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Gully erosion in southern Nigeria: an integrated geological and electrical resistivity study

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ABSTRACT

The study area lies in the rainforest belt of sourtheastern Nigeria, an area of about 15, 600Km^2, devastated by acute and chronic gully erosion. It is underlain by a sequence of Creaceous to Recent sedimentary rocks, which are dominantly shally, tending formations towards the top. The region is characterized by steep slopes, complex geological and tectonic settings and bordered to the east and west by uplifted Precambrian crystalline rocks of the basement. We investigated whether drainage density and coefficient of anisotropy do actually affect gully development. Drainage linears were analyzed statistically and expressed as drainage densities D_d, while azimuthal resistivity soundings were used to develop anisotropy figures from which the coefficients of anisotropy ( ) were determined. The drainage density and coefficient of anisotropy varies from 0.12 to 0.64 (km/km^2) and from 1.06 to 1.50, respectively. Each of these data set was grouped into three frequency classes and integrated with ground-based information to determine gully frequency in each class interval. Gully frequency was found to be maximum in high drainage density and coefficient of anisotropy classes, which suggested that areas of high surface flows and underlying structure were more susceptible to gully related activities. The results revealed a direct relationship between the occurrence of gully erosion and these terrain parameters. It thus followed that gully erosion in the belt is controlled by structures (joints and faults) and lithology. The Ajali sandstones and Nanka Sands suffer severe gully erosion while the other lithologic units suffer from slight to moderate gully erosion.

INTRODUCTION

Gully erosion is a visible form of soil erosion. It develops when surface runoff is concentrated in the form of channeled flow during rainfall. The flow pattern is actually anisotropic, governed by lithology, slope and structural characteristics of the underlying formation (Ebirim and Ebeniro, 2006). The runoff must flow at a velocity sufficient to detach and transport soil particles from their parent material, thereby creating deep gullies along their path. Gullies are relatively steep-sided water courses which experiences ephemeral flows during heavy or extended rainfall (Carey and Gray, 2001).

Gully erosion has caused severe damage and untold hardship to the government and inhabitants of the affected areas in Nigeria. It affects soil productivity, restricts land use and threatens roads, fences and buildings. The worst affected area in Nigeria is the rainforest belt of Southern Nigeria, enclosed by latitude 5^0 20' to 6^0 30'N and longitude 6^0 to 8^{0}00E. the belt lies on the southern flank of the Lower Benue trough sedimentary basin and comprises the states of Abia, Anambra, Ebonyi, Enugu and Imo (Fig. 1). Here, gully erosion has reached endemic proportions and both old and fresh gullies on farmlands, roads, and urban centers adorn much of the landscape.

The gullies are presumed to be surface expressions of deep-seated structures that developed as a result of the interplay of a variety of processes geological, geomorphologic, meteorological and anthropogenic factors.

The important terrain parameters which influences gully erosion is lithology, structure, drainage, slope and land use (Grabs, 1 Egboka and Okpoko, 1984).

A complete understanding of gully evolution requires the analysis of all these terrain factors leading to instability in the belt. The feature extraction of some of the factors can be done from the analysis of drainage density and coefficient of anisotropy. The feasibility of geological and geophysical methods to resolve details of gully erosion and related instabilities has been studied (Caris, and Van Asch,, 1991; and Sarkar, and Kanungo, 2003). The resolved that if appropriate geophysical interpretation routines are applied to acquired data (Seismic refraction, geoelectric and electromagnetism) are integrated with geological data such as lithology, structure, topography, permeability and porosity of the formations, details of gully erosion and landslides can be mapped. Drainage systems in the belt tend to flow in pre-determined trend directions and are unequally distributed. They are closely spaced in the earliest Cretaceous sediments of Abakaaaliki basin to the North east and Tertiary sediments of the Anambra basin to the Southwest. They are spaced far apart in the central and southeastern part of the Anambra basic and the adjacent Niger Delta (Fig. 2). The differences are primary related to the structural setting and arrangement of surface rocks, lithology, tectonics, permeability of the substratum and climatic settings.

