Relative Vulnerability to Gully Erosion of Three Geological Sediments: A Texture-Based Assessment.

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Abstract
This study was carried out to evaluate the particle size distributions and erodibility indices at two soil depth ranges, 0 – 60 cm and 60 – 90 cm, of the three geological sediments underlying 100% of the landscape of the Idah-Ankpa Plateau of the Anambra Basin, Nigeria. The aim was to explain why the three geological sediments, namely, the Upper Coal Measures (UCM, 36%), the Ajalli Sandstones (AS, 44%) and the Lower Coal Measures (LCM, 20%) are exposed to varying degrees of vulnerability to gully (soil) erosion. The depth range 0 – 60 cm was considered the topsoil most prone to rill erosion, the range 60 – 90 cm (and above) was the subsoil, the normal depth of a formed gully. The particle size distributions were determined by the hydrometer method plus NAOH for dispersion, and the erodibility indices were computed in decimal units using the clay ratio method. Data were analyzed using descriptive statistics. In the top and subsoils, the LCM was observed to have the highest mean clay contents (39% and 41% respectively). This was followed by the UCM (20% and 36%), while the As had the least (5% and 18%). Nevertheless, the mean erodibility indices of the AS in both the top- and sub-soils were respectively the highest (0.244 and 0.084), followed by the UCM (0.041 and 0.022), whereas the LCM was the least (0.016 and 0.016). The results show that the AS is the most erodible both in the top and subsoils, followed by the UCM. The LCM is the least. The relative vulnerability to soil (gully) erosion of the three sediments can, therefore, be ranked as AS>UCM>LCM. The ranking agrees with the observed order of proliferation of gullies on the IAP. Expenditure on gully erosion control on the IAP should be concentrated on the areas covered by the underlying sediments in the descending order of their vulnerability to gully formation: AS > UCM > LCM.
Keywords: Vulnerability, Rill Formation, Gully Formation, Soil Erodibility.

1. Introduction

Soil Erodibility is an intrinsic property of the soil which can be assessed as a measure of a soil's vulnerability to erosion. Lal (1990) stated that when two or more soils located in the same ecological region are brought under the same management practices, they suffer different amounts of erosion which are attributable to their inherent erodibility. Morgan (2005) identified the different factors that influence erodibility to include texture, structure, aggregate stability, shear strength, permeability, infiltration capacity, organic matter and other chemical properties of the soil. However, soil texture is widely considered the most important factor influencing the vulnerability of soils to erosion (Morgan, 2015; Singl & Khera, 2008; Michael & Ojha, 2013)

Soil texture affects Erodibility in the sense that the larger particles are easier to detach but more difficult to transport, whereas the smaller particles are more difficult to detach because of cohesive forces, but easier to transport when detached. Wischmeir & Mannering (1969) reported that soils that are high in silt, low in clay, and low in organic matter are the most erodible. Bouyoucos (1935), cited by Morgan (2005), emphasized the influence of sand particles on erodibility when he stated that the % sand plus % silt in a soil sample is a direct function of its erodibility. O'Green et al. (2006) confirmed this assertion, stating that soils high in sand and silt are highly erodible. Evans (1980), on the other hand, showed strong interest in the use of clay content in the assessment of soil erodibility, stating that soils with restricted clay contents less than 30% are erodible. This shows that the higher the sand plus silt fraction of a soil, the more is its erodibility (vulnerability to erosion). Conversely, the more the clay content, the less it is exposed to erosion. The influence of texture on soil erodibility is quantitatively expressed by the clay ratio (Bouyoucos, 1935) formula given by % sand + % silt / clay.

Oparaku (2015) reported that the three geological sediments underlying 100% of the landscape of the Idah-Ankpa Plateau (IAP) of the Anambra Basin, Nigeria, exhibit varying degrees of disproportionate vulnerability to gully erosion. These geological sediments are the Upper Coal Measures (UCM) (36%), the Ajalli Sandstones (AS) (44%) and the Lower Coal Measures (LCM) (20%). He estimated that about 100 gullies were in occurrence on the UCM, 740 on the AS, and only one on the LCM.

However, soil erosion studies on the IAP have been few and these have been very much confined to the AS. Onuoha and Uma (1988) and Hudec et al. (1998) noted that most gully erosion sites in the southeastern states of Nigeria were located on either the Nanka sands or the Ajalli Sandstones. They observed that these two geological formations bear striking similarities from the gully erosion point of view. Hudec et al. (2006) reported that gully erosion processes are localize on the fine-to-medium grained AS sediments of the Anambra Basin region. The geological causes of the proliferation of gullies at Ankpa, a growing semi-urban town situated on the AS was the subject of investigation by Schneidegger and Ajakaiye (1994). After a numerical study and statistical analysis of the orientation of the gullies and surface cracks, they compared the pattern of the gullies with joint orientation measurements and came to the conclusion that the gullies resulted from neotectonic forces since the joints were found in recent laterites. These geological processes were also reported by Egboka et al. (1990) as the principal causes of gullies in the southeastern states of Nigeria.

