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Soil erosion risk assessment: a case study of the Jos Plateau, Nigeria

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ABSTRACT

Soil erosion is a treat to global food security. The objective of this study was to evaluate factors influencing erosion on the arable lands of the Jos Plateau; and to estimate the extent of soil erosion in the area. Universal Soil Loss Equation (USLE) model was used to evaluate soil erosion processes in the study area. This was facilitated with the aid of Geographic Information System Both for Interpolation and Geospatial analysis. Soil data from field survey was the primary source of data for analysis of soil erodibility. Topographic factor was determined from 90-meter elevation data. Rainfall erosivity was determined from rainfall data at 1 kilometer resolution. Whereas vegetation cover factor was determined from Normalized Difference Vegetation Index. Results of the study indicate that rainfall erosivity values were remarkably high and have mean values of 5117MJ.mm/ha.h.y. Analysis of percent areal coverage indicate that the entire area had 52, 34, 7, and 7% low, moderate, high and very high topographic factors respectively. Further analysis indicate that anthropogenic factors had severely affected vegetation coverage of the Jos plateau, especially on the arable lands. Furthermore, during this research, the mean annual actual and potential soil erosion rates were estimated spatially over the Jos Plateau area. Soil erosion rates were far more than tolerable rates thereby affecting soil fertility and productivity.

1.0 Introduction

1.1 Background

A major factor affecting agriculture on the Jos Plateau is the extensive erosion going on in the area. The main causes of soil erosion in the area are mining, deforestation, inappropriate cultivation methods, over-grazing, road construction and high soil erodibility status (Olowolafe, 2002). Rainfall is a major factor influencing soil erosion processes on the Jos Plateau. Rainfall characteristics influencing soil erosion are amount, duration, intensity, and seasonal distribution. Rainfall intensity influences soil loss in two major ways (Brady and Weil, 1999): (1) intense rains have a large drop size which results in much greater kinetic energy being available to detach soil particles; and (2) the higher the rate of rainfall, the more runoff occurs, providing the means to transport detached particles.

The severity of accelerated erosion on landscapes is affected by the gradient, length and shape of slope, and size and shape of watershed. (Olson et al, 2002). The greater the steepness of slope while other conditions remain constant, the greater would be the erosion due to increased velocity of water flowing down slope (Brady and Weil, 1999). Bergsma et al. (1996) reported that erosion at a certain steepness depends on the slope shape immediately above the point of observation; and that on concave slopes most erosion takes place on the upper one-third, while on convex and straight slopes, most erosion takes place about three-quarter down the slope. Soil texture is an important indicator of soil erosion risk. Especially the finer fractions, such as clay and silt, are vulnerable to erosion, if they are not bound in stable aggregates that are resistant to breakdown by erosion forces. Often, the term erodibility is used to define the resistance of a soil to both detachability and transportability (Schwab et al, 1999). These characteristics vary with soil texture, aggregate stability, shear strength, infiltration capacity, soil organic matter content and soil chemical parameters (Brady and Weil, 1999). Larger soil particles are more resistant to erosion because more force is required to move them. Consequently, silt and fine sand require the least force to be moved by rain drop splash or runoff. The objective of this study is therefore to evaluate factors influencing erosion on the arable lands of the Jos Plateau; and to estimate the extent of soil erosion in the area.

1.2 Geological Settings

The geology of the Jos Plateau comprises Precambrian basement complex rocks (migmatites, gneisses and older granites), the Jurassic younger granites (mostly biotite-granites) and the Tertiary as well as Quaternary volcanic rocks (mainly basalt, pumice, lava flows and ash deposits) (Macleod, Turner, & Wright; 1971). According to Hill (1978), the major relief characteristics of the Jos Plateau are closely related to the underlying rock types. The resistant Younger and older Granites have formed a resistant core throughout a long erosional history and still form the hill masses of the present landscape rising to over 1 500 m, or the hilly broken country along parts of the dissected edges of the Plateau. The morphology of these hills is largely controlled by the joint pattern. Lower lying areas within the Plateau are usually associated with migmatites whilst the Newer Basalt flows give flat to gently undulating terrain. Over much of the rest of the Plateau the underlying rock is obscured by unconsolidated material. The physiography of Jos Plateau is comprised of three "broad physiographic units: hills and mountains, dissected terrain and undulating terrain (Hill, 1978).

Geographic distribution analysis shows that about 55% of the arable soils of the Jos Plateau are derived from the Basement complex rocks with basalt and younger granite comprising 18 and 27%.