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The spacing is also a reflection of the ruggedness of the water shades, which has a direct bearing on the topography of the area (Thompson and Turk, 1991). The measurement and analysis of drainage density provides a useful numerical measure of landscape dissection and run off potential which may likely give clues to the lithology, permeability and structural setting of the belt (Dudash et al, 2003).

The structural in homogeneity of the Benue trough sediments caused by lithological variations, bedding trends, dips, fractures and intrusive bodies cause the resistivity anisotropic when azimuthally impress D C electric current is injected into the subsurface (Ehirim and Ebeniro, 2006). The analysis of the resulting apparent resistivity variations with azimuth results in the development of anisotropy figures (AFs), from which the coefficient of anisotropy ( ) can be determined. The coefficient of anisotropy provides a useful numerical index for determining the structural texture and homogeneity of the subsurface formations.

The main purpose of this work therefore, is to determine whether drainage density and coefficient of anisotropy do actually affect gully evolution. The spatial information obtained from drainage density analysis and coefficient of anisotropy was integrated with ground based information to determine the influence of these parameters to gully development and propagation in the belt.

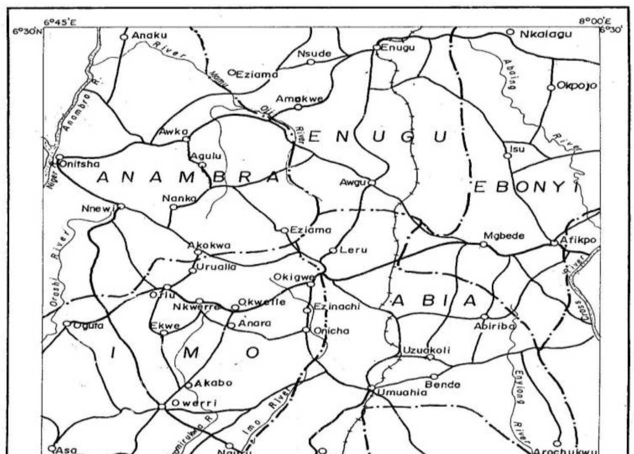

Fig.1. Rainforest belt of Southern Nigeria

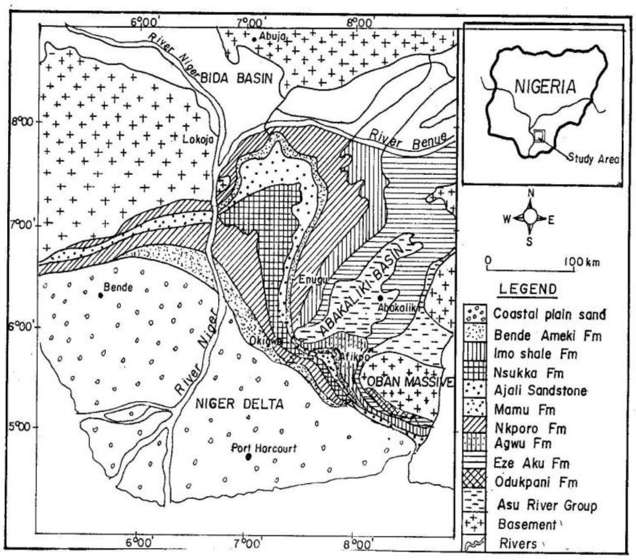

Fig.2. Anambra basin and the adjacent Niger Delta

GEOLOGY AND PHYSIOGRAPHY OF THE AREA

The rain forest belt of southeastern Nigeria is located in the geologically active area of the Lower Benue trough where crystal instabilities are endemic, with steep slopes, complex geological and tectonic setting and bordered to the east and west by uplifted rocks of the Precambrian crystalline basement. It is underlain by a thick sequence of Cretaceous to recent sedimentary rocks. The sequence of sedimentary rocks is subdivided into three main tectonic and depositional cycles which lasted throughout the formation of the trough and the adjacent Niger Delta (Short and Stauble, 1967; Murat, 1970, Burke and Whiteman, 1970). The stratigraphic units of the area range from the youngest as follows.

