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Digital Elevation Models as a Tool for Monitoring and Evaluating Gully Development in a Humid Tropical Environment

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Abstract: Gully erosion is a serious geo-environmental issue causing land degradation in different parts of South Eastern Nigeria. In this study, DEMs were generated at different spatial scales viz; Order-3 Basin, Order-1 and Dominic Utuk Avenue gully sub-catchment in Uyo area of Akwa Ibom State, South Eastern Nigeria. The study was conducted to achieve the following objectives viz; generate the geospatial database applying the principles of Geographic Information System (GIS) and field measurements, conduct catchment analysis; specifically erosion estimation studies, employ GIS in mapping the entire catchment area vis-a-vis erosion prone areas and compute the maximum discharge in the sub-catchment area to aid in the design of erosion control structures. The results obtained, i.e., 78.9 m^3 sec^{-1} pre-supposes that a rainfall event that lasts for an hour will generate a maximum discharge of 111.127 m^3 sec^{-1} into the gully complex; while, a rainstorms of 3 h duration will generate a maximum discharge of 333.38 m^3 sec^{-1} into the gully system. The results of the research has implications for gully erosion stabilization/control in the study area.

Key words: DEMs, gully erosion, Iba Oku Basin, runoff and coastal plains sands, GIS, Nigeria

INTRODUCTION

Large gully systems have received much attention from researchers using modern geospatial analysis (Tabatabaei, 2000; Zinck *et al*., 2001; Feoli *et al*., 2002; Martinez-Casasnovas, 2003; Martinez-Casasnovas *et al*., 2004; Sirvio *et al*., 2004; Raoofi *et al*., 2004; James *et al*., 2007). Sirvio *et al*. (2004), for instance, have investigated gully erosion hazard assessments in Taita Hills, SE-Kenya, applying airborne digital camera orthomosaics and GIS for small-scale studies and field measurements for large-scale studies. Raoofi *et al*. (2004) categorized rill and gully erosions in Taleghan Basin-Tehran province by using visual interpretation of images derived from the fusion of ETM+bands and cosmos image. James *et al*. (2007) investigated the ability of the ALS (Airborne Laser Scanning) baselineographic data to identify headwater channels and gullies. The extension of the use of modern spatial information technologies such as Geographical Information Systems (GIS), Digital Elevation Modeling (DEM) and remote sensing seems to be limited to the developed countries and studies in Nigeria are few (Igbokwe *et al*., 2008; Adedeji *et al*., 2009).

It appears that an appropriate methodology for providing information on runoff and its intensities with regards to gully initiation and sustenance have not been done. The aim of this research is to develop a methodology based on GIS-DEMs for providing data on runoff, gully morphometric properties and growth rates needed for gully control and stabilization in a data poor country such as Nigeria. In this regard, the present study, attempts to generate DEMs at different spatial scales for gullies in Uyo with the aim of determining the volume of runoff from the sub-catchment. The study was conducted to achieve the following objectives:

- To generate the geospatial database applying the principles of Geographic Information System (GIS) and field measurements
- To conduct catchment analysis specifically erosion estimation studies
- To employ GIS in mapping the entire catchment area vis-a-vis erosion prone areas
- Compute the maximum discharge in the sub-catchment area to aid in the design of erosion control structures

MATERIALS AND METHODS

The study area: The Dominic Utuk sub-basin with 67898.22 m^2 located between 5°02' and 5°07'N and by longitudes 7°29' and 7°31' E latitudes E was considered for the investigation of erosion features. It extends from Nitel headquarters Southwest to Northeast Government House Area of Uyo Town, Akwa Ibom State, Nigeria. The highest and the lowest height of the basin are 90 and 11 m above msl, respectively (which translates to a basin relief of 79 m) while the basin length is 2597 m. It is

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drained by a 1st Order stream which runs into the Order-3 Iba Oku Basin (26.5 km^2 Order-3 Basin in Ikpa River Basin). This 1st Order stream has a fairly steep channel (2°), relief ratio of 0.0304 and total length of 2.6 km. It has enormous potential energy for further erosion and hence, the balance between amount of vegetation cover and the loose, weakly cemented soils is precarious.