2.0 METHODS AND MATERIALS

2.1 Materials

The following is a list of some of the major maps studied and utilized for this study:

1. Soil map of Nigeria (Sheet 5 of 8); Scale: 1: 650,000; Federal Department of Agricultural Land Resources (FDALR), Kaduna, Nigeria, 1990.
2. Jos Plateau (Present Land use); Scale: 1: 250, 000; Prepared by the Directorate of Overseas Surveys, England. Published for the Nigerian Government by the British Government's Ministry of Overseas Development (Land Resources Division); 1977.
3. Jos Plateau (Land Systems); Scale: 1: 250, 000; Prepared by the Directorate of Overseas Surveys, England. Published for the Nigerian Government by the British Government's Ministry of Overseas Development (Land Resources Division); 1977.
4. Post-1976 Administrative Boundaries of the Jos Plateau. Scale: 1: 650, 000; Prepared by the Directorate of Overseas Surveys, 1977. Published by Land resources development centre, Ministry of Overseas Development, England; 1978.
5. Jos Plateau (Physiographic Units); Scale: 1: 650, 000; Prepared by the Directorate of Overseas Surveys, 1977. Published by Land resources development centre, Ministry of Overseas Development, England; 1978.
6. Jos Plateau (Crop Options: based on environmental limitations); Scale: 1: 250, 000; Prepared by the Directorate of Overseas Surveys, England. Published for the Nigerian Government by the British Government's Ministry of Overseas Development (Land Resources Division); 1977.

Data base that were consulted and utilized for this study include the following:

1. Climatic data from WORDLCLIM: Contains long term (1950 to 2000) spatially distributed grid climatic data (precipitation, mean temperature, maximum and minimum temperature, and bio climatic variables) at one square kilometer resolution.
2. Climatic data from FAO CLIMWAT software database: Contains long term (1971 to 2000) spatially distributed climatic data (precipitation, mean temperature, maximum and minimum temperature, etc.) of point location of selected meteorological stations.
3. Elevation data from WORLDCLIM: Contains elevation data obtained from the Shuttle Radar Topography Mission (SRTM) at one square kilometer resolution.
4. Elevation data from CGIAR Consortium for spatial information: Contains elevation data obtained from the Shuttle Radar Topography Mission (SRTM) at 90 meter resolution.
5. African soil database version 1.0
6. Normalized Difference Vegetation Index (NDVI) for Nigeria at a resolution of 250m from the International Research Institute for Climate and Society (IRI) analysis tool.

2.2 Methods

2.2.1 Field study and laboratory analysis

Stratified random sampling approach formed the basis of the field work. Stratification was based on geological units. Surface soil samples were obtained with the aid of an auger to a depth of 15cm. Environmental conditions around the study area was also documented and included geographic coordinates, landform, erosional processes, surface soil condition, land use and vegetation. Sixty-nine (69) sampling sites were visited during the field work and data from these constituted the primary data used for this study. Secondary data were sourced from Hill et al (1974) and Leenaars et al (2014). Total number of soil sampling points used in this study was 127 and presented in Figure 1.

Soil samples collected from the field were air-dried in the laboratory, crushed with porcelain pestle and mortar and sieved to remove material greater than 2mm (gravel and other coarse fragments). The soil samples were dispersed in 5% calgon (sodium hexametaphosphate) solution by shaking on a reciprocating shaker. The particle size distribution was determined by the hydrometer method as described by Gee and Bauder (1986). Particle size distribution data was used to estimate soil erodibility using the method described by Van der Knijff et al, (2000).

2.2.2 Geostatistical Analysis and Application of Geographic Information Systems for Soil Erosion Status Assessment

Current trends in soil erosion research involve the incorporation of advances in geographic information system (GIS) for the assessment of soil erosion risk (Van der Knijff et al, 2000; Menesses-Tovar, 2011). Specifically, geographic information system technologies have been widely incorporated in soil erosion risk assessment (Pallaris, 1999 a, and b; Bayramin et al, 2006; Dengiz, 2007).

Potential and actual soil erosion risk was estimated using the Modified Universal Soil Loss Equation (USLE) as documented by Van de Knijff et al (2000) and Suri et al (2002). Geographic Information Systems (GIS) was used to facilitate the analysis over the arable soils of the Jos Plateau. Non arable soils in this study are as defined by Hill (1978) and are considered to be areas having hill and mountains, rock out crops, mine spoils; waterbodies and under urban influence. Soil erosion was assessed with the following equation:

•Actual soil erosion (A): $A = R*K*LS*C$ (1)

•Potential soil erosion (Ap): $A = R*K*LS$ (2)

Where:

R = Rainfall erosivity factor (MJ.mm/ha.h.y)

K = Soil erodibility factor (t.ha.h/MJ.mm).

LS = Topographic factor

C = Vegetation factor.

