Gully length and average gully depth relationships on two geological sediments in the North Central Nigeria

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Abstract: Gully erosion is widespread in Nigeria and has been reported in all the states of the Federation: This study was carried out to examine the relationships between gully length (L) and average gully depth (D) on two geological sediments of varying vulnerability to erosion. The dimensions of thirty-seven and five random gully samples formed respectively on the Ajalli Sandstones (AS) and the Upper Coal Measures' (UCM) geological sediments underlying the Idah-Ankpa Plateau of North Central Nigeria were measured: The L and D variables were subjected to correlation analysis and the sample bivariate regression to examine their relationships and the predictability of D using L as a prediction tool on the two formations. Results show that on the highly erodible AS, L has no correlation with D (R=0.004, R^2=0.00). On the more resistant UCM, L is strongly, significantly, but negatively correlated with D (R=–0.899, R^2=0.808, P<0.05). The regression analyses indicate that L is not a predictive tool for D on the erodible AS (D_1 = 6.469 + 0.00L_1), whereas on the more resistant UCM, L is a useful parameter for the prediction of D (D_2=13.929−0.022L_2), which appears in the form of bed aggradation. The study suggests that the correlation of gully length with average depth transmutes to a stronger, negative, and significant value with increasing resistance to erosion of the geological formation housing the gully. It also suggests that the reliability of the gully average depth estimation using the length as a prediction tool improves with increasing resistance to erosion of the geological sediments. However, the relationship of gully length with the average depth could also be affected by other factors, such as the vertical homogeneity of the sediments.

Keywords: average gully depth, coefficient of regression, geological sediments, gullies, gully length, sediment volume

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1 Introduction

Gully erosion is one of the most serious environmental problems confronting the international community because it threatens soil productivity and the natural environment. Gully erosion differs from both rill and sheet erosion in that is an erosion process that causes runoff water to accumulate and recurs in narrow channels over a relatively short duration, and removes soil from the narrow area and transports it to considerable depth. If the channels created become too deep, typically ranging from 0.5 to 30 m depth and difficult to ameliorate with ordinary farm tillage equipment, then the gullies can be termed permanent gullies (Poesen et al. 2003). Pimentel (1993) was one of the first researchers who reported that worldwide, especially in the developing tropical countries, severe land degradation occurs on both urban and agricultural lands, and the problem increases as the human population grows and more marginal lands are brought under cultivation. He estimated that, worldwide, and on an annual basis, about six million hectares of land were lost to erosion-related land degradation. Lal (1988) reported that the United Nations Food and Agriculture Organization (FAO) had estimated that more than 85% of Africa north of the equator was experiencing rapid accelerated erosion in the form of gullies.

There is hardly a State in the Federal Republic of Nigeria that has not been ravaged by the menace of gully erosion, as reports of gully devastating effects are

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rampant. Grove (1951) and Floyd (1965) were among the pioneer environmental scientists to draw attention to the ravages of gully erosion in the old Eastern Nigeria. They outlined the human and physical causes of the gullies and stressed the need for soil conservation measures to be applied in the region. Ofomata (1965) focused on the causes and control of soil erosion in the eastern states. The ravenous Agulu-Nanka gully has been a subject of numerous studies (Nwajide and Hoque 1979; Osadebe and Akpokodje 2007) and has defied all technical solutions. However, other countless gullies that have reached devastating dimensions have been sighted in several states, particularly in the earthen and central regions of the country, including the Jos Plateau (Dorman 1978), the Kobani Basin in the Zaria area (Ologe 1972), the southwestern Nigeria (Jeje 1973; Faniran and Areola 1974), and on the Idah-Ankpa Plateau (IAP) (Agenson 1990; Schneidegger and Ajakaiye 1994; Oparaku 2015).

Documented reports on gully erosion studies carried out on the Idah-Ankpa Plateau are few and far between. After a numerical study and statistical analysis of the orientation of the gullies and surface cracks at Ankpa, a suburban town on the IAP, Schneidegger and Ajakaiye (1994) compared the pattern of the gullies with joint orientations and concluded that the gullies resulted from neotectonic forces, since the joints were found in recent laterites. Oparaku et al. (2016) studied the influence of soil texture on the relative vulnerability to erosion of the three geological sediments underlying 100% of the IAP, namely, the Upper Coal Measures (UCM); the Ajalli Sandstones (AS); and the Lower Coal Measures (LCM), and found that variations in soil texture was the dominant factor influencing the relative proliferation of gullies on these formations. The extent of gully erosion-induced land degradation occurring on the plateau lands was the subject of study by Oparaku et al. (2015), and they found that on the AS, the width of gullies was widening more than their floors were deepening by a ratio of 1.46, which has negative implications for urban and agricultural land development projects in the area.