The Ikpa River originates from Afaha Ise in Northern Akwa Ibom State and drains into alluvial plains of Cross River at Edik Ikpa (Fig. 1). Land covers were badland, sand borrow, agriculture land and urban surfaces. Basin lithology is basically coastal plains sands. The sands which make up by far the greater part of the deposits possess several characteristics which are always present where good exposures are found especially in deep gully channels. The soils are deep and have loamy sand to sandy surface materials (Coarse sand, 55-86%; clay, 2-15%; silt, 0-17%). The study area has climate characteristics that could be described as humid tropical, i.e., Af climate type based on Koppen's classification.There are two main season: The dry season (November to February/March) when the Northeast trade wind from the desert blows across the area. The rains come between March and October (and in some wet years it may extend into early November) when the ITD moves Southwards. In Uyo, the mean annual rainfall is 2466.6 mm, recorded between 1977 and 2010. The wettest year during this period was 1977 which had a rainfall of 3855.8 mm. The driest year, on the other hand, was 1983 with a total annual rainfall of 1599.4 mm. The spatial pattern of rainfall in Iba Oku Basin indicates slight variation which is not statistically significant (Udosen, 2008).

The Ikpa River Basin on the other hand covers an area of 413.5 km^2 (Fig. 1) and is bounded by latitudes 4°20' and 5°12'N and by longitudes 7°31' and 8°11'E. It is a major tributary of the Cross River. The entire basin is a 5th Order drainage basin with 192 1st Order, 47 2nd Order, 10 3rd Order and 2 4th Order. According to the 2006 Population census, the population of the Local Government Area was 309, 543 (NPC, 2006). This population settled in either agglomeration (mostly at stream heads of fingertip streams) in a haphazard arrangement in Uyo Town or in clusters in villages in the suburb of Uyo Town.

(a)