Input data for geospatial analysis were derived from field survey and other secondary sources as indicated in section 2.1. The System for Automated Geoscienticfic Analysis (SAGA) software was used basically for geospatial analysis. The flowchart for estimating the erosion risk map using GIS is presented in Figure 2. The following input parameters were used in the analysis:

Rainfall Erosivity Factor (R)

This was estimated using the following equation by Renard and Freimund (1994) as documented in Yu and Rosewell (1996):

$R = 0.04830P1.610$ (3)

Where:

R = Rainfall erosivity factor (MJ.mm/ha.h.y)

P = mean annual precipitation (mm).

Grid precipitation data (WorldClim, 2014) for Jos Plateau at 1km resolution was the primary input data for estimating rainfall erosivity.

Soil Erodibility Factor (K)

Soil erodibility was estimated using the following equation by Van der Knijff et al, (2000):

$K = 0.0034 + 0.0405 - \exp[-0.5((\log Dg + 1.659)/0.7101)2]$ (4)

Where:

K: Soil erodibility factor (t ha h ha-1 MJ-1 mm-1)

Dg: Geometric mean weight diameter of the primary soil particles (mm)

Dg is a function of surface texture, and its value can be calculated using:

$Dg = \exp [\sum f i.\ln (di + di\text{-}l)/2]$ (3.6)

For each particle size class (clay, silt, sand), di is the maximum diameter (mm), dil-1 is the minimum diameter and fi is the corresponding mass fraction.

Soil erodibility data of surface soil from field survey and that computed from other secondary sources was used in Universal Kriging analysis with relative slope position and terrain ruggedness index as covariables to estimate soil erodibility over arable soils of the Jos Plateau.

Topographic Factor (LS)

The topographic factor accounts for the effect of topography on erosion and redistribution soils. The LS factor was computed using the LS module of the SAGA software by the method of Desmet and Govers (1996) with STRM elevation data (90-meter resolution) as the primary input. The continuous form of the topographic factor equation at a point (x, y) as documented by Rodriguez and Suarez (2010) is:

$LS=(m+1)[(As/22.13)m]*[(\sin\beta/0.0896)n]$ (5)

Where:

m and n = parameters for a specific prevailing type of flow condition

LS = computed Topographic factor.

As = specific catchment area, i.e. the upslope contributing area per unit width of contour (which is assumed to be equal to the width of a grid cell), in m2 / m.

β = slope angle in degrees.

Vegetation Factor (C)

The C factor depends on vegetation cover and management practices. For this study C was estimated using The Normalized Difference Vegetation Index (NDVI) at a resolution of 250m. The Vegetation factor was estimated using the equation proposed by Karaburun (2010) as follows:

$C = 1.02-1.21*NDVI$ (6)

A field check was performed to ensure that computed values correspond with that observed in field surveys.