Gully length, average depth, and average width dimensions are required for the estimation of the average gully sediment volume (Mukai, 2016; Castilo et al. 2017), which is a useful index for the prioritization and targeting of gully erosion control expenditure. In addition, gully depth is an important parameter for the assessment of the volume of sediments produced by a gully. Notably, gully length can be easily measured in the field, from airphotos and from satellite images, whereas the task of measuring the average depth and average width is more complicated (Casali et al. 2015).

Studies on the interrelationships between and among gully dimensions have been reported worldwide, but no such related research endeavours have been carried out on the IAP. Ebisemiju (1989), working on lateritic soils in Guyana, reported that gully width was positively correlated with the depth ($R = 0.84$). His findings showed that the rate of gully width expansion in this area was proportional to the rate of gully deepening. As proposed by Cheng et al. (2007), the length of a gully is a very useful parameter for the estimation of sediment yield from the gully since there is a strong correlation between the length and average volume. The linear relationship between the form factor (W/D) and gully length (L) has been given by Radoane et al. (1990) as (Equation (1))

$$W/D = 1.287 + 0.00199L \quad (1)$$

where, W = Average gully width (m); D = Average gully depth (m).

Working on the black soil region of northeastern China, Zhang et al. (2007) gave a power function of the relationship between the average gully volume (V) and length as (Equation (2)).

$$V = 0.015L^{1.429} \quad (2)$$

Castlo et al. (2017) employed an automated method to delimit the cross-section of some selected ephemeral gullies in Spain and compared the results with those reported by other gully experts. They reported that the calculation of the gullies width and area were more prone to errors than the least sensitive average depth. They, however, did not take into account the influence of the underlying geological sediments on the variability between the dimensions of the 60 gullies used in their study. The numerous studies in the literature have not considered the effects of the vulnerability to erosion of the geological sediments on which gullies occur on the interrelationships between and among gully dimensions.

This study was therefore, carried out to examine the relationships existing between gully length and average gully depth on two uniquely homogeneous geological sediments (the UCM and AS), with varying degrees of vulnerability to soil erosion, underlying the IAP. The aim was to determine the effects of the soils' resistance to soil erosion on the correlation of gully length with the average gully depth, and the predictability of the average gully depth as gully migrate upslope using the length as a tool.

2 The study area

The study area comprises the Western Ankpa High Plateau and the Idah Flood Plains. It is situated in the Middle Belt of Nigeria, and lies between Latitudes 7°17′00″N and 7°23′30″N and Longitudes 8°20′20″E and 9°00′00″E (Figure 1). The total land area is estimated at about 5675 km^2 with a perimeter of 793,531.76 km (Oparaku 2015). About 96% of the area lies in Kogi State, while the remaining 4% lies in Benue State of Nigeria.

