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Monitoring of Soil Loss from Erosion Using Geoinformatics and Geotechnical Engineering Methods

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Abstract: In this study, the position of all major rill and gully erosion sites were located using hand held GPS (Global Positioning System) receiver during reconnaissance surveys. Based on severity rating and geopolitical considerations, six of the erosion gully sites were selected for monitoring. Control points were established around each of the gully sites using three Leica 500 dual frequency GPS receivers by method of DGPS (differential GPS) surveys. Detailed topographical survey of the gully sites was carried out using total stations. With the aid of SPOT satellite imageries in combination with total station data and GIS (geographic information system) location maps, contoured maps along with DEM (digital elevation model) were generated using ARCGIS 9.2 software. The morphological parameters of the gullies including depth, width, length and area of the gullies were determined. Volumetric estimate of the amount of soil loss from gully erosion was also carried out. Soil samples were recovered from the gully sites to determine their erodibility and other parameters to be used for soil loss modeling. The result of the studies was used as an indicator for determining the gully initiation point. Slope-area relationship and threshold of gully initiation was established. The minimum volume of soil loss occurred in gully No. 2 (Queen Ede). The minimum AS^2 value was 345 while the maximum was 3,267.

Key words: Differential GPS, gully erosion, rill erosion, morphological parameters, digital elevation model.

1. Introduction

Erosion is the detachment and transportation of soil particles on the earth's surface from one point to the other by erosive agents such as wind and water [1]. The two most common types of water erosion are sheet and gully erosion. Another type of erosion is rill erosion. In sheet erosion, soil is removed in sheet form by the influence of flowing water from a given area on a slope terrain. In sheet erosion, maximum movement of the soil takes place when the depth of flow is equal to the diameter of soil particle. In rill erosion, the erosive effect of flowing water leads to the movement of large amount of soil particles from the sides and bottom of the flow path which are mixed in the flowing water. These surface flows contain soil particles in suspension and form micro channel called rills [2]. The last stage of rill erosion is usually classified as gully. It is said that gully erosion takes place when excessive surface run-off flowing with high velocity and force detach and carry soil particles down the slope. They may also occur when run-off volume from sloppy terrain increases sufficiently or increase in flow velocity as to cut deep holes along its path [3]. Gullies may also develop on traces formed by the movement of machineries down the slope [4].

Gully erosion is defined as the erosion process whereby run-off water accumulates and also receives in narrow channels and over short periods removes the soil from this narrow area to considerable depths. In Refs. [5, 6] on the other hand, gullies are defined as unstable eroding channels formed at or close to valley heads, sides and floors. Recently, gully erosion has become of interest for the researchers. It is now well known that increased exploitation and exploration of land resources in upper parts of catchments results in increased sediment yield and elevated nutrients loss in run-off that reduced water quality and availability to

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downstream users [7]. Gully processes are usually the main source of sedimentation [8]. Gully erosion has for some time been neglected because gully processes are difficult to study and difficult to control. Gullies have three-dimensional nature affected by varied factors and processes including: surface hydrology, soils, topography, land use etc.. Many gullies grow initially rapidly to large dimensions [7, 9], making effective control technically difficult or prohibitively expensive. This is why studies on gully processes [10] and their modeling [11] are scarce. Recent research and field studies have shown that gully erosion is one of the most soil degradation processes in most states of Nigeria as it causes considerable soil loss and produces large volume of sediment. Gullies are also catalyst for transferring surface run-off and sediment from uplands to valley bottoms and creation of channels that aggravate the problem of flooding and water pollution. Field measurements and research findings in various countries have shown that the development of gullies increases the connectivity in the landscape and hence also the sediment delivery to low lands and water courses.