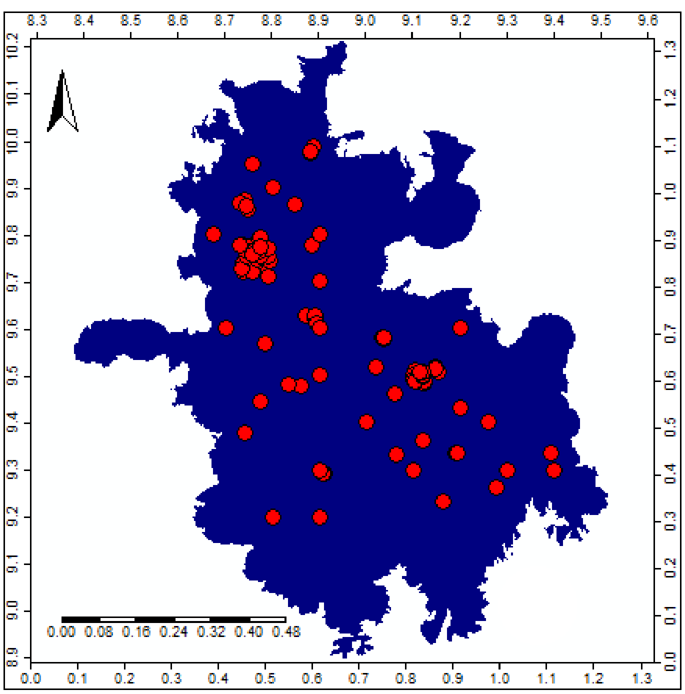

Figure 1: Location of Soil Sampling Sites

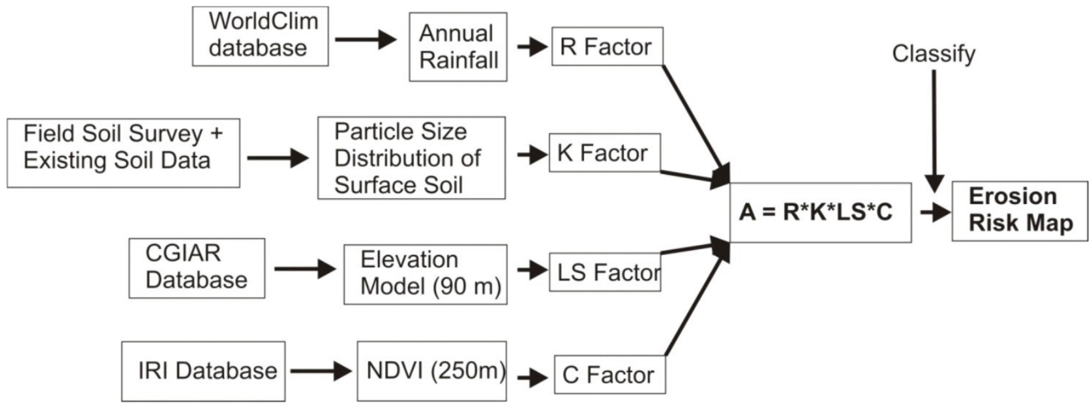

Figure 2: Flow chart for creating a USLE-based erosion risk map

3.0 Result and Discussion

3.1 Rainfall Erosivity in Contex of the Climate

The climate of the Jos Plateau is a variant of the Tropical Continental climate (Bunnett & Okunrotifa, 1984) and is the wet and dry type classified as tropical rainy climate. In addition, the climate is characterized by a mean annual rainfall of 1,260 mm (1050-1403 mm) which peaks between July and August (Olowolafe, 2002). The rains start in April and finish in October: little rain falls during the rest of the year (Hill 1978). The southwestern portion of the Jos Plateau receives greater amount of precipitation than its north eastern part. The month of June to September has the highest humidity (72-83%) with the distribution following similar trends with rainfall.

The Jos Plateau experiences a mean annual temperature of about 22^{o}C with mean monthly values varying between 19.4^{o}C in the coolest month of December when the area comes under the influence of the cool and dry desiccating north-easterly tropical continental air mass (harmattan) and 24.5^{o}C in the hottest month of April (Olowolafe, 2002). Similarly, solar radiation is highest in the dry season months of November to April (20.3 - 22.1 MJ/m^2/day) but lowest in the wet season moths of June to September (16.1 - 18.9 MJ/m^2/day). Spatial distribution of rainfall erosivity over the Jos Plateau is presented in Figure 3. Analysis of the data indicate that rainfall erosivity of study area had a mean of 5117MJ.mm/ha.h.y with a minimum and maximum value of 4032 and 6435 in the eastern and western portion respectively. Rainfall Erosivity values in the study area are not only high but well above the range of values reported by Van de Knijff et al (2000) for the entire European continent. This underscores the role of rainfall in initiating soil erosion on the Jos Plateau.

3.2 Vegetation and Agricultural Land Use

The Jos Plateau lies within the northern Guinea Savanna vegetation zone, which is an open woodland with tall grasses but has its own unique vegetation (Olowolafe, 2002). However open grasslands and farms have largely replaced the original savannah forest (Hill, 1978). In view of the tremendous changes that have been done to the vegetation, Jumbo (1986) grouped it into three categories: (1) Vegetation on hills or hill ranges and on the steep and less accessible plateau margins made up mostly of wood; (2) Vegetation on the 'plains' made up mostly of grass, considerably cultivated and grazed, and interspersed with trees and coppiced shrubs; and (3) Vegetation on mine dumps and ditches, made up principally of two forms of vegetation: (a) areas colonized by trees found on mounds, mine dumps and filled pits, and (b) artificially established vegetation of woody species which are mainly eucalyptus species.

The Jos Plateau is characterized by a mixed farming system. The average land holding size in the study area is 2.36ha per household (Thapa and Yila, 2010). Farmers are practicing rain-fed and irrigated farming, with livestock as integral component. Rainfed farming is practiced mainly in the uplands, characterized mainly by food crops such as maize, cassava, guinea corn, sweet potato, millet, groundnuts, and rice. Irrigated farming is practiced especially along the riverbanks.

Figure 4 shows the distribution of vegetation cover factor (C) over the entire Jos Plateau at the peak of the rainy season. Peak vegetation data of the rainy season was used because erosion by water is the major cause of soil erosion on the Jos Plateau. Analysis of vegetation cover factor indicate a minimum, maximum and mean of and 0, 1, and 0.32 respectively over the entire Jos Plateau area. Further analysis indicates that areas with high, moderate and low vegetation had an areal coverage of 11, 88 and 1% respectively. Spatial coverage of areas with high vegetation coverage is low obviously due to consistent deforestation in the area over the years. The role of vegetation in curtailing erosion has been underscored by many researchers (Morgan, 1995; and Brady and Weil, 1999). However, the prevailing general low vegetation density on the Jos Plateau indicate that (1) soil organic matter content would be low thereby affecting soil physical properties that influence productivity and resilience to agents of erosion; and (2) erosional processes would be on the increase except measures are put in place to reverse the trend.

