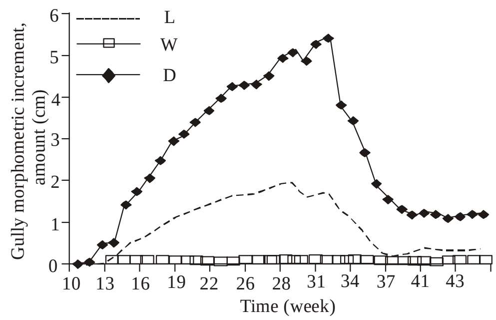


Fig. 10: Rate of Gully Growth under low- flow rainfall on GU 04 at tunnel drainage site, Uyo

GU 01 was explained by the duration which the gully growth took place under the annual rainfall condition at the gully site. The positive coefficient implies that gully morphometric parameters (length and width) increased over time while the negative coefficient is an indication of decrease in the rate of growth. The increase was obtained between March and July (weeks 10-30) when rainfall



$Y_L = 0.0003x^3 - 0.0334x^2 + 0.8282x - 1.7903$ $R^2 = 0.8323$

$Y_W = 0.0002x^3 - 0.0178x^2 + 0.382x - 0.9055$ $R^2 = 0.8064$

$Y_D = 0.0006x + 0.0376$ $R^2 = 0.0774$

Fig. 11: Weekly Gully Growth pattern for GU 05 under rainfall effect at tunnel drainage site, Uyo

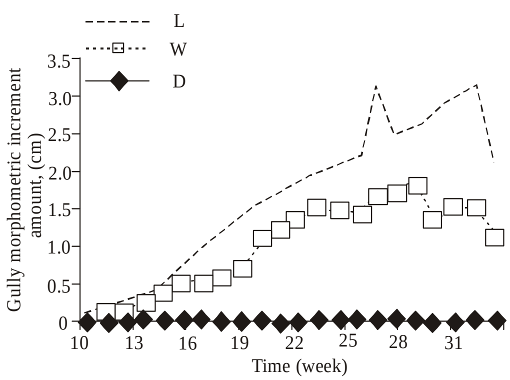


Fig. 12: Rate of Gully Growth under increasing-flow rainfall on GU 05 at tunnel drainage site, Uyo

amount was increasing while the decrease set in from weeks 31-43, especially in October, when rainfall was decreasing. Similar patterns were obtained for GU 02 - 05 but with different growth rate (Fig. 5, 8 and 11). Given the rainfall pattern at Uyo, minimum growth rate for gullies at the site was 0.31-0.33 m/yr for length and 0.16-0.18 m/yr for width of young gullies. The depth

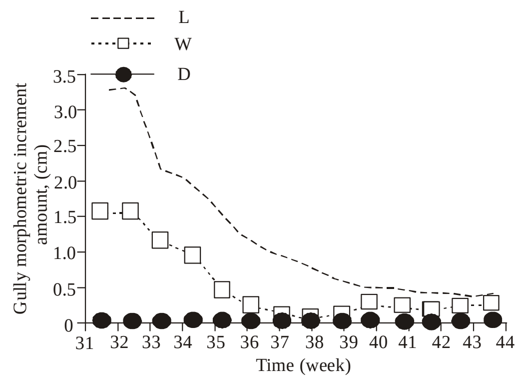


Fig. 13: Rate of Gully Growth under decreasing-flow rainfall on GU 05 at tunnel drainage site, Uyo

maintained a near constant dimension in the gully sites due to effect of reclaimed land that effectively removed the ground cover (Cheng *et al*., 2007; Wikipedia, 2011; Handley, 2011).