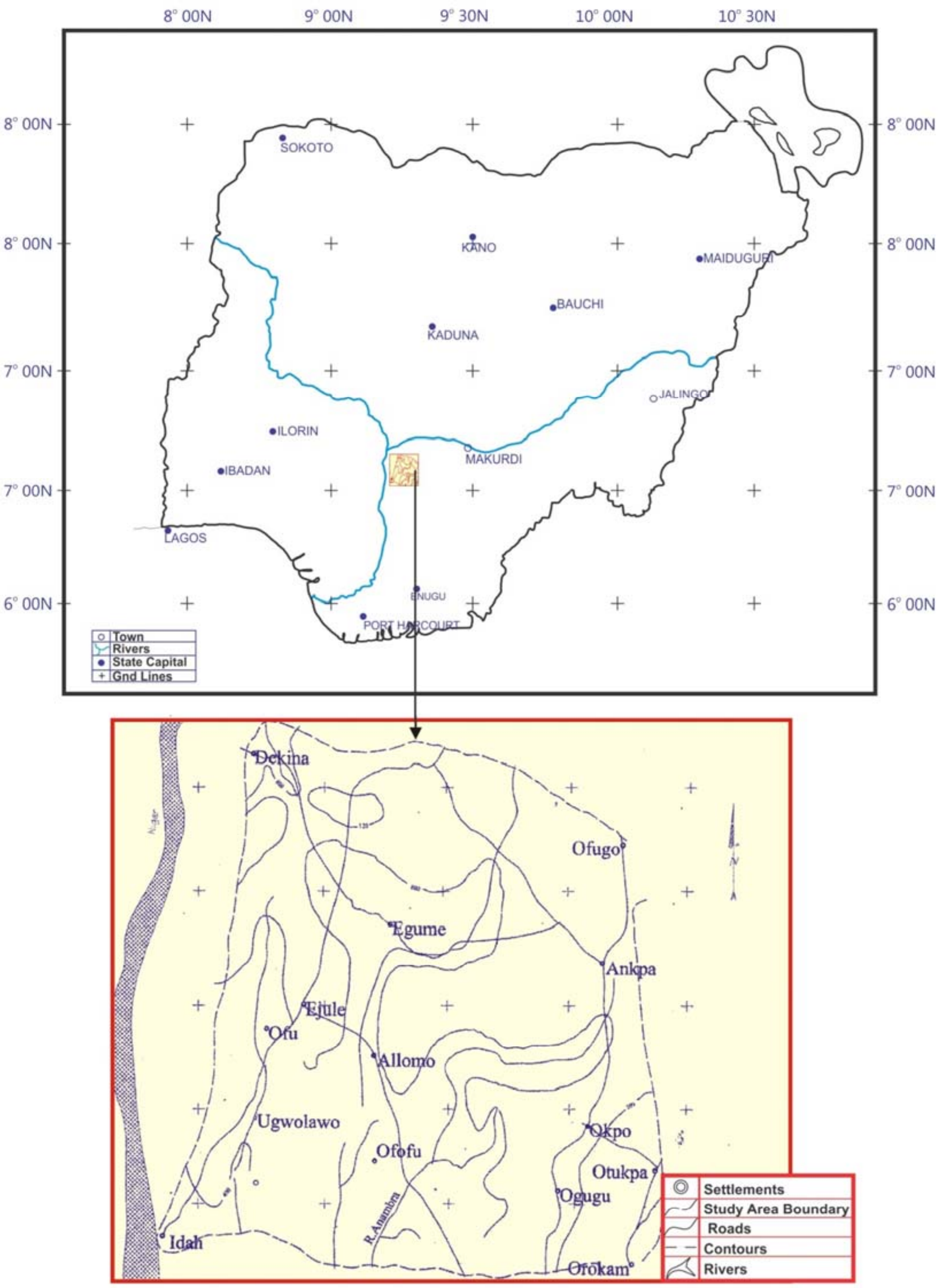


Figure 1 Map of the study area (Ida–Ankpa Plateau)

The area is located in the tropical hot climate. The mean annual rainfall is 1260 mm with a range varying from 714 to 1890 mm. There are two major seasons in a year: the rainy season and the dry season. The rainy season responds to the prevalence of the moisture-laden southwesterly maritime winds that originate from the Atlantic Ocean, whereas the dry season responds to the dry continental northeasterly winds that blow from the Sahara Desert. The rainy season lasts from the middle of April to the end of October, while the dry season lasts from November until the middle of April. Temperatures are high throughout the year, and the mean varies from 31.40^{o}C in December to 34.50^{o}C in March, with an average of 32.60^{o}C. The average relative humidity may be as high as 98.70% in October and as low as 75.20% in January. The evapotranspiration ranges from 73.40 to 166.90 mm. September has the highest number of rainy days (8.00) and March has the least (1.2).

The geology of the area has been described as follows (Preez and Barber 1965): The underlying geology (Figure 2) consists of cretaceous sediments made up of three major formations which underly 100% of the plateau landscape. These formations comprise the UCM (36%), The AS (44%), and the LCM (20%). The geological successions of these sediments are as follows: UCM-AS-LCM, i.e., the UCM is the overlying formation, the LCM the underlying formation, while the AS is sandwiched in between the two. The UCM and LCM are each homogeneous up to a depth of 70 m, whereas the AS is homogeneous up to a depth of 170 m. The AS is exposed to the erosive processes of the elements at locations where the UCM, which provides a protective overburden, has been denuded away. And the LCM is exposed and subject to erosive processes where both the UCM and AS are denuded away.