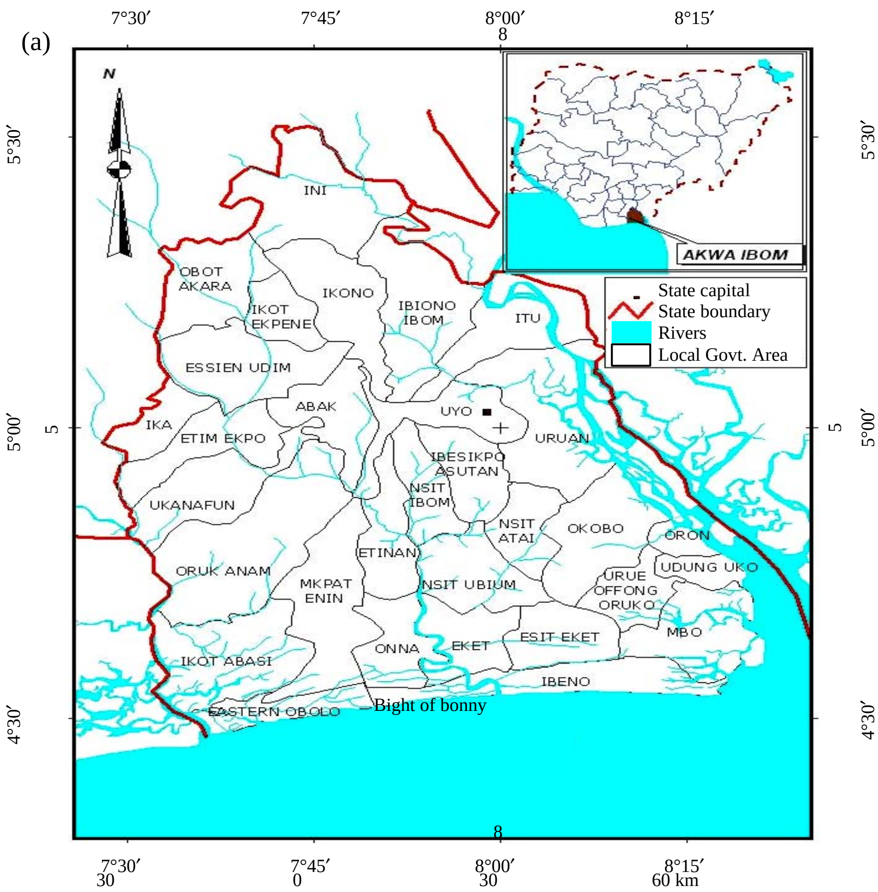

Fig. 1: Continue

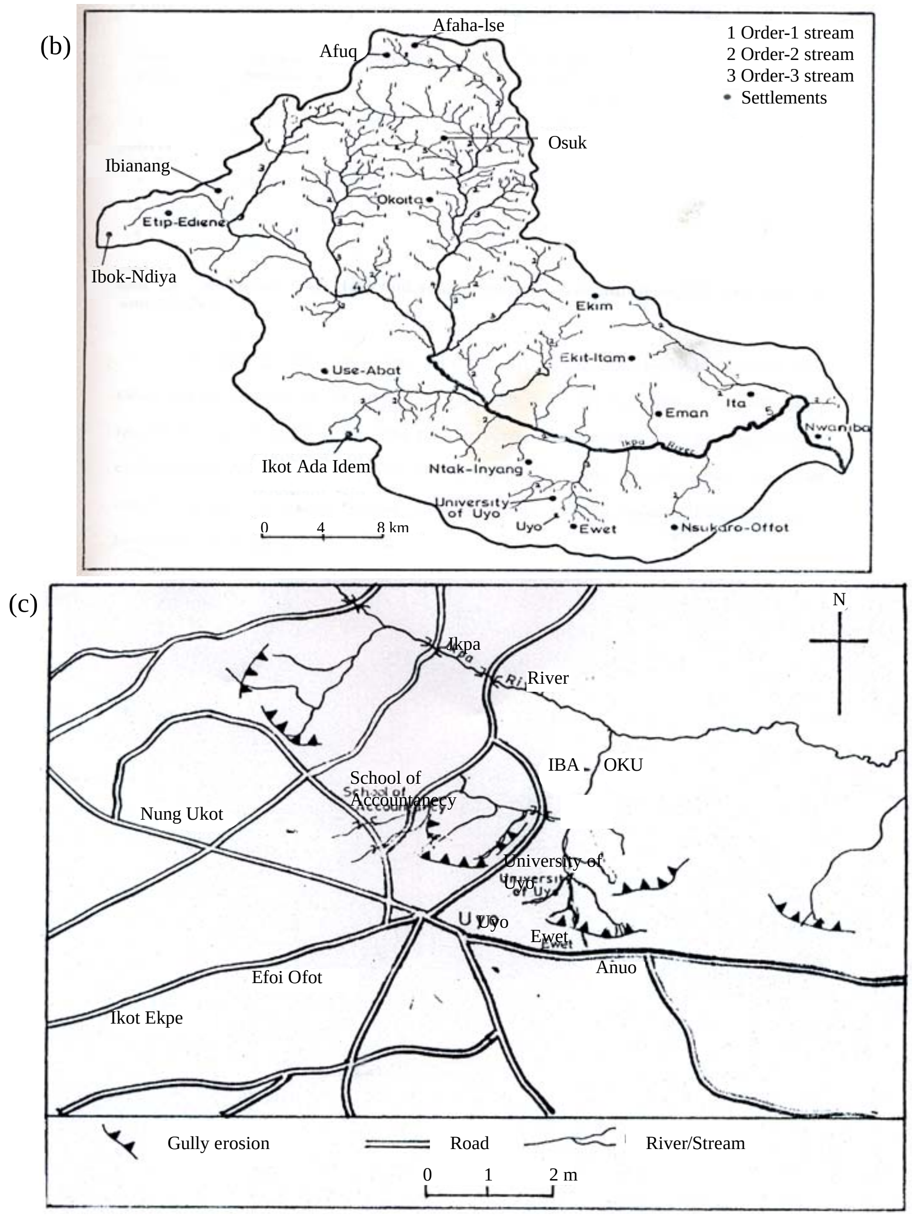

Fig. 1: Location of the study area

Data collection and analysis; digital elevation model: A GIS is typically used to represent maps as data layers that can be studied and used to perform analyses (ESRI, 2005). As a valuable research tool, its capabilities were deployed to capture, store, manipulate and analyze terrain data of an Order-3, Order-1 and sub-catchment of the gully erosion site at Dominic Utuk Avenue in Uyo Local Government of Akwa Ibom State. GIS was also used to generate 3D Models of the gully. Thus, in order to generate 3D Models of gully erosion at Dominic Utuk Avenue, a Germin e-trex GPS (Global Positioning System) receiver was configured to capture terrain information using world UTM (Universal Transverse Mercator) 1984 latlong geographic coordinate system with elevation values in meters. This GPS receiver was used to collect point data (Waypoints) of the gully area on an average spatial resolution of 3.5 m. A total of 236 waypoints representing spot heights spread across the gully site were generated. Based on Adedeji *et al*. (2009), the values of spot heights were plotted against the coordinates of each point in Surfer 8.0 software. Inverse Distance Weighting (IDW) interpolation method was used in converting the spot heights to a Surfer grid. This is a smooth surface of 100 rows by 92 columns. IDW uses surrounding measurements to forecast values for unmeasured points. In this method, values closest to the prediction points have greater influence on the interpolated values than those farther away and for each predicted value, a minimum of 2 and a maximum of 12 surrounding points were used to predict the value (Tancer *et al*., 2001). The Surfer grid was then as input data for mapping the 3D Model of the gully erosion site that can be viewed in different perspectives (Fig. 2-4).