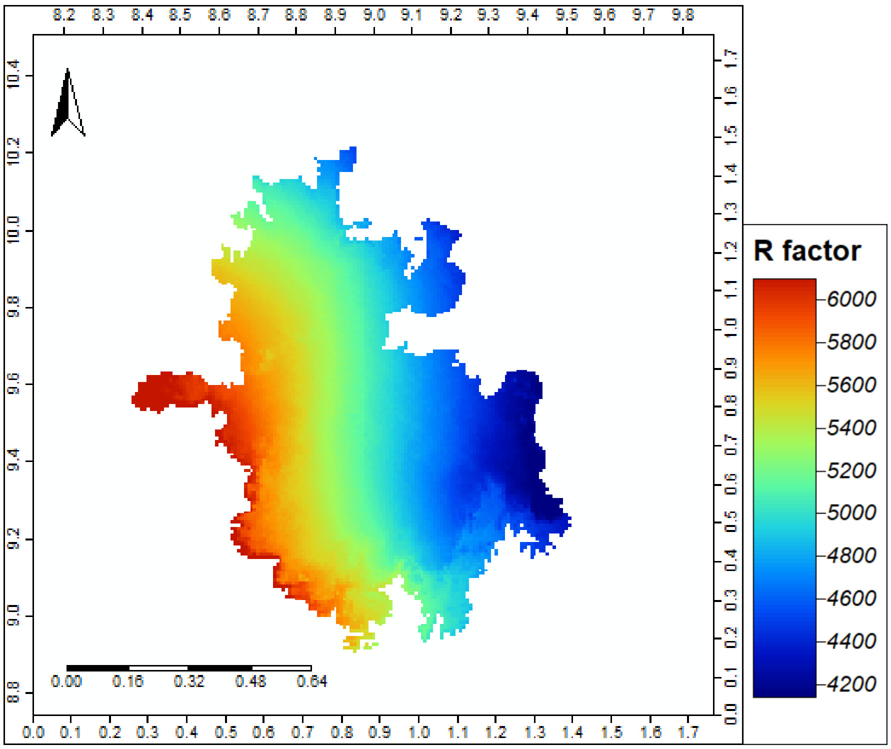

Figure 3: Rainfall Erosivity (MJ.mm/ha.h.y) over the Jos Plateau

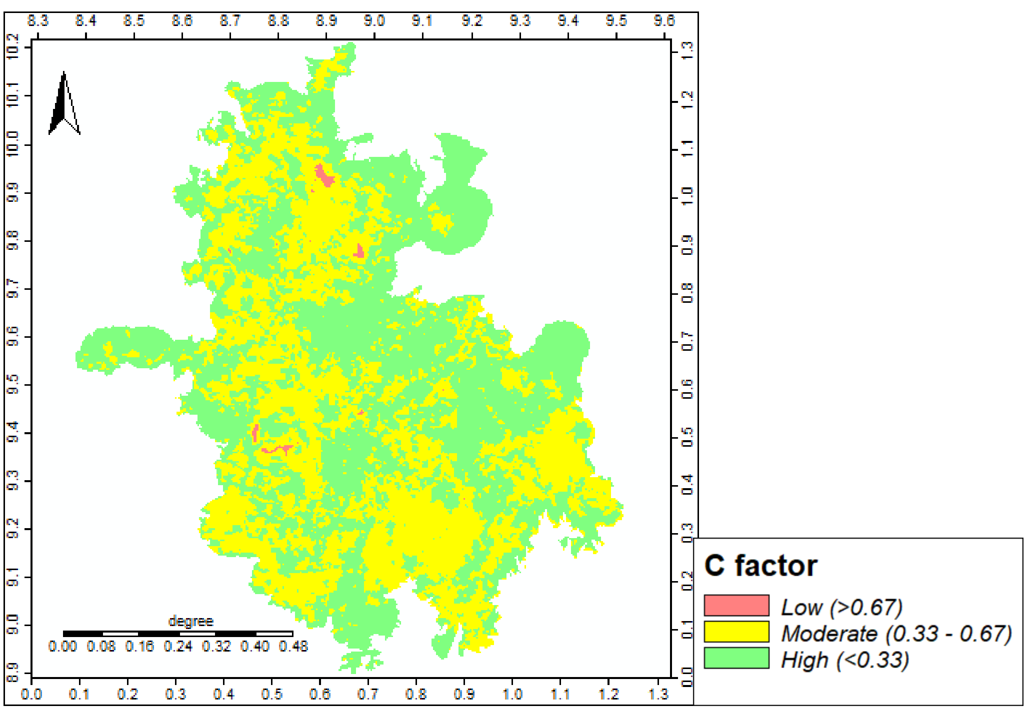

Figure 4: Vegetation cover factor over the Jos Plateau

3.3 Topography

Figure 2 shows the distribution of topographic factor on the Jos Plateau. Geospatial analysis indicates that topographic (LS) factor of the Jos Plateau had a minimum, maximum and mean value of 0.03, 166.17 and 7.24 respectively. Analysis of percent areal coverage imply that the entire area had 52, 34, 7, and 7% low, moderate, high and very high topographic factors respectively. This is similar to that reported by Vijith and Dodge-Wan (2019) who noted that areas with higher-than-normal topographic factors are most likely to generate higher soil erosion rates.