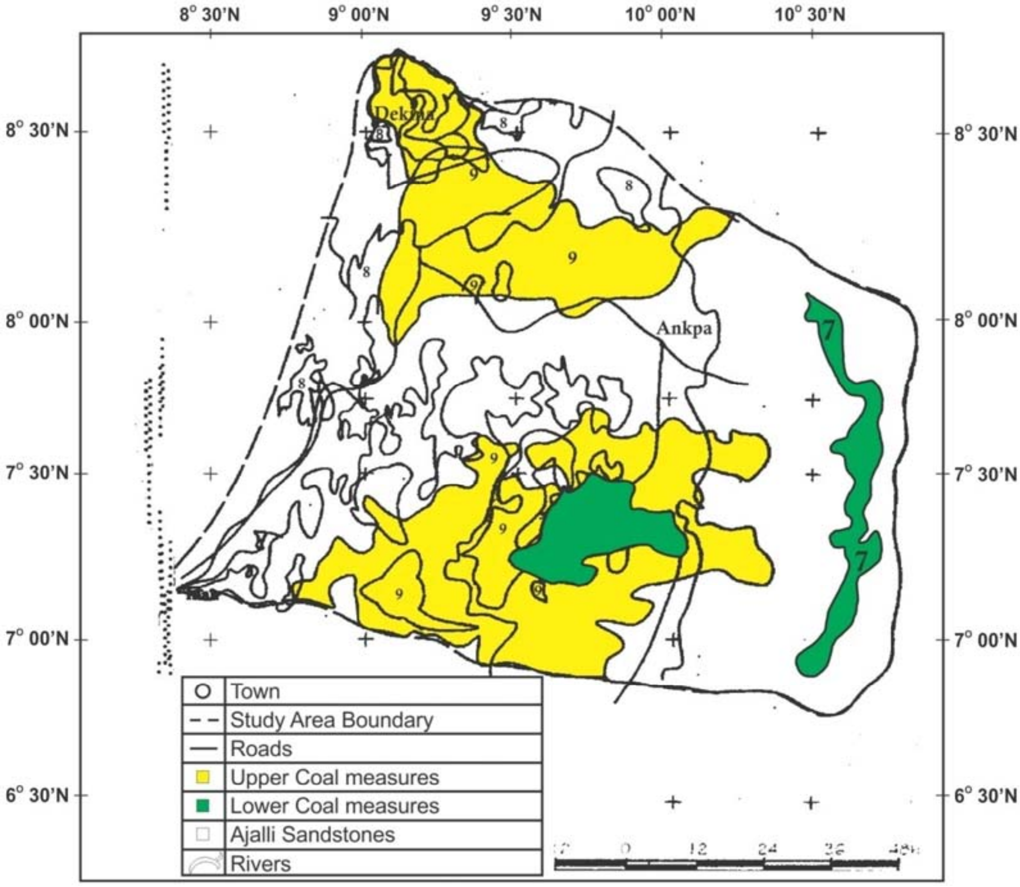


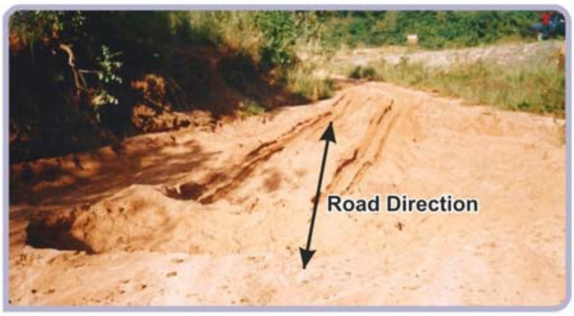
Figure 2 Geological map of Ida–Ankpa Plateau (IAP)

Oparaku et al. (2015) estimated that the total number of gullies in occurrence on the UCM was 100; the AS, 740; and the LCM, one (Figure 3). Their study showed that the mean %sand + %silt on the UCM was 80%; AS, 95%; and LCM, 61%. Thus, the vulnerability to erosion (erodibility) of the three sediments can be ranked as AS>UCM>LCM.