However, studies and data on the intrinsic characteristics of each unit of the geological sediments on the IAP are lacking. Availability of these data are required to explain the relative vulnerability of these sediments to gully (soil) erosion. This study was, therefore, undertaken in an attempt to fill this gap. The study examined the particle size distributions (texture) and the erodibility indices (computed using the clay ratio method) as factors influencing the disproportionate differentials in the proliferation of the gully form of soil erosion on the IAP. These factors were examined both in the topsoil and in the subsoil.

1.1 The study area

The Idah-Ankpa Plateau (IAP) of the Anambra Basin of Nigeria comprises the Western Ankpa Plateau and the Idah Flood Plains. It has been so named because the latter consists of an insignificant percentage of the whole area (ECAN, 1982). Nestled in the Guinea Savanna ecological zone of Nigeria, it lies between Latitudes 7° 17' 00''N and 7° 23' 30''N and Longitudes 8° 20' 20''E and 9° 00' 00''E. Parts of Kogi and Benue States are the only land areas encompassed by the IAP. The underlying geology consists of cretaceous sediments made up of the UCM, the AS and the LCM (Figure 1). Preez & Barber (1965) reported that the geological succession of these sediment are of the form: UCM – AS – LCM<, ie, the UCM is the overlying formation, the LCM the underlying formation with the AS sandwitched in between the two (Figure 2). The AS is exposed to erosive processes of the elements at locations where the UCM, which provides a protective overburden, has been denuded away by natural geological processes. And where both the UCM and the AS have been eroded away, the LCM becomes exposed (Preez & Barber, 1965). A full description of other environmental aspects of the study area is detailed in Oparaku et al. (2015).

2. Materials and Methods

Soil sampling units were selected based on the three geological formations in the area (the UCM, the AS, and the LCM). These units were chosen because Hudec et al. (1998) had noted that the textural uniformity of each is unique. For the determination of the particle size distributions of the sediments, gully sites were randomly selected and a pair of soil samples collected only from one side of a selected site in the depth ranges of 0 – 60 cm (topsoil) and 60 – 90 cm (subsoil). At sites where gullies were nonexistent, sampling pits were dug up to a depth of 90 cm and soil samples collect from the aforementioned depth ranges. The 60 to 90 cm range was chosen as representing the depth range of a normal gully since Brice (1966) stated that any earth channel with a depth greater than 60cm, conveying ephemeral flows, can be considered a gully. The depth ranges from 0 to 60 cm was, therefore, taken as the depth within which rill erosion occurs, whereas the depth ranges from 60 cm and above are those for gully formation.

A total of 34 pairs of samples were collected from gully sides and sampling pits; 14 from the UCM, 15 from the AS and 5 from the LCM. The particle size distributions were determined by the hydrometer method using calgon plus NAOH for dispersion. The erodibility indices (K) were computed in decimal digits using the clay ratio method (Bouyoucos, 1932) given by the equation:

$$K = \frac{\%\,\text{Sand} + \%\,\text{Silt}}{\%\,\text{Clay x}\,100}$$

The particle size distributions and the computed erodibility indices were analysed using descriptive statistics.

3. Results and Discussion

3.1. Particle-Size Distributions in the Topsoil (0 – 60 cm)

The descriptive statistics of the particle size distributions of the three geological sediments in the topsoil (0- 60 cm) are shown in Table 1, while Figure 3 is the histogram of the mean proportion of their particle sizes. The mean proportion of sand in the UCM is high with a value of 56%. The respective values for the silt and clay fractions are 24% and 20%. The mean proportion of sand in the AS (80%) exceeds its value in the UCM (56%) by a wide margin. Tijan and Nton (2008), working on the hydraulic, textural, and geochemical characteristics of the Ajalli formation, reported that the mean value of the sand fraction was 89%, which is in agreement with the value determined in this study. The values of the mean % silt and % clay in the AS are respectively 15 and 5, which are less than their equivalent values in the UCM.

Table 1: Descriptive Statistics of the Particle Size Distributions of the Three Geological Sediments in the Topsoil (0 – 60 cm)

Soil parameter	Descriptive statistics	Upper Coal Measures (UCM)	Ajalli Sandstones (AS)	Lower Coal Measures (LCM)
% Sand	Range	43 – 68	49 - 96	12 – 52
	Mean	56	80	37
	SD	6.72	15.15	15.53
	CV (%)	11.91	19.52	42.68
% Silt	Range	15 – 40	2 – 48	8 – 57
	Mean	24	15	24
	SD	7.62	14.93	19.26
	CV (%)	31.10	96.55	80.26
% Clay	Range	16 – 27	2 – 9	31 – 46
	Mean	20	5	39
	SD	3.50	2.45	4.28
	CV (%)	18.18	49	11.08
Typical texture		SCL	LS	CL

SD = Standard Deviation, CV = Coefficient of variation, SCL = Sandy Clay Loam, LS = Loamy Sand, and CL = Clay Loam

With a % sand plus % silt (95) in the AS greater than their value (80%) in the UCM, and the % clay (5) less than its equivalent values also in the UCM (20), the indication is that the AS is more vulnerable to erosion than the UCM.