Effect of increasing and receding rainfall amount on gully growth pattern: Figures 2, 3, 4 and 5 show aggregated curves which can be bifurcated or disaggregated into two parts: the rising limbs (Fig. 3, 6, 12) regressed with the effect of increasing rainfall with time from the onset of rains to the zenith in October (i.e. from week 10-30), while the falling limb (Fig. 4, 7, 9, 10, 13) regressed with the effect of reducing rains (frequency and low volume) after October (from week 31 - 43) in the year. Therefore, different rainfall amounts, hence, different volumes of runoff produced different quantum effect on gully morphometric growth. Their separate effects on gully geometric degradation, hence on soil loss, are expressed in the polynomial relationship summarized in Table 5. The quadratic polynomials for the separate growth profiles for gully length and width were

Table 5: Bifurcation of gully growth pattern under rainfall effect at underground drainage construction sites Uyo

Gully growth pattern (rising limb) in high rainfall amount			Growth decline (falling limb) under receding rains (week 31-43)	
GUO1	Y_L = -0.025 x^2 + 0.2246 x - 0.2562	R^2 = 0.969	Y_L = 0.0265x^2 - 0.5815x + 3.7353	R^2 0.974
	Y_W = -0.0046x^2 + 0.005x - 0.1953	R ^{2} = 0.3967	Y_W = 0.0195x^2 - 0.3663x + 1.8066	R^2 = 0.905
	Y_D = -1E - 04x^2 + 0.005x + 0.0058	R ^{2} =0.5004	Y_D = 1E -04x^2 - 1E -04x + 0.0301	R^2 = 1.334
GUO2	Y_L = -0.0049x^2 + 0.2556x - 0.4173	R^2 = 0.9191	Y_L = -0.0182x^2 + 0.405x + 2.4533	R^2 = 0.986
	Y_W = -0.056x^2 + 0.2103x - 0.4479	R^2 = 0.9085	Y_W = -0.0134x^2 + 0.2498x + 1.2031	R^2 = 0.781
	Y_D = -5E -05x^2 +0.0017x + 0.0186,	R^2 =0.079	Y_D = -3E -18x^2 + 5E- 04x + 0.0322	R^2 = 0.0454
GUO3	Y_L = -49E - 04x^2 + 0.2556x - 0.4173	R^2 = 0.9191	Y_L = -0.0182x^2 - 0.2498x + 2.4533	R^2 = 0.9839
	Y_W = -56E- 04x^2 + 0.2103x - 0.4479	R^2 = 0.983	Y_W = -0.0134x^2 + 0.2498x + 1.2031	R^2 = 0.7806
	Y_D = -0.0087x^2 + 0.4657x - 0.7745	R^2 = 0.991	Y_D = -3E -18x^2 + 5E.04x - 0.0322	R^2 = 0.0454
GUO4	Y_L = -0.0055x^2 + 0.2234x - 0.4938	R^2 = 0.5795	Y_L = -0.0265x^2 + 0.2581x + 3.8253	R^2 = 0.9748
	Y_W = -6E - 06x^2 + 0.22E04x - 0.0215	R^2 = 0.5795	Y_W = -0.0192x^2 + 0.3654x + 1.9177	R^2 = 9159
	Y_D = -0.0087x^2 + 0.4657x - 0.7745	R^2 = 0.9917	Y_D = -3E- 04 x^2 - 04E-04x +0.0609	R^2 = 0.0927
GUO5	Y_L = -32E - 05x^2 + 0.2401x - 0.03022	R^2 =0.9873	Y_L = -0.0265x^2 + 0.5815x + 3.8253	R^2 = 0.9748
	Y_W = -55E - 04x^2 + 0.2234x + 0.4938	R^2 = 0.9669	Y_W = -0.0192x^2 + 0.3654x + 1.9177	R^2 = 0.9159
	Y_D = -6E - 06x^2 + 0.0022x - 0.0215	R^2 = 0.3795	Y_D = -3E -04x^2 - 42E- 04x + 0.0609	R^2 = 0.0927

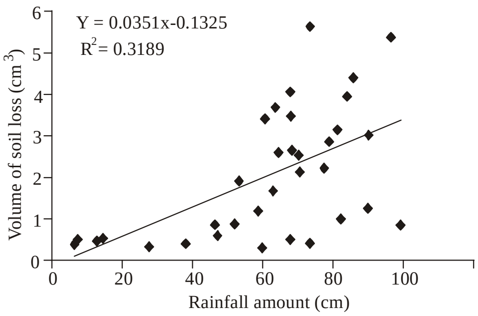


Fig. 14: Relationship between rainfall amount and volume of soil loss in GU 01. (Note: Y = Gully soil loss volume; R = rainfall amount)