Era	Period	Formation
Cenozoic	Tertiary	→ Benin Formation (Coastal plain sand) → Bende Amaki Group → Imo Shale Group
Mesozoic	Cretaceous	→ Nsukka Formation (Upper coal measure → Ajali Sandstone (False bedded sandstone) → Mamu Formation (Lower coal measure) → Asata Nkporo Shale Group → Agwu Ndeaboh Shale Group → Eze-Aku Shale → Asu River Group

Fig 3. Stratigraphic units of the area (Adapted from Murat, 1970)

The formation types vary thin beds of sandstones alternating with thick beds which forms the weak substratum on which the latter lies. Intercalation of limestones, mud stones, coals and granitic associations are common features. The granitic rocks are mostly localized to the earliest sediments of the trough to the Northeast.

The most important characteristic of the Cretaceous sediments is that they are dominantly shally tending to sandy formations towards the top. The sandstone formations are generally friable and unconsolidated lacking cohesion due to loose bonding in the matrix and subsequently, are prone to instability-triggering mechanisms in the belt. The belt is dominated by conjugate strike-slip faults trending NE-SW and NW-SE in consistence with the trends of the Benue trough (Wright 1968, Benkhelil, 1987).

The geomorphology of the belt reflects the combined process of gully erosion and active landslides that development from continuous interaction of teconics and climate with the bedrock geology. The sanstones generally form positive features while shale's are less resistant to erosion, form negative topographic features. The belt is exposed to high precipitations during the year, with an annual average of 250cm. the rainy season extends from March to early November characterized by short duration high rainful intensity in most times within the year (Ayoade and Onibande, 1976).

DATA ACQUISITION AND ANALYSIS

Geological and geophysical methods were integrated with field observations in the present study to investigate the structural evolution of gully erosion in the belt. Emphasis was laid on electrical resistivity survey, drainage lineament analysis and surface observations to evaluate the frequency of gully development and determine its relationship with the various terrain parameters analyzed in this study.

Drainage Density

The drainage map of the study area (Fig. 4) was linearized by tracing out the linear segment of streams. The drainage pattern was traced out on acetate paper placed over the drainage map. The resulting map was further divided into grid cells of 10km x 10km sizes with a unit are of 100km^2. The drainage features were then quantitatively analyzed by measuring the lengths (km) of the stream segments in each grid cell using a scale. The measurements were performed by placing the acetate paper on a glass base with a wooden framework and a light source underneath. The light source provided adequate illumination which ensured that every segment of the stream section was observed and measured accurately. Stream segments that extended across grid cells were counted and measured separately for the individual cells.

The drainage density Dd (km/km^2) was then computed for each grid as follows (Dudash et al, 2003):

$$Dd = \frac{\sum L_i}{A} \qquad (1)$$

where = sum of lengths of drainage in the grid cell of unit area A.

Fig.4 The drainage map of the study area

Azimuthal Resistivity Survey

Azimuthal electrical resistivity surveys have been adopted by numerous workers (Taylor and Fleming, 1988; Skjernaa and Jorgenson, 1994; Busby, 2000), in the study of electrical anisotropy, particularly fracture anisotropy. Azimuthul electrical resistivity surveys were conducted in selected grids in the belt based on the results of the drainage density and field observations. Grid cells of high drainage densities formed the focus of our sounding points but a few cases of low drainage densities were also sounded. The mappings were conducted with a digital readout ABEM Terre meter (Signal Averaging System), model 300B. A Schlumberger electrode array with non-polarizable stainless steel electrodes was used. The array, with AB/2 distance ranging between 20 and 100m and MN/2 distance ranging between 5 and 20m, was rotated about a central point on the earth's surface and measurements were made at 45^0 increments (0, 45^0, 90^0, 135^0), to denote measurements in the N-S NE-SW, E-W and NW-SE directions. The variations in apparent resistivity with azimuth were noted and plots of anisotropy figures (AFs) were obtained from the analysis (Fig. 5).