In the LCM, the mean proportion of % sand + % silt (61) is less than the sum of their values in the UCM (80). However, the clay fraction (39%) is relatively higher than its equivalent in the UCM (20%). So that the vulnerability of the sediments to erosion can be stated as LCM < UCM < AS in the topsoil.

3.2. Particle -Size Distributions in the Subsoil (60 – 90 cm)

The descriptive statistics of the particles size distributions of the UCM, AS, and LCM in the subsoil (60 – 90 cm) depth are shown in Table 2, and figure 4 is the histogram of the mean proportions of the particle sizes. In the UCM, the mean proportion of sand drops slightly from a value of 56% in the topsoil to 50% in the subsoil. The mean % silt also decreases from 24 in the topsoil to 14 in the subsoil, whereas the % clay increases from 20 in the topsoil to 36 in the subsoil (see Table 1 also). In the AS, there is a substantial decrease in the value of the mean % sand from 80 in the topsoil to 67 in the subsoil, while the % silt remains constant at a value of 15 in both depths. Nevertheless, the mean % clay in the AS increases from a value of 5% in the topsoil to 18% in the subsoil.

Table 2: Descriptive statistics of the Particle Size Distributions of the Three Geological Sediments in the Subsoil (60- 90 cm).

Soil parameter	Descriptive statistics	Upper Coal Measures (UCM)	Ajalli Sandstones (AS)	Lower Coal Measures (LCM)
% Sand	Range	27 – 84	34 – 92	14 – 51
	Mean	50	67	32
	SD	18.42	14.91	15.87
	CV (%)	36.69	22.41	46.39
% Silt	Range	2 – 22	1 – 55	12 – 45
	Mean	14	15	27
	SD	6.38	15.32	13.36
	CV (%)	47.27	98.60	52.17
% Clay	Range	14 – 54	4 – 30	34 – 51
	Mean	36	18	41
	SD	13.52	9.06	7.05
	CV (%)	37.23	48.36	16.07
Typical texture		SC	SL	C

SD = Standard Deviation, CV = Coefficient of variation, SC = Sandy Clay, SL = Sandy Loamy, and C = Clay

Clearly, the total mean % sand plus % silt (67 + 15 = 82) in the subsoil of the AS is greater than the equivalent value (64) in the UCM, and the % clay (5) in the subsoil of the AS is less than the % clay (20) in the UCM. The confirmation, therefore, is that the AS is more erodible than the UCM even in the subsoil. In addition, an increase in clay content in the subsoil of the AS gives rise to perched watertable conditions. A perched water table causes the lubrication of the subsoil, leading to the collapse of gully walls and head and the rapid growth of gullies in size. These processes are less pronounced in the UCM than the AS. Hence, the subsoil of the AS is again more vulnerable to erosion than that of the UCM.

In the LCM, the mean % sand + mean % silt (37 + 24 = 61) in the topsoil is slightly greater than the sum of their values in the subsoil (32 + 27= 59), whereas the % clay in the topsoil (39) is also slightly less than its value in the subsoil (41). This shows that, texturally, the LCM is a homogenous, erosion resistant clay formation up to the subsoil.

Comparing the sizes of the particles in the subsoil of the LCM with their equivalent values in the UCM, the mean % sand plus % silt (59) in the LCM is significantly less than the sum of their values in the UCM (74). However, the mean % clay in the LCM (41) is equally significantly greater than its value in the UCM (36). The data, therefore, again show that the sediments of the LCM in the subsoil are more resistant and therefore less vulnerable to erosion than those of the UCM in the subsoil. The problems posed by perched–water table conditions can be considered insignificant since infiltration and percolation in these two formations (UCM and LCM) are restricted because of their high and nearly uniform clay contents in both the top- and sub-soils.

A comparison of the particle size distributions of the three geological sediments in both the top- and sub-soils shows that the AS is more erodible than the UCM, and the UCM is more erodible than the LCM. The vulnerability to erosion of these sediments on the IAP can, therefore, be ranked as AS > UCM > LCM. An assessment of the erodibility indices of these sediments will give a clear picture of their vulnerability to gully erosion.

3.3. Assessment of Erodibiity Indices (K)

The descriptive statistics of the erodibility indices (K – values) of the three geological sediments are shown in Table 3. The K-values in the top soils have been categorized as the surface erodibility indices, while those in the sub soils are the profile erodibility indices.

3.3.1. The Ajalli Sandstones (AS)

The topsoil K-values of the AS range form 0.090 to 0.490 with a mean of 0.244. With an SD of 0.149 and a CV of 61.15%, the variability of the K over the topsoil is considered high. The high mean surface K value of the AS is attributable to its high mean value of the % sand plus % silt (95) and the low mean % clay (5) contents.

The corresponding profile K-values of the AS range form 0.023 to 0.280 with a low mean value of 0.084. A standard deviation of 0.076 and a CV of 90.46% indicate an extremely high variability of the K-values in the subsoil. Notably, the mean K-value drop drastically from 0.224 in the topsoil to 0.084 in the subsoil, which is attributable to the effect of eluviation processes taking place in the topsoil. This implies that the subsoil of the AS is more resistant to erosion than the topsoil. Thus any soil-incising surface flow in this formation will encounter more resistance in the subsoil than in the topsoil as it attempts to expand in width and depth.