Substantial efforts have been invested in developing soil erosion models resulting in a variety of empirical and more so publicized models, such as the USLE (universal soil loss equation), its revised version the RUSLE (revised universal soil loss equation), the WEPP (water erosion prediction project) and CORINE (coordination of information on the environment). The prediction of gully development using mathematical model is difficult as the different factors involved in the prediction are not so easy to be determined. Soil type and in particular the vertical distribution of the erosion resistance of the various soil horizons largely controls the size, the depth and cross sectional morphology of the gullies. It was found that soil shear strength at saturation of the various soils horizon is a good indicator of their resistance against concentrated flow erosion [4, 12].

In Nigeria, high land use pressure particularly in the South East and South-South zones renders the landscape more vulnerable to gully erosion. Land use changes have also caused the development of bank gullies along some river banks.

Gully represents some of the most destructive form of erosion, destroying soil, undermining infrastructure, damaging farm lands, altering transportation corridors and lowering water tables [7]. Gully erosion affects sediment budgets and flux rates, and influences stream dynamics as evidenced from data on hydrograph [13, 14]. Although gullies are visually striking, their small spatial extent generally renders them undetectable in most generally available topographical maps and low resolution imageries. The use of GPS and total station data along with high resolution satellite imageries and GIS (geographic information system) provides the geodesists with the possibility to effectively measure gully volume with high accuracy and reliability. Monitoring and experimental studies of the initiation and development of gullies need to be carried out. The critical thresholds for the initiation, development and filling of gullies in different environments in the terms of flow hydraulics, rainfall, topography, soils and land use need to be identified.

Patterns and rates of gully networks development as well as network geometric configuration are highly controlled by soil properties [15]. One of the main causes of rill and gully erosion in Edo State includes road construction with inappropriately terminated drainage network. While damages by surface run-off to the road may be limited, off site effects can be very severe. The road is said to induce a concentration of surface run off with diversion to other catchments and an increase in catchment size which enhance gully development after road construction [16]. Changes in drainage pattern associated with urbanization results in gully, particularly where illegal settlements without urban infrastructure exist.

Contrary to the sheet and rill erosion, where standardized procedures for the assessment of erosion rates exist, e.g., RUSLE (revised universal soil loss equation), no standard procedures are available for measuring the gully erosion rates and the controlling factors. In the past, both ground based and airborne techniques have been used to assess the gully erosion rates at a time scale. Short term monitoring of gully head or gully wall retreat has been conducted by measuring the change in distance between the edge of the gully head or wall and bench mark point, installed on the gully walls [17, 18]. Some other studies have used aerial photographic methods to determine the volume of soil loss by concentrated flow erosion [9, 19]. One of the most common methods in use lately is by integration of GPS, GIS and remote sensing technologies. In the current study, differential GPS was used to establish control points for each gully site while total station was used to measure the morphological parameters of the gullies.

2. The Study Area

Edo State is one of the 36 states of Nigeria and lies within the oil rich Niger Delta region. It has a population of 3.2 million and an area of 19,635 km^2. The state lies between latitude 05^{o}44' to 07^{o}34' N and longitude 05^{o}04' to 06^{o}45' E.

The landscape of Edo State varies with: intermittent valleys and flat terrains from the southern part of the state, with height above sea level varying from 15 m in the southern boundary with Delta State up to about 300 m above sea level in the northern part of the state. This, along with the relatively flat terrain in the south and dissecting plateau and hills in the northern parts of the state, with steep slopes in various parts of the central area, high rainfall and lateritic soils consisting of medium to coarse sands and clayed deposits account for the problem of gullying in this state. The average annual rainfall ranges from 1,400 mm in the northern part of the state to 2,000 mm in the south. In 2011 an average rainfall was 2,500 mm. Gullying which is rapidly developing in many parts of the state mainly due to urbanization has been identified in terrains covered by friable and highly erodible A-3 soil deposits. Examples of such gullies include the ones at the University of Benin and Queen Ede secondary school both in Benin City, the state capital, the Ibore and Emu gully sites in Edo Central, Oshiobugie-Auchi and Ikabigbo gullies in Edo North (Fig. 1). In the state, an estimated land area of 2,000 km^2 is degraded land. About 30% of this area is degraded by gullying and rill erosion while 70% is estimated to be area under sheet erosion.