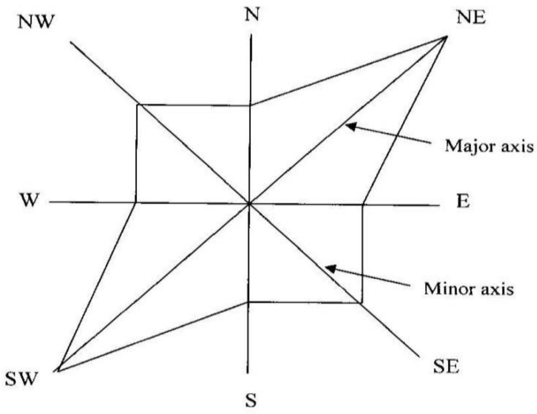

Fig. 5. Plane view of a typical anisotropy figure (AF)

The coefficient of anisotropy ( ) was computed for the grid cell using the expression (Habberjam, 1975)

$$\lambda = \sqrt{\frac{\rho_T}{\rho_L}} \quad (2)$$

where ρ_T = Transverse resistivity equivalent to the length of the major axis of AF

ρ_L = Longitudinal resistivity equivalent to the length of the minor axis of AF

Field Observation

The gully erosion sites within the belt were mapped based on surface observations in the field. The mapping was carried out using the relative values of drainage densities determined in each grid cell from the analysis of the drainage map. (Fig,4) of the belt. Areas with high and low drainage densities were delineated on the drainage map and subsequent detailed field survey was carried out by visiting these areas. The gully sites observed were recorded within the corresponding grid cell (Fig. 6). Ephemeral water courses and man made excavations were distinguished from the natural gully paths in the belt.

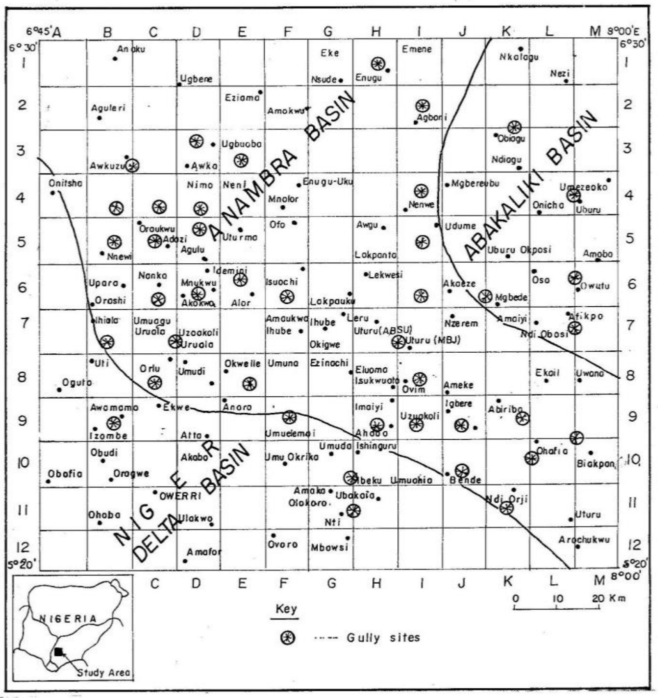

Fig. 6. Gully map of the study area

RESULTS

Results revealed that drainage density and coefficient of anisotropy varied from0.12 to 0.64 (km/km2) and 1.06 to 1.50, respectively, in the belt (Figures 7 and 8). High drainage density of $\geq$ 0.36 coefficient of anisotropy of $\geq$ 1.35 are concentrated mostly in the Abakaliki basin to the North East and the Anambra basin to the Southwest. The central part and Southeastern flank of the Anambra basin exhibits relatively low values of drainage density and anistropic coefficients of 0.12 – 0.23 and 1.00 – 1.15, respectively. The Niger Delta basin exhibits low to moderate drainage density values, with relatively low values of coefficient of anisotropy. Grouping these data into three classes of low, moderate and high drainage density and coefficient of anisotropy classes, we determined the gully frequency, G_f (Tables 1 and 2,) which is defined as follows (Saker and Kanungo, 2003).