3.3.2. The Upper Coal Measures (UCM)

On the UCM (Table 3), the K-values range from 0.030 to 0.056 in the topsoil, with a mean of 0.041. Its variability is low (CV = 24.39%). This suggests that the constituent materials of the UCM are fairly homogenous in the topsoil. However, in the subsoil, the K-values range from 0.010 to 0.061, with a mean that decreases to 0.022 from the topsoil value (0.041). Surprisingly, the variability increases sharply to 68.80, which, nevertheless, leads to the deduction that the subsoil is composed of non-uniform, erosion – resistant materials.

An examination of Table 3 shows that the mean K-value in the subsoil of the AS (0.084) is significantly greater than its equivalent value in the subsoil of the UCM (0.022). This indicates that the UCM is clearly more resistant to soil erosion than the AS.

Significantly, the drastic increase in the variability of the K-values from 24.39% in the topsoil to 68.18% in the subsoil coupled with a slight decrease in the mean K-value from 0.041 in the topsoil to 0.022 in the profile could suggest that at some locations on the UCM, denudative process have so gnawed away at this formation that only a thin layer of it overly the more erodible AS. So that, at these locations, what has been indicated as the subsoil of the UCM could as well be the topsoil of the AS unaffected by eluviation processes. This assertion agrees with the finding by Oparaku (2015) who reported that the side walls of gullies formed on the UCM cut across soil profiles of seemingly varying resistance to erosion.

3.3.3 The Lower Coal Measures (LCM)

The range of values of the erodibility index (K) in the topsoil of the LCM varies from 0.012 to 0.022. The CV is low at a value of 18.75%, with a mean value of 0.016 (Table 3). The low mean K-value evidences high predominance of binding clay fractions and a low presence of sand and silt. In the subsoil, the K-values are equally low with a range varying from 0.010 to 0.019 and a mean of 0.016. With a CV of 18.75%, the variability is remarkably low.

Table 3: Comparison of the Erodibility Indices of the Three Geological Formations on the Idah-Ankpa Plateau.

Geological Formation	Depth (cm)	Categorization of erodibility index, K.	Statistic	Erodibility index, K-value
	d_1	Surface	Range	0.090 – 0.0490
			Mean	0.244
			SD	0.149
			CV (%)	61.15
Ajalli Sandstones	d_2	Profile	Range	0.023 – 0.280
			Mean	0.084
			SD	0.076
			CV (%)	90.46
	d_1	Surface	Range	0.030 – 0.056
			Mean	0.041
			SD	0.010
			CV (%)	24.39
Upper Coal Measures	d_2	Profile	Range	0.010 – 0.061
			Mean	0.022
			SD	0.015
			CV (%)	68.18
	d_1	Surface	Range	0.012 – 0.022
			Mean	0.016
			SD	0.003
			CV (%)	18.75
Lower Coal Measures	d_2	Profile	Range	0.010 – 0.019
			Mean	0.016
			SD	0.003
			CV (%)	18.75

d_1 = depths from 0 – 60cm
d_2 = depths from 60 – 90cm

Some significant features of the LCM are that the mean of the K-values on the topsoil is equal to that of the subsoil (0.016), and that the SD and CV in the topsoil are equal to their corresponding values in the subsoil (0.003 and 18.75% respectively). The indication here is that the LCM is homogenous, compact clay of very high resistance to erosion up to the subsoil. This explains the absence of any trace of active or dormant erosion processes on this formation.

Compared to the UCM with a mean K-values of 0.041 in the topsoil and 0.022 in the subsoil, the correspond values in the LCM are lower (0.016). This shows that the LCM is more resistant to soil erosion both in the topsoil and in the subsoil than the UCM. Therefore, the Vulnerability to erosion of the three geological sediments on the IAP is rankable as AS>UCM>LCM based also on the criteria of their erodibility indices.

3.3.4 Vulnerability to gully formation

To evaluate the Proneness of the sediments to gully formation, it is considered that Bouyoucos (1935) stated that all soils with erodibility indices (K) greater than 0.10 are erodible. From Table 4, therefore, only the mean K value of the AS at the 0-60 cm depth (0.244) is greater than 0.10, whereas those of the UCM and LCM (0.041 and 0.016 respectively) are less. In the subsoil (60 – 90 cm), the mean K Values of all the sediments are less than 0.10. These findings again show that, in the topsoil, only the AS is considered erodible, whereas the UCM and LCM are resistant to erosion.

Table 4: Mean Erodibility indices of the Three Geological Formations at the 0-60 and 60-90 cm Depth Ranges.

Soil depth (cm)	Ajalli Sandstones	Upper Coal Measures	Lower Coal Measures
0-60	0.244	0.041	0.016
60-90	0.084	0.022	0.016

And in the subsoil, the three formations can be said to be resistant to erosion. However, the mean erodibility index of the AS (0.084) approximates to 0.10 in this depth range (subsoil), showing clearly that the AS is appreciably an erodible formation up to the subsoil and is the most vulnerable to gully development.