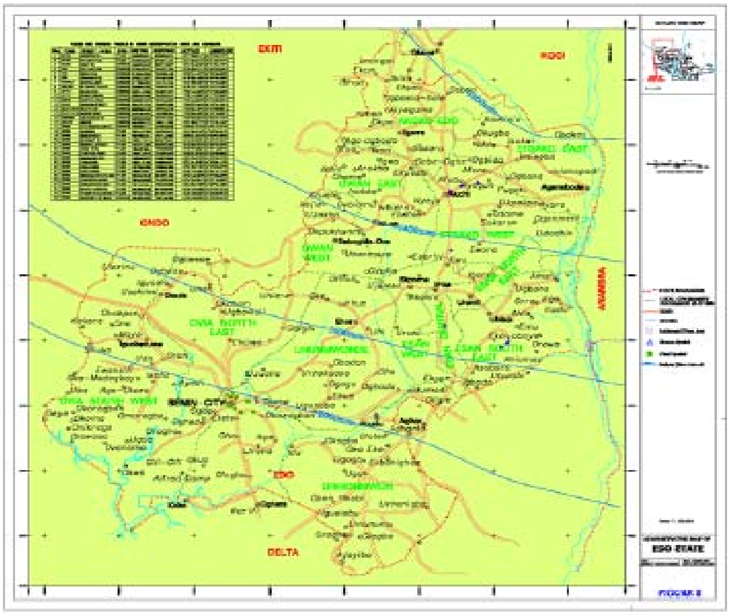

Fig. 1 Edo state map showing gully sites.

3. Methodology

It involves the application of GIS, remote sensing, GPS and total station for acquiring the necessary data for assessment of soil erosion—particularly gully erosion, study the spatial temporal distribution pattern of gully erosion initiation and the effect of land were used on gullying erosion.

Gathering of information, field measurement and studies, the first phase of this study included acquisition of information and report on erosion in Edo State from the State Ministry of Environment. Thereafter, topographical maps at scale of 1:25000 were acquired from the OSGOF (office of the Surveyor General of the Federation).

During field reconnaissance survey, the positions of the major gully sites were located and geo referenced on the ground using hand held GPS receivers.

Control points were then established around each gully site by use of DGPS surveys.

In establishing control points, 3 Nos of Leica 500 GPS receivers and their corresponding antenna were used. The Leica 500 system is a dual frequency receiver with GA (geodetic antennae) for L1 and L2 signals (at 1,575.42 and 1,227.60 MHz) and an interactive hand held receiver.

The reference points and the control points were occupied simultaneously with the dual frequency receivers. In the course of data collection, the GPS reference station was first activated and the GPS antenna was oriented to the north. After routine battery checks and entering of all acquisition parameters, the antenna height was measured in each station and entered at the appropriate prompting before commencement of data recording. Once the data recorded have been screened, adjustment and analysis of results were carried out using Leica geo-office software for post processing. The final adjustment results consisted of baseline vectors, estimated points coordinates and their covariance matrices.

On completion of the control surveys, detailed topographical surveys of the gully sites together with the flood basins were carried out using total station.

During the topographical surveys, the average number of points in some areas such as the gully heads, gully edges and terraces was more intense than the other parts of the flood basin. The total station data were processed using the coordinates of the control points, determined by DGPS. Measurements were taken at six gully sites, cross sections along with topographic profile running along the gully channels were prepared. The morphological parameters of the gullies including depth, width, length and the area of the gullies were determined. The classical measurements were collected at centimeter-level resolution to capture breaks in slope and other topographic features important for producing accurate DEMS (digital elevation models).

Hand auger soil samples were collected both within the catchment basins and on each encroaching layers of the gullies. The samples were taken to the Geotechnical Engineering Laboratory for standard classification and other tests which included particle size distribution, natural moisture content, specific gravity, Atterberg limits test, compaction, consolidation, permeability, etc., of these, the most important for gully erosion modeling include particles size, moisture content and specific gravity.