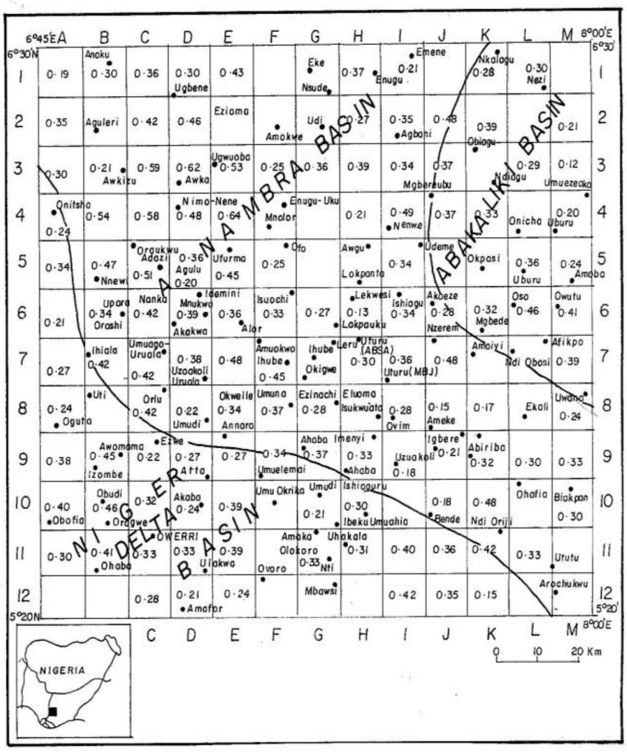

Fig. 7. Map showing drainage density

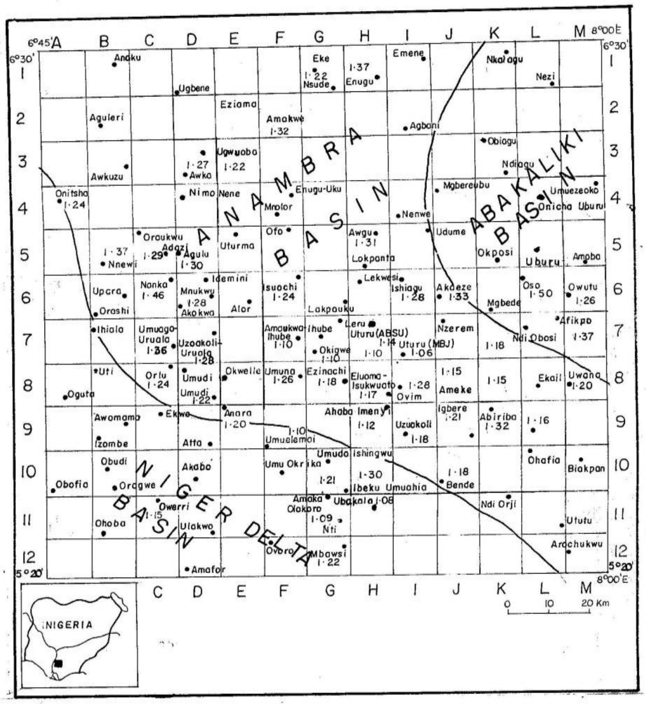

Fig. 8. Map showing coefficient of anisotropy

$G_f = N_G/A_T$ (3)

where N_G = Number of gullies

A_T = Total area of grid cells in km^2

The result obtained from these analyses showed that gully frequency is high in class intervals having high values of drainage density and coefficients of anisotropy. Structural contour maps of drainage density (Fig. 9) and anisotropy coefficient map (Fig. 10) were finally prepared using Geocom basic subroutine to contour gridded data (Bourke, 1987). The two maps exhibit high and low contour densities, which conforms with the result of earlier observations.