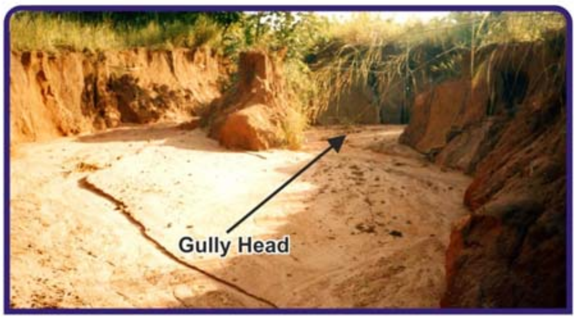
The three geological units control the hydrology of the area. The AS and the sandy units of the UCM form copious aquifers, whereas the argillaceous units of the

UCM and LCM form aquitards. The geomorphology of the area consists of the Ankpa Plateau and the Ankpa Piedmont which lies over sandstones, but differentiated in the deep valleys. The Anambra River, which empties into the River Niger, is the main drainage basin in the area. The soils are predominantly cretaceous sandstones. They are deep, well drained, and frequently red or reddish brown in colour with sandy surface horizons occurring on the interfluves and the upper and middle slopes. Subsistent agriculture is practised in the area.

(a) An Urban roadway undermined by soil erosion in Dekina



(b) An intercity roadway overtaken by eroded sediments between Otukpa and Orokam



(c) A portion of a landscape degraded by gully erosion at Ankpa

Figure 3 Some land devastations caused by soil erosion on the IAP

3 Materials and methods

Random samples of five percent of the estimated gullies in occurrence on the AS (740) and on the UCM (100) respectively were selected. These gave 37 gullies on the AS and 5 on the UCM. The thirty-seven gullies randomly selected on the AS were studied: 16 of which were treated, 14 inactive and 7 active; whereas all the gullies in occurrence (including the five studied) on the UCM were untreated. The dimensions of the sixteen treated gullies on the AS were obtained from the Lower Benue River Basin Development Authority (LBRBDA), Makurdi, while the dimensions of the untreated ones were measured directly in the field using the methods described by Iorkua (1999).

The gully length (L), average depth (D), and average width (W) were measured with a linen tape and ranging poles. The length for each gully was obtained by marking and measuring out 10-m interval points on the floor of the gully from the head to the mouth using the linen tape and ranging poles. The gully length (L_1 in metres) was obtained by multiplying the number of interval points by 10.

To measure the bed and shoulder widths, each of the 10-m interval points was marked with a ranging pole in succession, and at each point, the tape was stretched across the gully bed from one side (perpendicular) to the other. At this point, the bed width reading on the tape was recorded in metres. The same procedure at the same interval point was repeated at the shoulder with the tape tight-stretched across the gully to ensure that it did not sag at the middle. The shoulder width was also recorded in metres. These procedures were repeated for all the marked interval points along the floor and the average gully width (W) were obtained as follows:

$$\text{Average bed width, } W_b = \frac{\text{sum of bed width readings}}{\text{Number of interval points}} \quad (3)$$

$$\text{Average shoulder width, } W_s = \frac{\text{sum of shoulder width readings}}{\text{Number of interval points}} \quad (4)$$

$$\text{Average gully width, } W = \frac{W_b + W_s}{2} \quad (5)$$

To measure D, one of the poles was placed at the deepest part of the gully floor (at the same interval point where the bed and shoulder widths were measured) by a third person. The tape was placed at ground level and stretched across the gully channel over the ranging pole. The third person holding the ranging pole on the gully floor noted and recorded the reading of the ranging pole as it made contact with the linen tape. At points where the gully depth was more than 1.9 m, the ranging poles were tied together using 10-m ropes to increase their total vertically height. The elongated poles were then used to measure the depth using the above procedures. Thus, D was obtained by using Equation (6).

$$D = \frac{\text{sum of interval depths}}{\text{Number of interval}} \tag{6}$$

The gully dimensions actually measured in the field and collected from the LBRBDA were the L, D and W. Other variables computed from these parameters were the average volume (V), average cross-sectional area (A), and the average form factor (W/D). For these sets of variables (L, D, W, V, A and W/D), a total of six for each gully, the Pearson's correlation matrices were used to show the inter-correlations among the variables, the simple correlation analyses used to examine the relationships between L and D, and the sample bivariate regression employed to determine the predictability of D using L as a prediction tool on each of the formations.

4 Results and discussion

The descriptive statistics of the physical characteristics of the sampled gullies formed on the two formations are shown in Tables 1 and 2. In a previous discussion of these results, Oparaku et al. (2015) showed that the mean value of the W/D ratio was 1.46 on the AS and 0.91 on the UCM. A mean W/D value of 1.46 on the AS is an indication that gullies formed on these AS sediments are expanding more rapidly in width than in depth. This has adverse implications for urban and agricultural land development projects located, or to be located, on this formation. On the other hand, a mean W/D value of 0.91 on the UCM shows that the subsoil is more erodible and is deepening faster than the surface soil is attacked. The implication is that gullies formed on the UCM sediments pose a threat to ground water exploitation in the area.