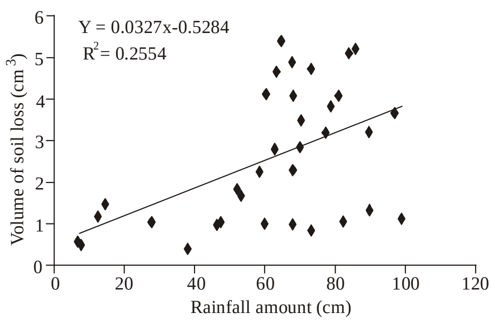


Fig. 15:

highly associated with progression period (R^2 = 0.916-0.987). However, the depth had very low growth increment with time and rainfall (R^2 = 0.045-0.380). This is the effect of grading land for drainage, which made the surface so impervious that runoff cannot easily excavate vertically and delaying completion in time so much that erosion sets in. Thus, the effect of land grading at tunnel drainage site on gully made. The erosion of soil depth was not proportional to time and increasing rainfall amount, thereby resulting in a near constant depth change over time. The high value of R^2 (0.992) for Y_D in the middle slope (GU 03, GU 04; Table 5) for the rising limbs is noted.

Bifurcating the annual profiles into two arms has improved the regression prediction coefficient (R^2). The R^2 for the separate regression function of rising limb and receding limb in GU 01 - GU 03 except GU 04 has improved to 91.6-97.4% for Y_L and Y_W while R^2 for Y_D varies (Table 5). These are higher determination coefficients than those of the lumped annual patterns with R^2 = 65.8-73.9% (Fig. 2, 8, 11, 14 and Table 4).

Prediction efficiencies: The performance coefficient of the gully morphometric functions was statistically tested with Se and ANOVA on the curve fit for the L, W and D.

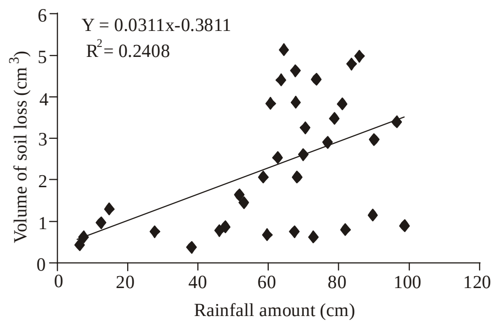


Fig. 16: Relationship between rainfall amount and volume of soil loss in GU 03

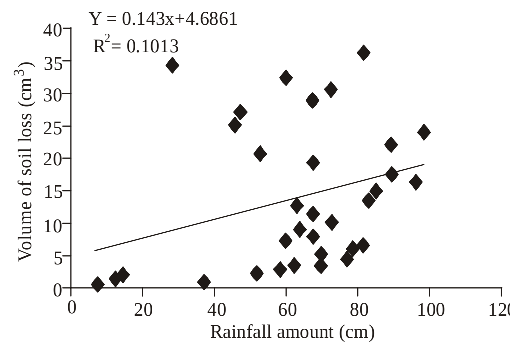


Fig. 17: Relationship between rainfall amount and volume of soil loss in GU 04

Keeping the growth periods as the independent variable, the quadratic prediction function performed better than its linear counterpart as observed in Table 6. There was no significant difference between the prediction data and the observed data for quadratic functions, unlike in the case for linear regression functions where significant difference was observed (Table 6). Test of significant difference between R^2 for the whole year profile and the bifurcated arms show F-ratio of 4.999, 1.63 and 0.009 for L, W and D, indicating significant difference at $p<0.05$ between the lumped annual season and bifurcated periods for L and W and none for D.