Measurement of sub-catchment area: The contour map of the study area was used to compute the drainage area of the gully-catchment. The total area of catchment was delineated onto a transparent tracing study. This area mapped out was super-imposed on a graph sheet ruled in

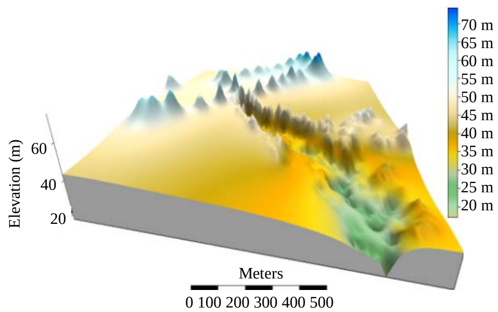

Fig. 2: DEM of the gully as it approaches Dominic Utuk Avenue

square centimeters. The squares method was employed to calculate the area in cm^2 and the multiplied by the scale factor and the gully-catchment area expressed in m^2. Furthermore, the computed area was converted to hectares by multiplying it with 0.0001 ha.

Measurement of surface runoff: The Rational Method was employed in estimating maximum discharge in the study area.

This method that was first introduced in 1889 is still used in many engineering works such as road construction (Ayoade, 2003). Although, it has frequently come under criticism for its simplistic approach, no other drainage design method has received such widespread use. The 1st step in applying the Rational Method is to obtain a good topographic map and define the boundaries of the drainage area. A field inspection of the area was also carried out to determine if natural drainage divides have been altered rainfall intensity of 122 mm h^{-1} was determined from the precipitation Intensity Duration Frequency (IDF) curve; length of longest axis was computed from sketch map; the difference in elevation was calculated too (90-11 m); while, bare fallow was assumed in the study. The total area was converted to hectares.

In determining the runoff coefficient C value for the gully-catchment (Drainage area), thought should be given to future changes in land use that might occur (Fig. 5). The rational formula estimates the peak rate of runoff at any location in a watershed as a function of the drainage