Table 1 Summary of the variations of the physical characteristics of gullies formed on the Ajalli Sandstones (AS) formation

Statistics	Length L (m)	Average depth D (m)	Average width W (m)	Average volume V (m^3)	Average CSA A (m^2)	Average form factor W/D
Total	16,700.00	240.06	294.04	146×10^4	2,300.00	54.02
RG	45.20-1,500	1.05-16.30	2.20-30.00	1,277.92-540,000.00	3.26-360.00	0.75-6.25
$\bar{X}$	452.27	6.49	7.95	39,513.00	62.16	1.46
SD	322.12	3.47	5.53	31.416.29	24.09	1.20
CV	71.22	53.47	69.56	79.51	38.76	82.19

Note: $\bar{X}$ = Mean, RG = Range, SD = Standard Deviation, CV = Coefficient of Variation and CSA = Cross Sectional Area.

Table 2 Summary of the variations of the physical characteristics of gullies formed on the Upper Coal Measures' (UCM) formation

Statistics	Length L (m)	Average depth D (m)	Average width W (m)	Average volume V (m^3)	Average CSA A (m^2)	Average form factor W/D
Total	1808.32	29.82	31.17	27,900.00	324.84	4.55
RG	18.32-500.00	2.70-14.62	2.30-18.87	2173.50-10,000.00	6.21-275.88	0.71-1.30
$\bar{X}$	361.66	5.96	6.23	5,587.30	64.97	0.91
SD	200.52	4.91	0.87	2974.10	53.05	0.23
CV	55.44	82.38	13.97	53.23	81.66	25.27

4.1 Correlation of gully length with the average gully depth

A correlation of the interrelations of the measured and computed six gully variables of L, D, W, V, A, and W/D on the two sediments are shown in Tables 3 and 4. On the AS (Table 3), out of 30 correlation coefficients, 18 were significantly correlated (4 at the 0.05 level and 14 at the 0.01 level), representing 60% of the total (13.33% and 46.67%, respectively). About 66.67% of the variables were significantly correlated on the UCM (Table 4). These results agree with those of Ebisemiju (1989), Udosen (1991), and Iorkua (1999), who reported 60.00%, 60.70%, and 42.90%, respectively of significant correlations in their related gully erosion studies.

The results of the correlation analyses further show that on the AS (Table 3), L is not correlated with the D at any level ($R = 0.004$; $R^2 = 0.00$). This indicates that an increase in L does not result in any increase or decrease in D. And an R^2 of 0.00 shows that no percentage increases or decrease in D is accounted for by an increase in L on the AS.

On the more resistant UCM (Table 4), L is negatively, strongly, and significantly correlated with D at the 0.05 level ($R = -0.899$; $R^2 = 0.808$). An R-value of –0.899 indicates that the negative relationship is nearly a perfect, linear one, and an R^2 value of 0.808 shows that an increase in L explains 80.82% of the decrease in D. The study therefore, suggests that the linearity of the negative correlation between gully length and average gully depth becomes more pronounced as the resistance to erosion of the soil formation on which a gully is cut increases.

Table 3 Correlation of the variables of the gullies formed on the Ajalli Sandstones' formation

	Length, L (m)	Average depth, D (m)	Average width, W (m)	Average volume, V (m^3)	Average CSA, A (m^2)	Form factor W/D
Length, L	1					
Average Depth, D	0.004	1				
Average Width, W	0.201	0.565**	1			
Average Volume, V	0.503*	0.447**	0.849**	1		
Average CSA, A	0.243	0.780**	0.913**	0.870**	1	
Form Factor, W/D	–0.076	0.380*	0.346	0.130	0.021	1

Note: ** Correlation is significant at the 0.01 level (2 – tailed); * Correlation is significant at the 0.05 level (2 – tailed); CSA = Cross Sectional Area.
Source: Statistical computer analysis by the author

Table 4 Correlation of the variables of the gullies formed on the Upper Coal Measures' formation

	Length, L (m)	Average depth, D (m)	Average width, W (m)	Average volume, V (m^3)	Average CSA, A (m^2)	Form factor W/D
Length, L	1					
Average Depth, D	–8.899*	1				
Average Width, W	–0.930*	0.997**	1			
Average Volume, V	0.341	0.069	–0.003	1		
Average CSA, A	–0.946*	0.992*	0.998**	–0.056	1	
Form Factor, W/D	–0.940*	0.938*	0.958*	–0.089	0.957*	1

Note: ** Correlation is significant at the 0.01 level (2 – tailed); *Correlation is significant at the 0.05 level (2 – tailed).