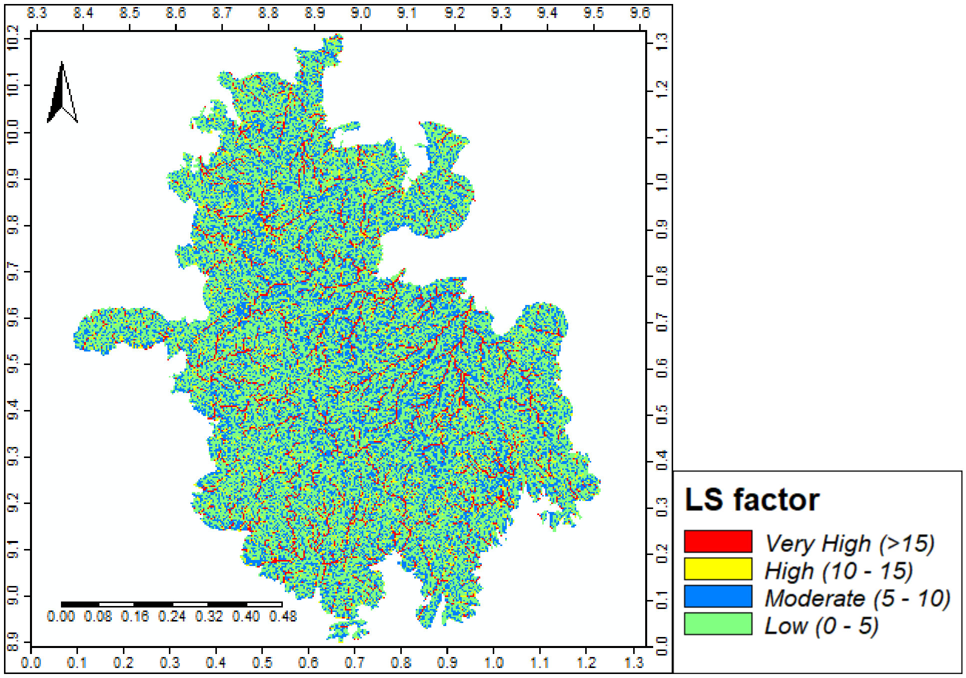

Figure 5: Topographic Factor (LS) over the Jos Plateau

3.4 Soil Erosion

Soil erodibility factor (K) gives an indication of the inherent susceptibility of soils to erosion. The spatial distribution of soil erodibility over arable lands of the Jos Plateau is shown in Figure 6. Minimum, maximum, and mean erodibility values were 0.002, 0.333, and 0.045 t. ha.h/MJ.mm respectively. Soil erodibility values were within the range reported by Gitas et al (2009) for soil derived from granite and gneiss. Percent areal coverage for low, moderate, and high erodibility classes were 9, 71 and 20% respectively. The spatial coverage of the moderate to high erodibility class is most likely because of low organic matter contents and general poor soil structure observed in the study area. Brady and Weil (1999) had noted that low organic matter contents and poor soil structure are some of the factors responsible for susceptibility of soils to erosion.

From Table 1 areas with high to extremely high actual erosion rates cover about 95% of the arable soil of the Jos Plateau. The resultant of this is (1) the wearing away and redistribution of soil materials within the landscape thereby altering soil characteristics and facilitating the evolution of new soil types; and (2) consequently leading to the development of soils with:

i. coarse textures
ii. low organic matter content
iii. none to weak structural development
iv. low available water holding capacity
v. low base saturation
vi. low cation exchange capacity
vii. low fertility and productivity
viii. poor rooting depth

Figure 7 shows a schematic presentation of erosion processes on the Jos Plateau. Spatial distribution of actual and potential erosion rates is presented in Figure 8. A field check was also performed in selected areas and indicated that qualitative assessment of erosion rates on the field corresponded with predicted estimates (Figure 9). It can be seen clearly that virtually the entire area of arable lands of the Jos Plateau is vulnerable to remarkably high potential erosion rates. The percentage of land that is cultivated within a geographic unit indicates the stress or pressure on the land, due to anthropogenic disturbance. Natural vegetation- such as forest or grass - protects the soil from the impact of rainfall and runoff, thus reducing erosion risk (Brady & Weil, 1999). With high proportions of cultivated land within an area, high exposure to the erosive agents may result, thus leading to increased erosion risk.