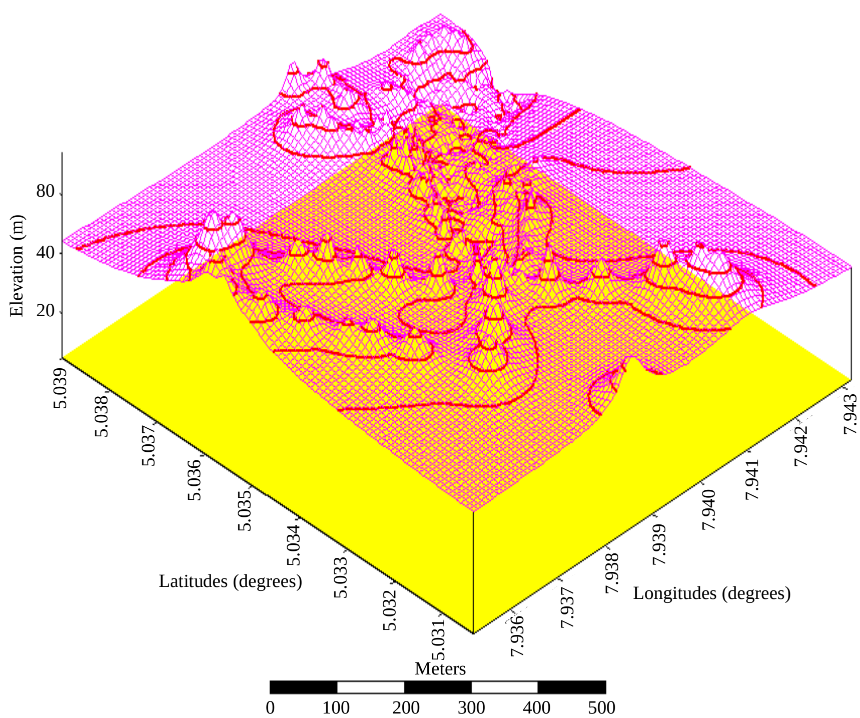

Fig. 3: DEM of Dominic Utuk Avenue

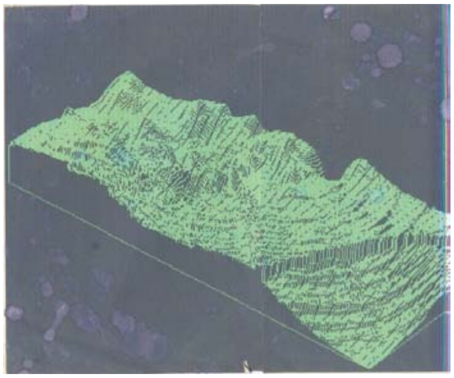

Fig. 4: DEM of Iba Oku River Basin (Order-3)

Fig. 5: a) Gully stretching towards the toe; b) An active gully that has damaged the drainage facilities

area, runoff coefficient and mean rainfall intensity for a duration equal to the time of concentration (The time required for water to flow from the most remote point of the basin to the location being analyzed) the rational equation is expressed as:

$$Q = CIA\ [Q = 0.00278CIA]$$

Where:

Q = Maximum rate of runoff in $m^3\ sec^{-1}$

C = Runoff coefficient representing a ratio of runoff to rainfall

I = Average rainfall intensity for a duration equal to the time of concentration for a selected return period of 50 years ($mm\ h^{-1}$)

A = Drainage area tributary to the design location, ha (acres)

In this study, the runoff coefficient C is 0.90; since, the overlay of satellite image of land-cover on the mapped area indicates bare and paved/compacted roads/street interspaced between buildings and farmlands:

$$1\ m^2 = 0.0001\ ha$$

The maximum discharge was estimated by first computing the time of concentration of runoff. Time of concentration designated as Tc is defined as the time required for water to flow from the most remote (in time of flow) point of the area to the outlet once the soil has become saturated and minor depressions filled. It is given quantitatively as:

$$Tc = 0.0195\ L^{0.77} \Sigma^{-0.385}$$

Where:

Tc = Time of concentration of runoff

L = Maximum length

S = Slope

RESULTS AND DISCUSSION

The generated DEM of Iba Oku catchment shows that surface runoff ponders over the steep escarpment (Southeast of the DEM in Fig. 4) through the heavily built-up sub-catchment of Dominic Utuk Avenue sub-catchment down to the gully channel. The severity of gully erosion menace was influenced by the volume of runoff generated from this source, the gradient of intervening lands (Stream valley) and the proportion of Hydrologically Significant Impervious Aarea (HSIA), among other factors. Apart from the haphazard concentration of buildings at stream heads, runoff generated from the built-up areas are channeled through Ekpo Obot, Ekpenyong, Paul Bassey and Gibbs streets roadside drains into a steep sided Order-1 stream valleys. By the late 1970s, especially between 1977/78 and early 1980s all these areas had become devastated by deep gullies. For instance, a 38% reduction in the proportion of previous surfaces and careless disposal of surface runoff from Dominic Utuk Avenue catchment in Uyo initiated 1,368 m a long gully system on a 1st Order valley near a storm drain inclined at an angle of 10°. The gully system about 21 m wide, 9-14 m deep was produced by undercutting, slumping and rapid headscarp retreat (Udosen, 1998).

The proportion of impervious surfaces (HSIA) increases surface runoff beyond a threshold value due largely to population pressure. As it is today, the population of the LGA had grown steadily from 743 people in 1931; 37,963 in 1963; 48,468 in 1973; 309,573 in 2006 (Table 1). As noted earlier, high population growth rate of about 3% has given rise to a sharp increase in the proportion of the HSIA and consequently increase in runoff which overtaxes the existing drainage structures leading to severe flooding upslope and erosion near the stream channel downslope.

Also, due to population pressure, water leaf vegetation is being planted within the vicinity of the headrim by making mound which encourages the concentration of runoff thereby aggravating the menace of gully development leading to localized slumping and collapse of gully sides. Once, gully sides collapses, high velocity runoff at the gully base facilitates rapid removal of sediment as the gully system is being sustained by basal Spring sapping.

Table 1: Population growth of Uyo from 1931-2006

Years	Population	Density/SQM
1931	743	46
1953	6,156	384
1963	37,963	-
1970	45,008	-
1973	48,468	-
1976	52,213	-
1981	75,332	-
1991	244,762	1149
2006	309,573	-

NPC (2006)

Furthermore, the generated topographic map of the entire gully complex shown in Fig. 6 illustrates that the gully complex had extended to the newly constructed Government House and the massive structure is being threatened by the awe-inspiring chasm.

Calculation of time of concentration and maximum discharge: A topographic map of the Dominic Utuk Avenue sub-catchment was also generated to facilitate the computation of the gathering time of surface runoff as well as the volume of runoff. From the map the sub-catchment area of Dominic Utuk Avenue gully complex was calculated, i.e., 815.914.1 m^2 and the Tc (Time of concentration) was computed as 42.6 min. the implication is that runoff from the farthest point (2480 m) enters the gully channel barely 43 min during any rain event, suggesting steep gradient. The runoff/discharge for the Dominic Utuk Avenue gully complex was calculated using the Rational Method (m^3 sec^{-1}) and the computed value of 78.9 m^3 sec^{-1} pre-supposes that a rainfall event that lasts for an hour will generate a maximum discharge of 111.127 m^3 sec^{-1} into the gully complex; while, a rainstorms of 3 h duration will generate a maximum discharge of 333.38 m^3 sec^{-1} into the gully system.

Morphometry of Dominc Utuk Avenue gully complex: We do know that gully erosion is an advanced stage of rill erosion where surface channels have been eroded to the point where they cannot be corrected by normal tillage operations. Once a mature gully is initiated