In Table 4, the mean erodibility indices of the three sediments in the topsoil have the ranking stated as AS>UCM>LCM. In the subsoil, the ranking remains the same (AS>UCM>LCM). Therefore, the confirmation is that the relative vulnerability to gully (soil) erosion of the three geological sediments on the IAP can be ranked as AS>UCM>LCM. This finding (ranking) agrees with the order of proliferation of gullies on the three geological sediments underlying the landscape of the IAP.

The soil erodibility map of the IAP, illustrated in ranges of the K-values of the three geological formations both in their top- and subsoils, is shown in Figure 5. That a vast area of the IAP is underlain by the highly erodible

Ajalli sandstones (AS) is a cause for serious concern to the Federal Government of Nigeria and the affected states of Kogi and Benue on the score of the impacts of soil erosion on the landscape and urban and rural infrastructure.

4. Conclusions and Recommendations

This study leads to the following conclusions:

(1) The surface and profile soils of the AS consist of loose, erodible, sandy materials with a total % sand plus % silt = 95 in the surface and 82 in the profile.

(2) The AS is highly prone to gully formation with a mean erodibility index of 0.244 in the surface and a value that approximates to 0.10 in the profile.

(3) The growth and expansion of gullies formed on the AS is due to a combination of linear incision, surface infiltration, perching of ground water, and bank saturation. These processes explain the proliferation and size of gullies formed on the AS.

(4) The UCM and LCM have their mean K values less than 0.10 both in the surface and profile soils, and are therefore resistant to gully formation. However, the mean erodibility indices of the UCM in the two depth ranges are greater than their equivalents in the LCM. Hence, the UCM is more erodible than the LCM.

(5) With K values are constant at 0.016 in both the surface and profile soils of the LCM. This shows that the LCM consists of sediments that are uniformly resistant to soil erosion. This explains why no dormant or active erosion processes were manifest on this formation.

(6) Based on the criteria of soil texture and erodibility indices, the vulnerability to gully (soil) erosion of the three geological sediments underlying the IAP can be ranked as AS>UCM>LCM.

(7) The above ranking agrees with the order of proliferation of gullies on the plateau lands stated at the outset of this paper.

Governments' attention and expenditure on gully erosion control, population (human and animal) control, and land use planning on the IAP should be concentrated on the areas underlain by these geological sediments in their descending order of vulnerability to gully (soil) erosion, namely: AS>UCM>LCM.

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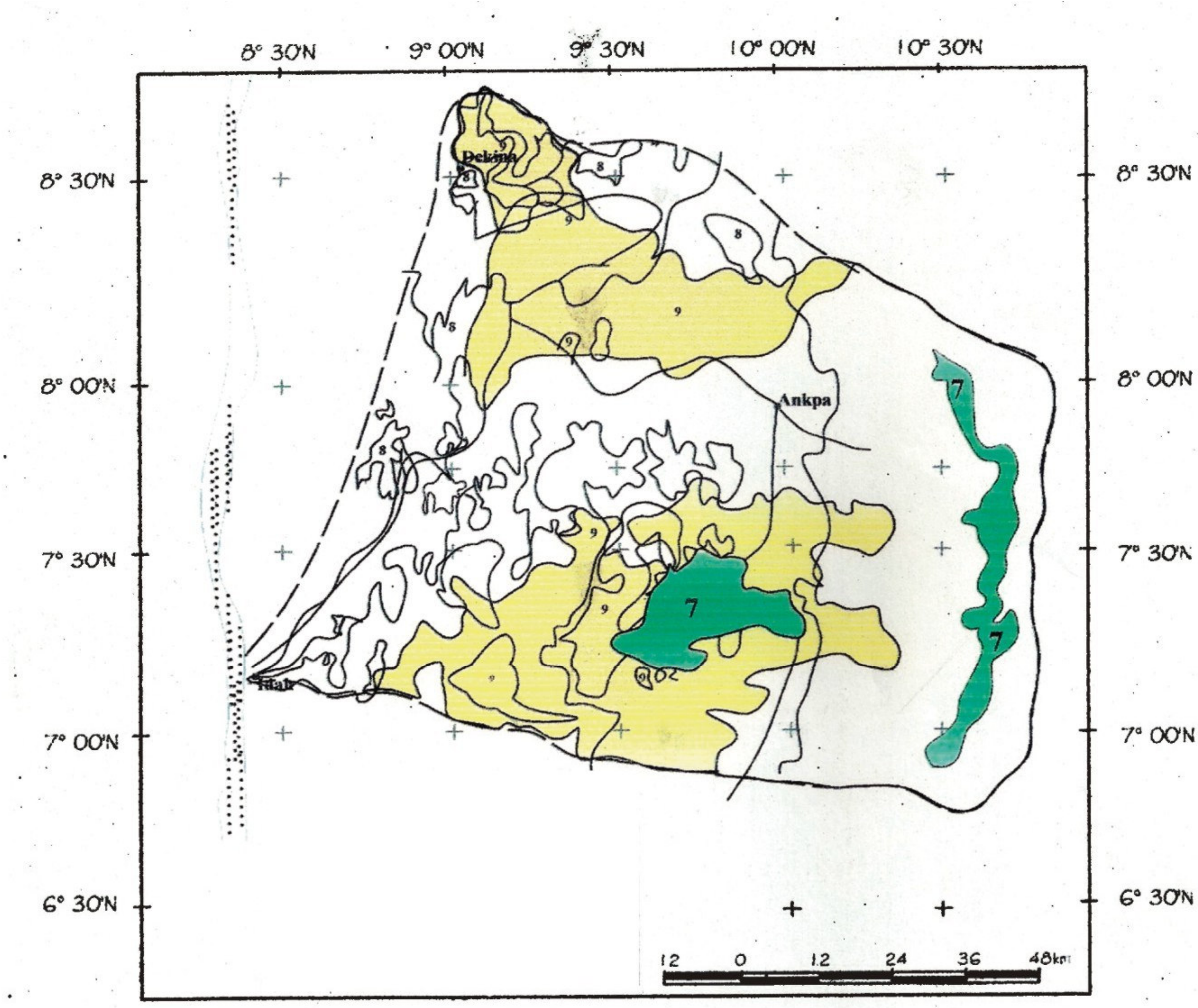