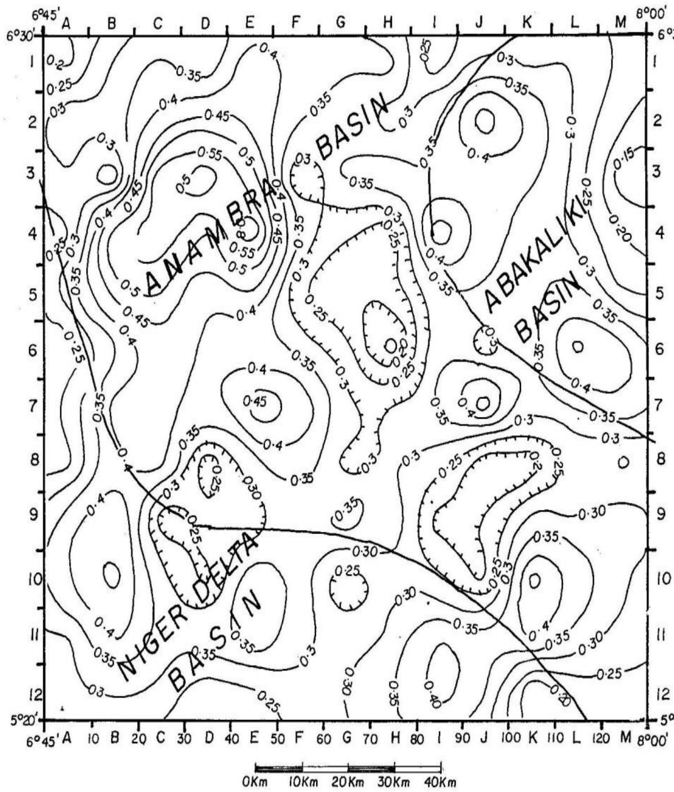

Fig. 9. Structural contour maps of drainage density

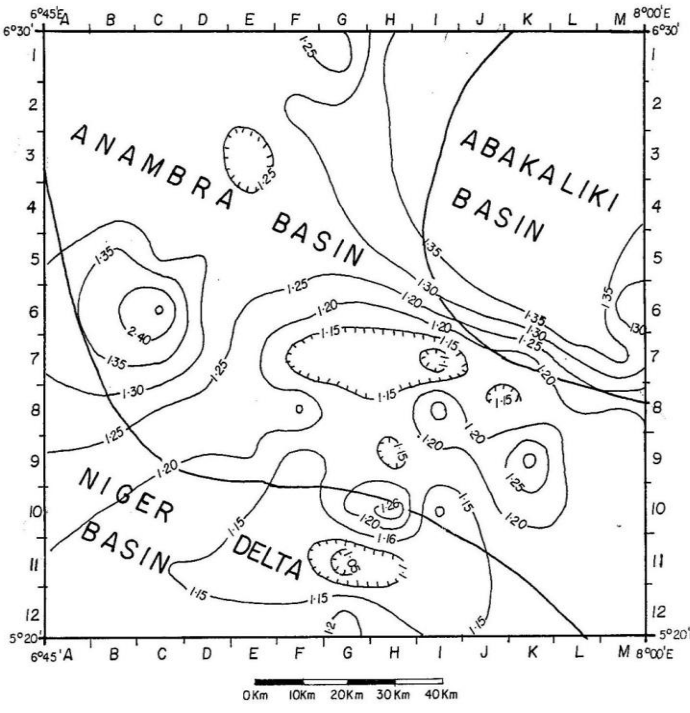

Fig.10. Anisotropy coefficient map of the study area.

DISCUSSIONS

The resulting data from drainage density and coefficient of anisotropy were integrated with the spatial data obtained from gully sites to determine the gully frequency (km^{-2}) in the belt. The trend in gully distribution for each class interval was remarkable. The trend obtained showed that gully frequency km^{-2}) is maximum in the high drainage density class interval. This suggests that areas having high drainage density are highly susceptible to gully and vice versa. It thus follows that the relationship between drainage density and gully erosion is linear governed by lithology, structure and climate.