4. Data Processing and Results

Point coordinates and heights of the gullies were calculated using DGPS and classical surveys by the built-in instruments' software. The coordinates of the control points were calculated using DGPS. Based on the computed coordinates and heights of the points, the morphology parameters, length, width, depth, and areas of the gullies, along with the total soil loss were determined. Next, the project coordinates for each erosion site were exported into personal geo database as shape files in Arc GIS environment.

The shape files created for the elevation data were then added and a TIN (triangulated irregular network) was created using the Z coordinates. DEM (digital elevation models) were then generated by converting the TIN into raster. Contour lines were generated using the created TIN to interpolate for the contours with the aid of 3D analyst extension. Arc scene was then used for the visualization of the 3D model. From the contours, the slopes were generated as necessary. The pixel size of the DEM was 1 m. The morphological parameters for the six gullies are listed in Table 1. Figs. 2a-2c show the location maps while Figs. 3a-3c show the contour maps for the University of Benin, Queen Ede and Auchi erosion gully sites, respectively. Figs. 4a-4c present the triangulated irregular network for the same sites.

Table 1 Morphological parameters for the six gullies sites.

No. of gully	Name of gully	L (m)	W (m)	D (m)	A (m^2)	S (m/m)	AS^2 (m^2)	WDR	V (m^3)
1	University of Benin	1,020.23	44.17	26.58	44,880.00	0.022	2,172	1.661	358,336.085
2	Queen Edo College	1,250.00	54.03	11.83	67,480.00	0.010	675	4.567	385,113.568
3	Oshiobugie Auchi	2,200.00	62.76	25.33	127,600.00	0.160	3,267	2.479	129,085.000
4	Ikabigbo	467.66	22.98	7.77	11,675.00	0.172	345	2.958	57,901.108
5	Ibore	1,300.00	45.00	12.00	56,680.00	0.151	1,279	3.750	208,800.000
6	Emu	1,700.00	22.50	10.00	38,760.00	0.254	2,500	2.250	103,625.449

L—length, *W*—average width of gully, *D*—average depth of gully, *A*—gully area, *S*—critical slope gradients, *WDR*—width-depth ratio, *V*—volume of soil loss.

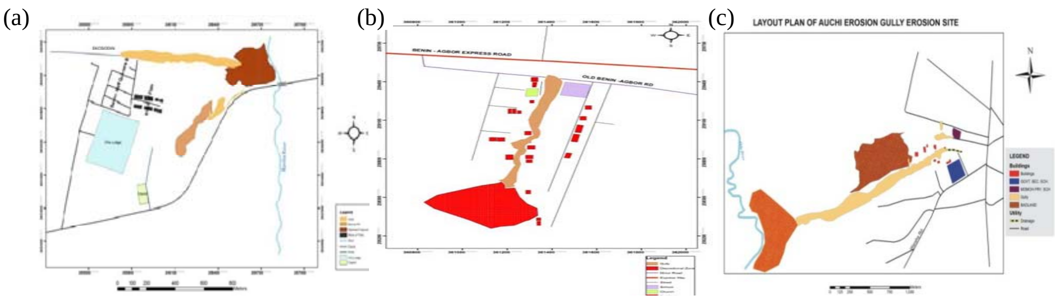

Fig. 2 Layout of University of Benin, Queen Ede and Auchi gully erosion sites.