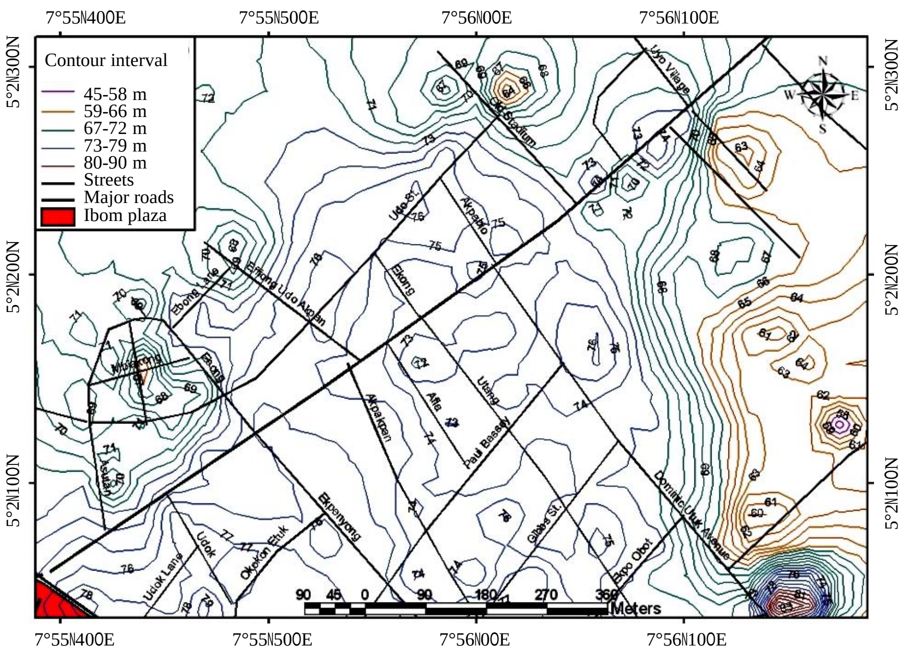

Fig. 6: Topographic map of Dominic Utuk/Government House gully complex

the process becomes self perpetuating in most instances and the gully deepens and enlarges, depending on the runoff contributing area. It could be stabilized naturally if the contributing area decreases to an insignificant proportion (Negative feedback mechanism which hardly occurs in urbanized basins). This is so because urban development exposes the surface to direct raindrop impact and impedes infiltration process. In the study area infiltration rates ranges from 5, 19 to 111.3 mm h^{-1} for bare, scanty vegetation and forest cover, respectively. Hence, removal of vegetation cover leads to destruction of soil structure and structurally unstable soils are readily slaked and tend to form a semi-permeable surface crust which encourages concentration of surface runoff on slopes and consequently, soil erosion (Table 2).

The high volume of runoff generated from these impervious surfaces accounts for the rapid growth in gully size over the years and experience has shown that years with above normal total annual rainfall are characterized by high rates of soil erosion.

The rapid retreat of gully head scarps at an average rate of 50.9 m per year which is spasmodic and extensive slumping/sliding of the walls of existing gullies is gradually destroying the physical existence and economic base of the study area/farming communities in the catchment area (Table 3). Storm drains channeled into Dominic Utuk Avenue normally encourages the concentration of urban runoff but improper handling may enhance accelerated erosion. In this regard as observed in the study area, the termination half way of the construction work on erosion channels being constructed some years back by the State Government in the study site triggers accelerated erosion (Gully erosion). Runoff in the form of falls from the concretized portion of the channels onto the bare earth below gave rise to a gully from the points where the concrete gutters terminated. Infact, during the field survey, a broadly-loped gully head (semi-circularity ratio of 1.94) which is 24 m deep and 33 m wide was measured where the concrete channel terminated at the edge of Dominic Utuk Avenue. However, the runoff that brought about the gully was generated from the network of concrete drains that covers just about half (50%) of the total gully catchment area (845,918.1 m^2).

Table 2: Values of infiltration rates at DominicC Utuk Avenue gully complex

Location	Bare surface	Scanty vegetation	Forest cover
Ewet, Uyo	7	18.8	104.0
Dominic Utuk Avenue	5	17.9	121.8
Near Government House	3	20.2	108.8
Mean	5	19.0	111.3

Udosen (2008)

These gullies are U-shaped with near vertical side walls (>75°), wide valley bottom (Fig. 2) and characterized by an average cross sectional area of 1386 m^2 caused extensive loss of valuable oil palm trees, agricultural soil and soil nutrients (Including oxides of nitrogen from fertilizer application by the water-leaf farmers). This encourages algae/to grow on stream channels leading to silting up of streams.

Further, the slope shapes as revealed by the DEMs of the study gullies are dominantly convex. This implies that overland flow will be generated from all sides of the slope which invariably increase runoff into the gully channels (Adediji *et al*., 2009). In other words, the convexity of most of the gully catchments allow runoff from all sides of slopes and the termination of drainage channels half way coupled with the poor roads and drains maintenance by the community and government have led to the development of large deep gullies at the study site. The DEM for Dominic Utuk Avenue gully system exhibits very steep terrains which ordinarily should encourage intense erosion and flooding in the upslope area where buildings are often inundated by flood water ass in Assemblies of God Church and buildings in the neighborhood.