Figure 1: Geological Map of the Idah-Ankpa Plateau

◎	Town
– –	Study Area Boundary
—	Roads
	Upper Coal Measures
	Lower Coal Measures
	Ajalli sandstones
	Rivers

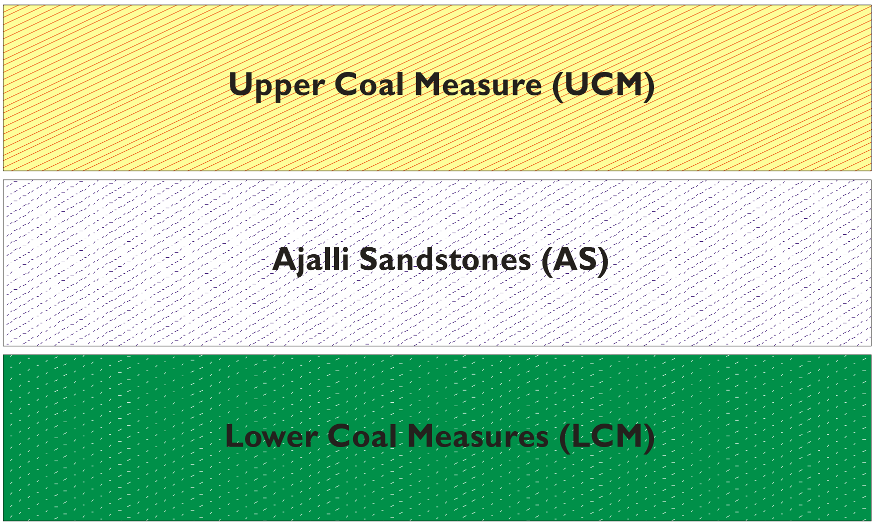

Figure 2: Geological Succession of the Three Sediments Underlying the Idah-Ankpa Plateau