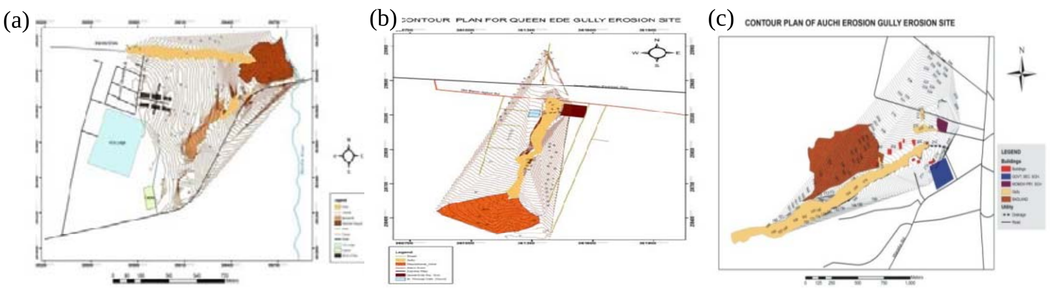

Fig. 3 Contour plan of University of Benin gully, Queen Ede and Auchi gully erosion sites.

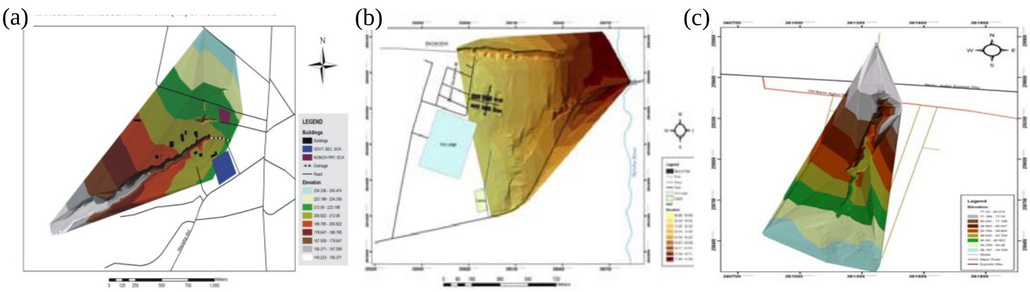

Fig. 4 TIN T (triangulated irregular network) of University of Benin, Queen Ede and Auchi gully erosion sites.

5. Analysis and Discussion of Results

The results from the field measurements showed that the erosion rates in the selected gullies for detailed studies are intense. If the position of the gully heads can be predicted and the erosion rates of the gullies are measured, actions can be taken to protect the areas from further gullying. The areas of the gullies are ranged from 11,675 m^2 to 127,600 m^2, depth varies from 7.768 m up to 26.575 m, and width starts from 22.50 m up to 62.785 m. The longest of the gullies was Auchi gully with a total length of 2.2 km. The WDR varied from 1.661 to 4.567. The volume of soil loss varied from 57,901.11 m^3 at Ikabigbo gully to 385,113.57 m^3t Queen Ede gully, in the six gullies studied. The results from the measurements in December 2010 and September 2011 showed that the University of Benin gully indicates a retreat of 66 m within a nine month period. This was found to be as a result of improper channeling of storm runoff from different directions into the gully head along with the unprecedented intensity of rain fall in 2011 which was the highest experienced in the area for the past 30 years. The values of AS^2 considered as an indicator for the gully initiation point ranged between 345 and 3,267. The lower limit conforms to range of between 41 and 814 m^2 while the upper limit conforms to range of between 500 and 4,000 m^2 [20-22].

6. Conclusions

In this study, an attempt was done to assess gully erosion based on the integration of: remote sensing, GIS, GPS and classical technologies. Using this expertise, the spatial distribution patterns of gully erosion, the topographical threshold, initiation, and the effect of land use were studied.

The result of the study showed that gully volume has significant relationship with both the gully length and areas and also with the depth and width of the gully. The study established a relationship between the drainage basin area (A) and the critical slope (S) for entrenchment. Montgomery et al. [21] proposed that there is a threshold between the contributing area and the critical slope and that the value of AS^2 of 500-4,000 m^2 was an indicator for determining the gully initiation point slope-area relationship, and threshold of gully initiation was established.

The results in this study showed that the gullies No. 1-6 satisfied proposal that the values of AS^2 of 500-4,000 m^2 is an indication for determining the gully initiation point slope-area relationship while gully No. 4 satisfied the relationship of range between 41 and 814 m^2 [20, 21].

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