The situation of no correlation existing between the gully length and the average gully depth on the highly erodible AS is a puzzling one considering that the general notion is that when a gully increases in length, the depth at any cross section also increases. The explanation for this unexpected outcome could be that an increase in length of a gully does not result in an increase in the rate of runoff causing it at the head. As a highly erodible gully head (such as on the AS) advances rapidly and progressively into the catchment area, its rate of advance is slowed down because the volume of runoff eroding that head is reduced as a result of a decreasing catchment area supplying the runoff to it. However, at any cross section, the volume of runoff remains constant for any amount of rainfall event because the catchment area supplying runoff at every cross section is constant, i.e. it neither increases nor decreases to cause a change in the configuration of the cross section of the gully; so that the retreat or increase in length of a gully from a gully crosses section on an erodible formation does not have any effect on the gully depth.

In the case of the more resistant UCM, a gully formed on it can be likened to a lined channel in which, for the reason of the bed being resistant to the wearing action of running water, the floor allows more net deposition of sediments from the retreating gully head and sides upstream on, than erosion of the bed (which translates to a negative increase in the average gully depth). Hence, the correlation of the gully length and the average depth is negative but significant.

In a study in Israel, Seginer (1966) reported a significant, positive correlation between gully length and depth. His report, which did not specify the degree of vulnerability to erosion of the sediments on which he worked, disagrees with the findings in this study which shows that gully length is negatively correlated with the average gully depth on the UCM.

The correlation analyses, therefore, show that gully length has no correlation with the average gully depth on the highly erodible AS (R=0.004; R^2=0.00), whereas the correlation is strong, negative, and significant on the UCM (R=–0.899; R^2=0.8082; P<0.05). This suggests that the negative correlation of the gully length with the average gully depth becomes stronger as the resistance of a soil formation to erosion increases.

4.2 Sample bivariate regression of the gully length with the average gully depth

On the erodible AS, the average gully depth is related to the length by Equation (7).

$$D_1 = 6.469+0.00L_1 \quad (7)\#$$

$$(R=0.004, R^2=0.00)$$

where, D_1 = Average gully depth (AS) (Dependent variable); L_1=Gully length (AS) (Independent variable).

The correlation was tested and found not significant (Table 3), and the representation is shown in Figure 4.

The relationship on the more resistant UCM is given as Equation (8)

$$D_2=13.929-0.022L_2 \quad (8)\#$$

$$(R=-0.899; R^2=0.8082)$$

where, D_2 = Average gully depth (UCM) (Dependent variable); L_2 = Gully Length (UCM) (Independent variable).

The correlation of the relationship (shown in Figure 5) was tested at the 0.05 level and found significant (Table 4).

An R^2 value of 0.00 shows that gully length has no relationship with the average gully depth on the AS. This is confirmed by the regression coefficient (RC) of 0.00 in the regression equation: D_1 = 6.469 + 0.00L_1, which indicates that a unit increase in L, does not result in any increase or decrease in D. Therefore, L is not a predictor of D on the AS. The intercept on the D_1 axis (6.469 m) (Figure 4) could represent the maximum average depth attainable by gullies on the AS.

On the UCM, the regression equation is given by D_2 = 13.929–0.022L_2. With a negative RC (slope of the regression line) of –0.022, the indication is that when L increases by one metre, D decreases by a value of 0.022 m. And from the regression equation, the boundary conditions are that a D value = 0.00 gives an L value of 633.14 m, and an L value = 0.00 gives a D value = 13.929 m. Therefore, the valid range of L values for the prediction of D on the UCM can be ranked as $0=L< 633.14$ m.