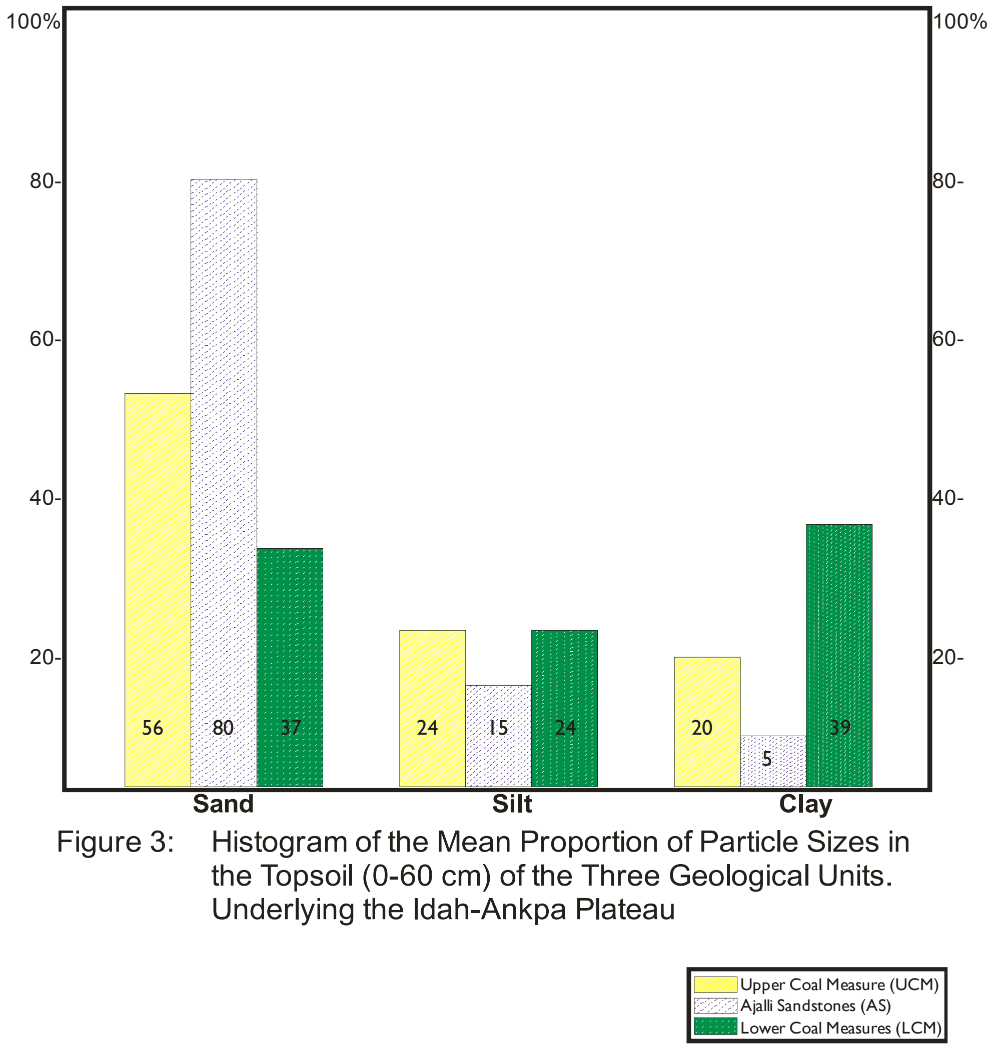

Figure 3: Histogram of the Mean Proportion of Particle Sizes in the Topsoil (0-60 cm) of the Three Geological Units. Underlying the Idah-Ankpa Plateau

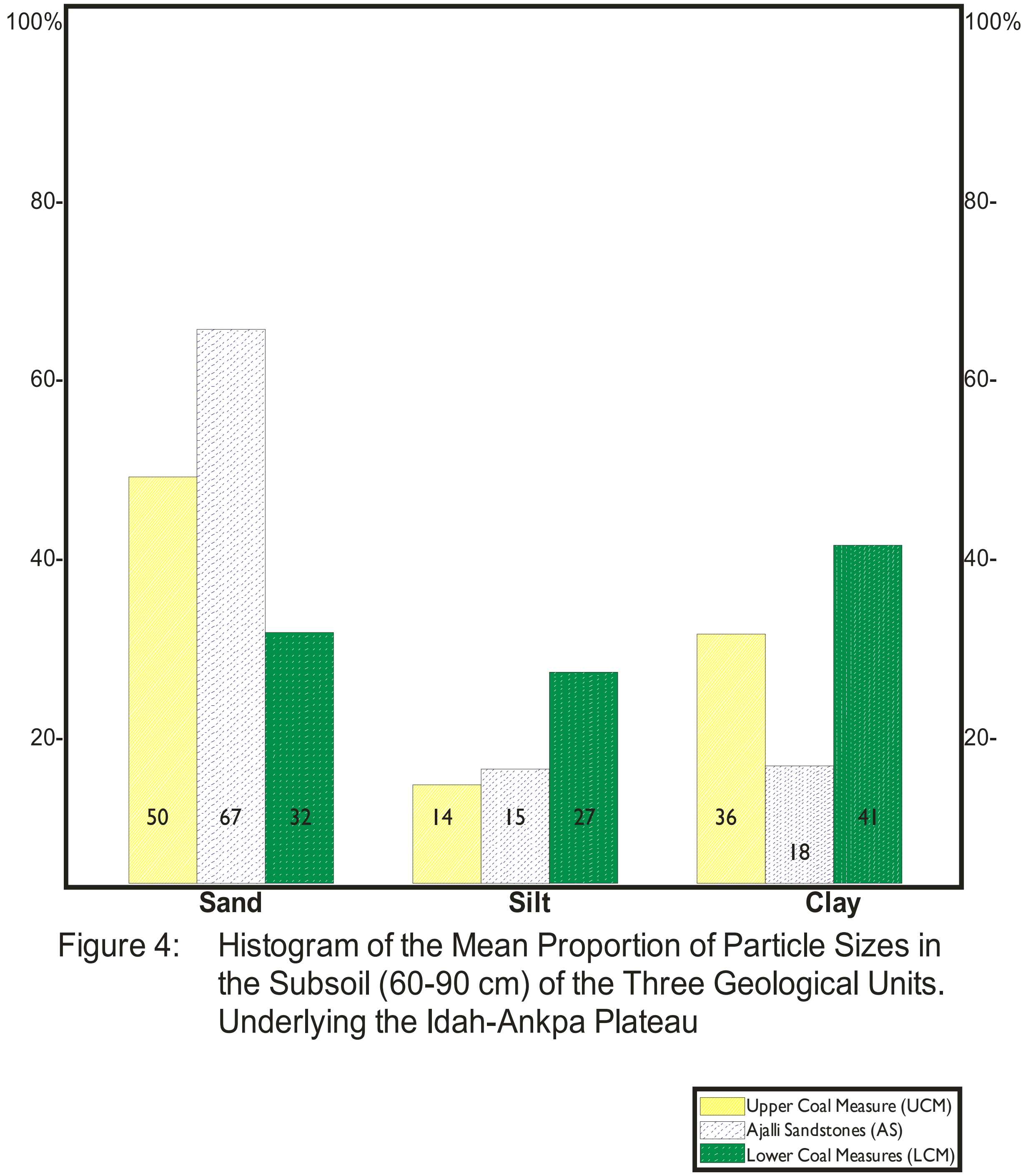

Figure 4: Histogram of the Mean Proportion of Particle Sizes in the Subsoil (60-90 cm) of the Three Geological Units. Underlying the Idah-Ankpa Plateau