Similarly, the intensity of cropping influences the rate of erosion. Cropping intensity indicates the extent to which an area is used for cropping. High cropping intensity means high exposure of the soil to erosive energy and other factors that influence the erodibility of a soil. High intensity seasonal cropping with tillage loosens the soil breaks the soil structure and thus makes the soil more vulnerable to erosion. Forest area plays a major role in the interception of rain and the dissipation of its erosive energy. Plants catch the raindrops and from there it slowly trickles down to soil surface reducing surface runoff and allowing more time for infiltration. It is widely established that very minor changes in land cover can causes significant changes in soil erosion (schwab et al, 1993). As such forest cover is an especially important erosion risk indicator.

The following soil conservation measures are proposed based on the erosion classes above:

None to slight: Contour cultivation, and conservation tillage
Moderate: Contour strip cropping, conservation tillage, graded terraces, and grassed waterways; vegetative barriers and agroforestry.
High: These areas require conservation measures organized on a catchment rather than individual farm basis. They should not be used for large scale conventional mechanical tillage schemes.
iv. Very high: These areas have a very high erosion hazard and intensive conservation measures such as terracing, and installation of check dams in gullied areas are required. They are more suited to tree crops than arable crops.
v. Extremely high: These areas require highly intensive conservation measures and should be kept permanently under forest vegetation cover.

4.0 Conclusion

During this research, the mean annual actual and potential soil erosion rates and factors of the Universal Soil Loss Equation were assessed spatially over the Jos Plateau area. Soil erosion rates were far more than tolerable rates thereby influencing soil fertility and productivity. Soil erosion study and mapping is significant to estimate future soil productivity accurately and is of fundamental concern; to balance the use of natural resources against the need for the ecosystem protection from the field and regional scale to the national level. Therefore, concerted efforts should be made in Nigeria to develop a detailed soil erosion data base like the developed countries to aid in making proper and timely decisions for conserving soil resources and sustain agricultural production.