This study, therefore, suggests that the coefficient of regression of the relationship between gully length and average gully depth is negative for erosion resistant formations, and the value increases and tends to a perfect, linear, and negative relationship (R=–1) with increasing resistance to erosion of the formation. Thus, the predictability of the average gully depth using the gully length as a prediction tool improves with increasing resistance to soil erosion of the geological sediments on which a gully is developed. In addition, the study suggests that imperceptible aggradative, rather than degradative, processes take place on the floor of gullies formed on erosion resistant materials. However, the relationship between gully length and average gully depth could also be influenced by the vertical homogeneity of the sediments on which the gully develops.

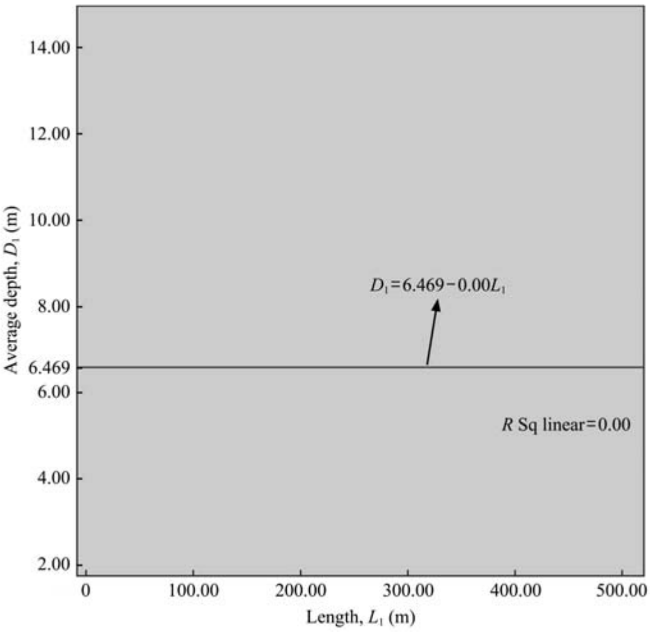


Figure 4 Linear regression between the gully length and the average gully depth, Ajalli Sandstones

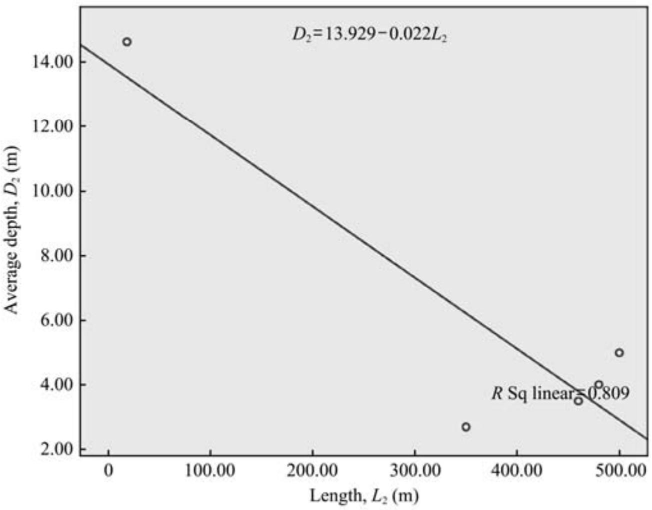


Figure 5 Linear regression between gully length and the average gully depth, Upper Coal Measures

5 Conclusions

The following conclusions can be drawn from this study:

1. On the highly erodible AS, gully length does not correlated with the average gully depth at any level (R=

0.004, $R^2 = 0.00$).

2. On the more resistant UCM, the correlation analyses show that gully length is strongly, negatively, and significantly correlated with the average gully depth ($R = -0.899$; $R^2 = 0.8082$; $P < 0.05$).

3. The correlation analyses suggest that the linearity of the negative relationship between gully length and the average gully depth becomes more pronounced as the resistance to erosion of the geologic formation on which a gully develops increases.

4. On the AS, the sample bivariate regression equation of the gully length on the average gully depth is of the form $D_1 = 6.469 + 0.00L_1$.

5. The regression equation shows that gully length is not a predictive tool for the average gully depth on the AS formation.

6. On the more resistant UCM, the regression equation is given as $D_2 = 13.929 - 0.022L_2$.

7. The equation on the UCM indicates that gully length is a useful parameter for the prediction of the average gully depth.

8. Rather than degradation, imperceptible aggradative processes are taking place on the beds of gullies formed on the UCM formation.

9. The regression analyses suggest that the coefficient of regression increases and verges to a minus unity (–1) as the resistance to erosion of a geological formation increases. This in turn improves the reliability of the average gully depth estimated using the gully length as a prediction tool.

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