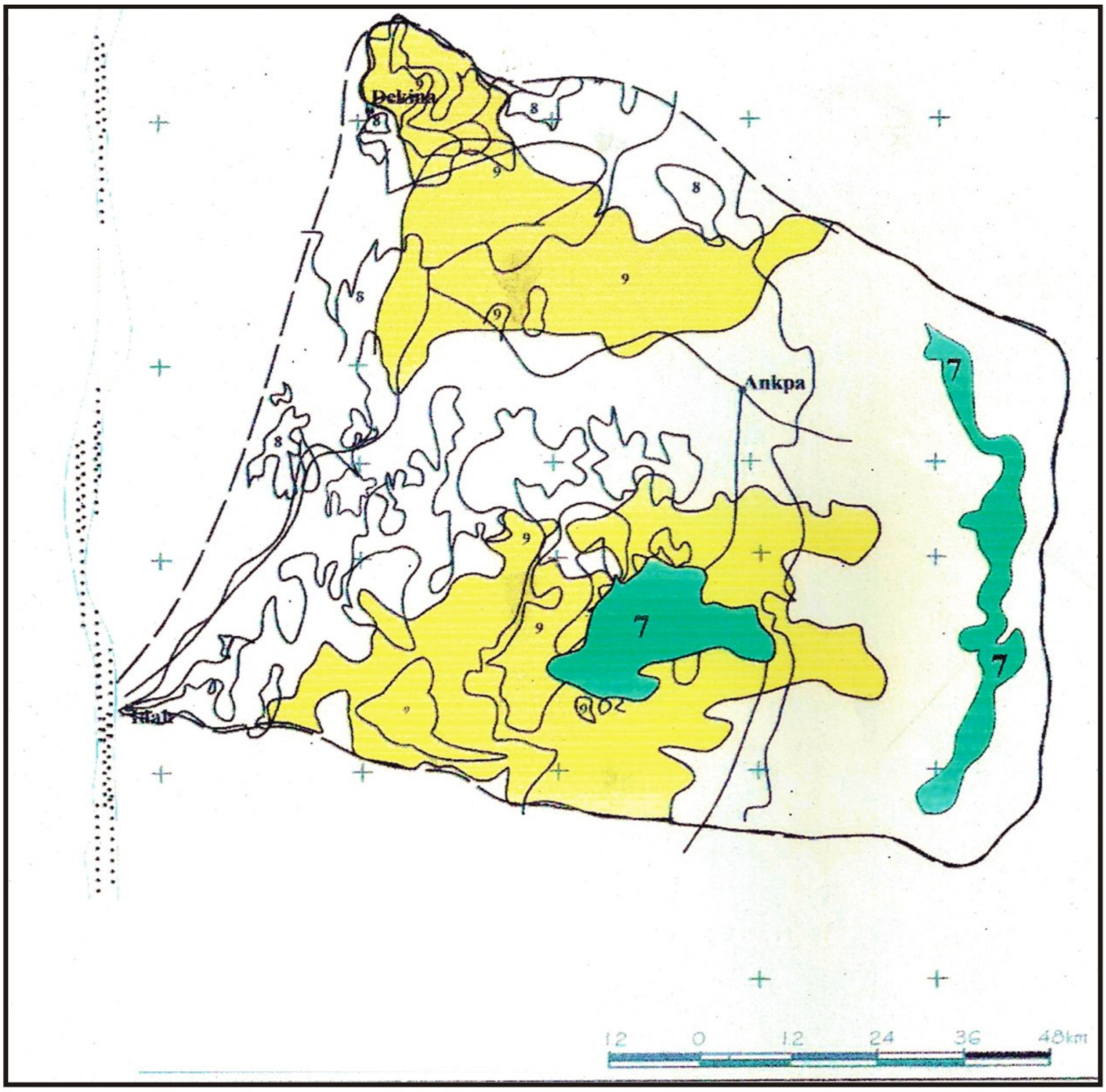

Figure 5: Erodibility Map of the Idah-Ankpa Plateau based on the Geological Sediments and in Ranges of K-Values

Ks - Surface erodibility index
Kp - Profile erodibility index

☐	Ajalli Sandstones:	0.090 < Ks < 0.490 0.023 < Kp < 0.280
(yellow)	Upper Coal Measures:	0.030 < Ks < 0.056 0.010 < Kp < 0.061
(green)	Lower Coal Measures:	0.012 < Ks < 0.022 0.010 < Kp < 0.019