Relationship between rainfall amount and volume of soil loss in gully growth in the study area: Predictions about the pattern of gully growth can be made when the constructions of the independent variable is accounted for. Rainfall played significant role in gully growth as graphically shown in Fig. 14-17, which indicate the positive contribution (R^2= 23.6-31.9%) of rainfall amount to volume of soil loss in gully growth in the area. This was determined using volume of soil loss per sample gully.

From the above Fig. 14-17 regression equations, using mean data, are given as follows:

Table 6: Test of significance with ANOVA for linear and quadratic

	Linear			Quadratic		
Gully site	R^2	F-value	Sig.	R^2	F-value	Sig.
GUO1Y_L	0.286	0.038	0.847	0.298	64.379	0.000**
Y_N	0.188	0.478	0.494	0.223	37.629	0.000**
Y_D	0.084	4.745	0.037*	0.140	4.719	0.016**
GUO2Y_L	0.308	12.816	0.001**	0.311	6.592	0.004**
Y_W	0.296	7.427	0.010**	0.298	4.452	0.020*
Y_D	0.122	2.941	0.096	0.174	2.522	0.097
GUO3Y_L	0.001	14.269	0.001**	0.801	6.990	0.003**
Y_W	0.014	13.453	0.01**	0.702	6.591	0.004**
Y_D	0.126	4.436	0.043*	0.477	3.269	0.052*
GUO4Y_L	0.053	1.847	0.183	0.687	35.160	0.000**
Y_W	0.088	3.172	0.084	0.591	23.111	0.000**
Y_D	0.000	0.003	0.956	0.000	0.002	0.998
GUO5Y_L	0.005	0.65	0.687	0.790	60.305	0.000**
Y_W	0.035	1.187	0.284	0.663	34.375	0.000**
Y_D	0.033	1.113	0.299	0.132	2.425	0.105

N/B: = Y_L, Y_W, and Y_D = Gully length, width and depth functions respectively.* = significant at p = 0.05, ** = very significant at p = 0.01; R = coefficient of determination; F value = F ratio calculated; Sig = significance.

$$\text{GU 01, } Y = 0.0511x + 0.1883,\ R^2 = 0.357 \quad (1)$$

$$\text{GU 02, } Y = 0.0480x - 0.5277,\ R^2 = 0.341 \quad (2)$$

$$\text{GU 03, } Y = 0.0496x + 0.3157,\ R^2 = 0.346 \quad (3)$$

$$\text{GU 04, } Y = 0.0488x - 4376,\ R^2 = 0.338 \quad (4)$$

$$\text{GU 05, } Y = 0.0541x - 0.2000,\ R^2 = 0.382 \quad (5)$$

where, Y is mean volume of soil loss in (m^3) which denotes the extent of gully growth while x is mean rainfall amount in (cm).

Rainfall amount was positively related with volume of soil loss in all the gullies. Thus, gully growth was probably faster when rainfall amount increased since rainfall amount determines volume of run-off along the gullies. The unit effect of rainfall was shown in the volume of soil loss per unit rainfall amount at the gully site, given as follows: 6.993 cm^3/cm for GU 01; 30 cm^3/cm for GU 02; 28.57 cm^3/cm for GU 03; 32.25 cm^3/cm for GU 04 and 33.333 cm^3/cm for GU 05; the smallest rate (volume) of soil loss being 6.993 cm^3/cm at GU 01 and the highest at GU 05.

This may be attributed to slope position of GU 05. The contribution of rainfall to the growth of these gullies was very strong as indicated by the R^2-values, which varies as 36, 34, 35, 34 and 38% for GU 01, GU 02, GU 03, GU 04 and GU 05 respectively. The least contribution was 10% in GU05, while the highest contribution was 31% in GU02. Apart from GU 05, at most 30% of the volume of soil loss at the gullies was explained as effect of rainfall; the 70% unexplained proportion of volume of soil loss was attributed to other factors which may include soil structure, slope and other properties of the area. Hence, gully growth is a function of several factors out of which rainfall is a principal factor.

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Provide self explanatory caption of Fig (15)