The trend also revealed that gully frequency (km-2) is maximum for the high coefficient of anisotropy ( ) class intervals. This also indicates a direct relationship between gully erosion and coefficient of anisotropy, which compliments the fact that areas with more fracturing and faulting are always prone to gully erosion.

The coefficient of anisotropy, and hence, inhomogeneity are caused by structural features such as joints and faults (Habberjam, 1975). It can as well be caused by bedding trends, dips, foliation axis and facie changes, which are products of tectonic activities. These features have been documented in the Benue trough (Reyment, 1965).

Table 1. Gully Frequency in Drainage Density Classes

Drainage Density Classes (km/km^2)	Frequency	Area of Grid (km^2)	Number of Gullies	Gully Frequency (km-2)
Low (0.12-0.23)	19	1,900	5	0.0027
Moderate (0.24-0.35)	49	4,900	15	0.0031
High ($\geq$0.36)	53	5,300	19	0.0036

Table 2. Gully Frequency in Anisotropic Coefficient Classes

Anisotropic Coefficient ( ) Classes	Frequency	Area of Grid (km^2)	Number of Gullies	Gully Frequency (km-2)
Low (1.00 – 1.15)	11	1,100	4	0.0036
Moderate (1.16 – 1.31)	28	2,800	15	0.0054
High ($\geq$0.32)	9	900	8	0.0089

A comparative look at the contour maps of (Figures 9, 10) and geologic map (Fig. 2) reveals some remarkable correlation between areas of high drainage density and anisotropic coefficient and lithologic units associated with gully erosion in the belt. Lithologic units associated with gully erosion were delineated and the affected towns and their instability classifications based on intensity and area coverage are depicted in Table 3. The gully erosion follows mostly two distinctive lithologic units. The units of the Ajali Sandstone and Nanka Sands suffer severe gully erosion, while the other lithologic units suffer from slight to moderate characteristically poor porosities and perm abilities of the underlying shally formation. The surface unconsolidated sandy formations (Ajili and Nanka sands) get saturated quickly during rainfall due to the underlying shally formation, and surface runoffs are concentrated as channeled flows along lines of structural weaknesses down slope to cause spectacular gully erosion and landslides in this areas.

CONCLUSION

Gully erosion in relation to drainage density and coefficient of anisotropy in Southeastern Nigeria has been studied to verify the influence of these terrain parameters on the occurrence of gully erosion. The results obtained have shown a direct relationship between gully erosion and these terrain parameters. Gully frequency was found to be maximum in high drainage density and anisotropic coefficient classes, indicating that areas of high surface flows and structure are more susceptible to gully erosion. It thus follows that gully erosion in the belt is controlled by structures (joints and faults), lithology and partly to climate.

The contour maps correlated with the geologic map of the belt revealed that the Ajali sandstones and Nanka sands suffer severe gully erosion. The other lithologic units suffer from slight to moderate gully erosion. The differences are principally of lithology and structure

Table 3. Lithological Distribution of Gully Erosion in the belt.

s/no	Formation type	Location	Instability classification
1.	Benin formation (coastal plain sands)	Nnewi, Orashi, Awomama and Ihiala	Slight to moderate
2.	Bende-An\meki Shales	Awkuzu, Onitsha, Akokwa, Orlu, Bende, Uzuakoli and Umuahia	Slight to moderate
	Bende-Ameki (Nanka sands) formation	Urualla, Nanka, Agulu and Adazi	Severe
3.	Imo shales	Igbere, Awka and Nimo Neni	Moderate
4.	Nsukka shales	Abiriba, Okigwe, Isuochi, Ezinanachi and Ugbuoba	Slight to moderate
5.	Ajali sandstones	Inube abd Ohafia	Severe
6.	Mamu shales	Enugu	Slight
7.	Nkporo shales	Enugu, owutu, uwana and Afikpo	Moderate
8.	Ezeaka shales	Oso	Slight
9.	Asu River group (shales)	Ishiagu and Akaeze	Slight

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