The mechanisms involved in soil erosion by water vary over space and time. Some of these mechanisms are rain drop splash, unconcentrated down-slope wash (Sheet erosion), concentrated down-slope wash (Rill and gully erosion) and a mixed process in which entrainment is by raindrop splash and down-slope transport is by surface wash. It has also been observed that man can also influence the dynamics of each of these mechanisms and thus improper human land management can accelerate the rates of erosion which may result in the development of rills and gullies. However, the factors of gully development in the study area are similar to the observations by Udosen (2008) and Adediji *et al*. (2009) and does not warrant elaboration in this study.

Table 3: Morphometry of Dominic Utuk Avenue Gullies (1998-2011)

Year of measurement/Source	Mean values of height of headrim to gully base (m)	Mean values of gully length (m)	Mean values of gully depth (m)	Mean values of gully width (m)	Gully width depth ratio	Slope angle of surface on which gullies develop
Udosen (1998)	11.6	1,136.6	9-14 Mean (11)	21	1.91	17°
Okon (2001)	18	-	16-18	-	-	-
Nigerpet Ltd. (2009)	21	-	19.0	34	1.79	17°
Field measurement/DEMs (2011)	24	1,798	21	36	1.71	19°

(Udosen, 1998; Okon, 2001; NS, 2011)

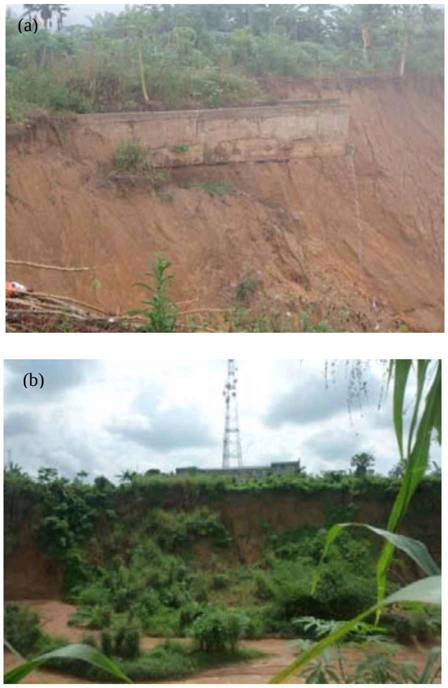

Fig. 7: Ill-aligned storm drains and gully development

As noted earlier, the catchment area is underlain by Coastal Plains Sands that consist mainly of sandy loam and in some places the proportion of sand is >75% which are porous but, however, suffered from excessive internal drainage and intensive leaching. However because of compaction of the ground in the built-up (Urban) environment as in the case of the study gully catchments, the soils are relatively permeable and, therefore, susceptible to the action of sheetwash and gullying. It is obvious that gully erosion develop/originate as a result of improper land use pattern based on ignorance. If the farmers and other land use types are adequately sensitized, most gully development would be prevented and huge funds committed to control measures (in the early 1990s 40 million naira was spent in controlling the same gully) would be saved for other developmental purposes (Fig. 7).

CONCLUSION

The results of the research also have implications for gully erosion stabilization/control in the study area. The DEMs generated at different spatial scales were employed in determining gully morphometric properties, runoff direction and velocities as well as slope shape/steepness. It is evident from the study that man's activities provide the stimuli to exceed natural threshold conditions or yield points within the 26.5 km^2 Iba Oku River Basin. Gully development has been shown to be a threshold-exceeding event in the area. Hence, the understanding of critical runoff volume required for gully incision, both natural and man-induced (and sometimes urban-induced) is required for proper environmental management. Further research is needed on the threshold runoff required to initiate a gully channel in the coastal plains sands of South Eastern Nigeria. It would be recalled that Udosen (2008) established values of drainage basin parameters such as relief, slope angle, vegetation and organic matter content for gully initiation and sustenance in the study area.

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