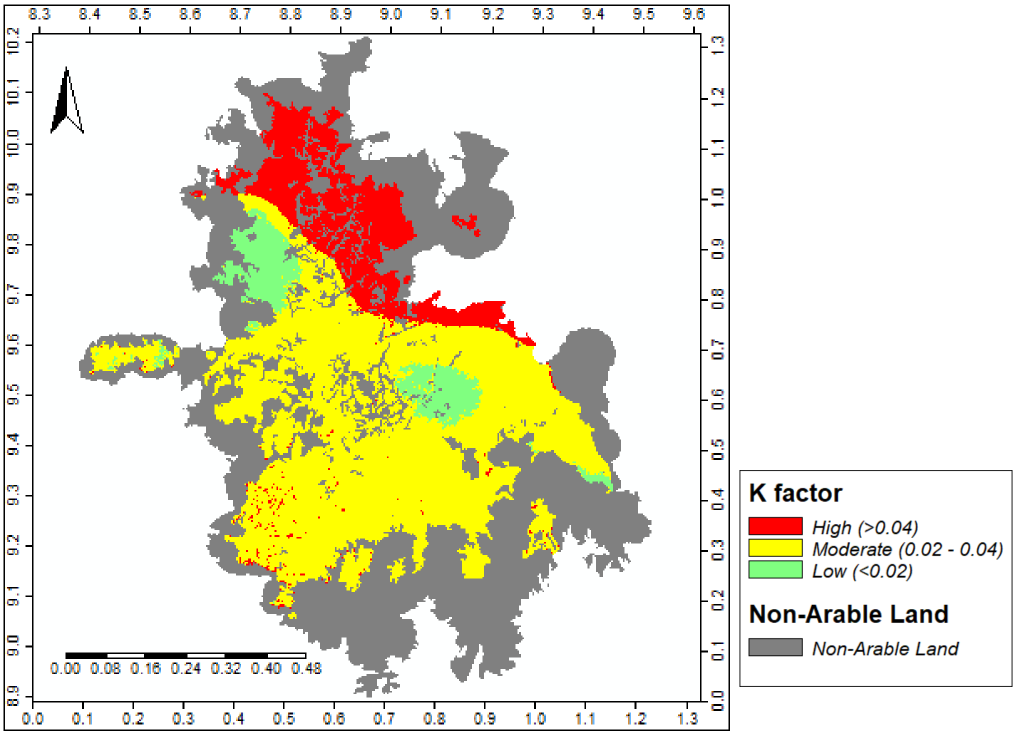

Figure 6: Soil Erodibility over Arable lands of the Jos Plateau

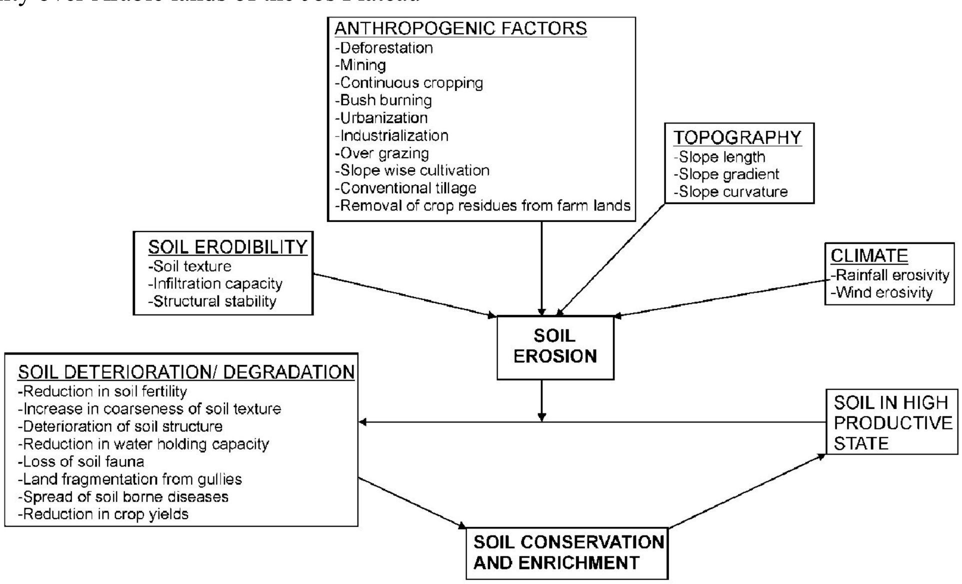

Figure 7: A Model of Soil Erosion Processes over the Jos Plateau (note: soil erosion by wind is negligible)

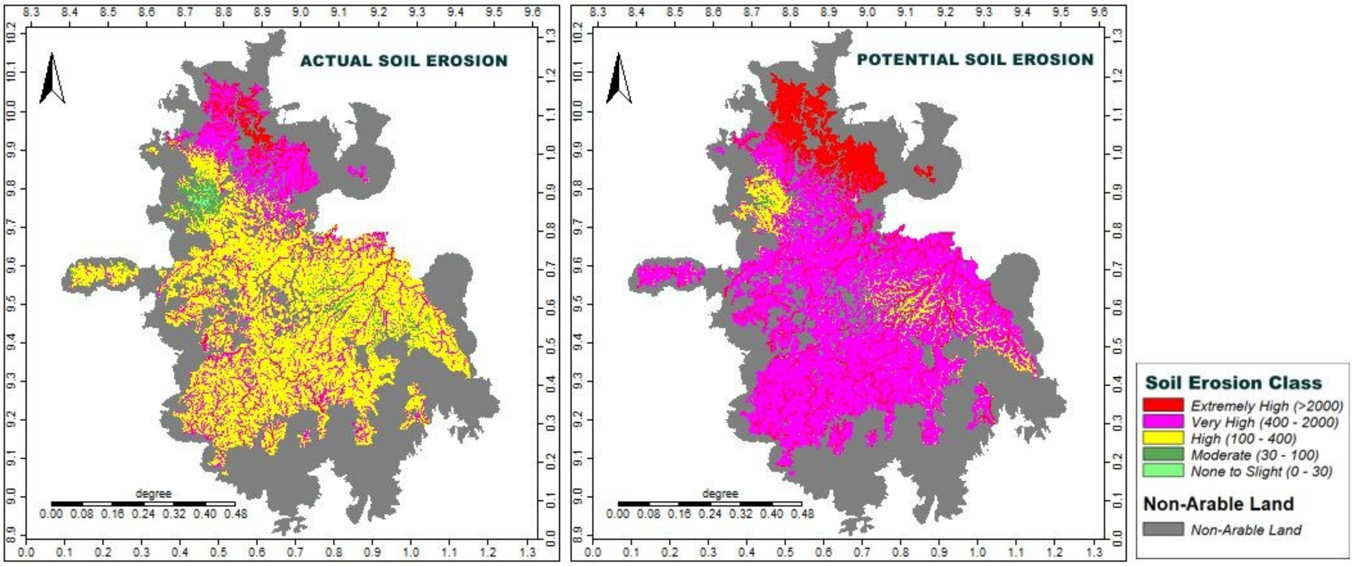

Figure 8: Average Annual Rill and Interrill erosion (tons/ha/year) over Arable Lands of the Jos Plateau Jos Plateau

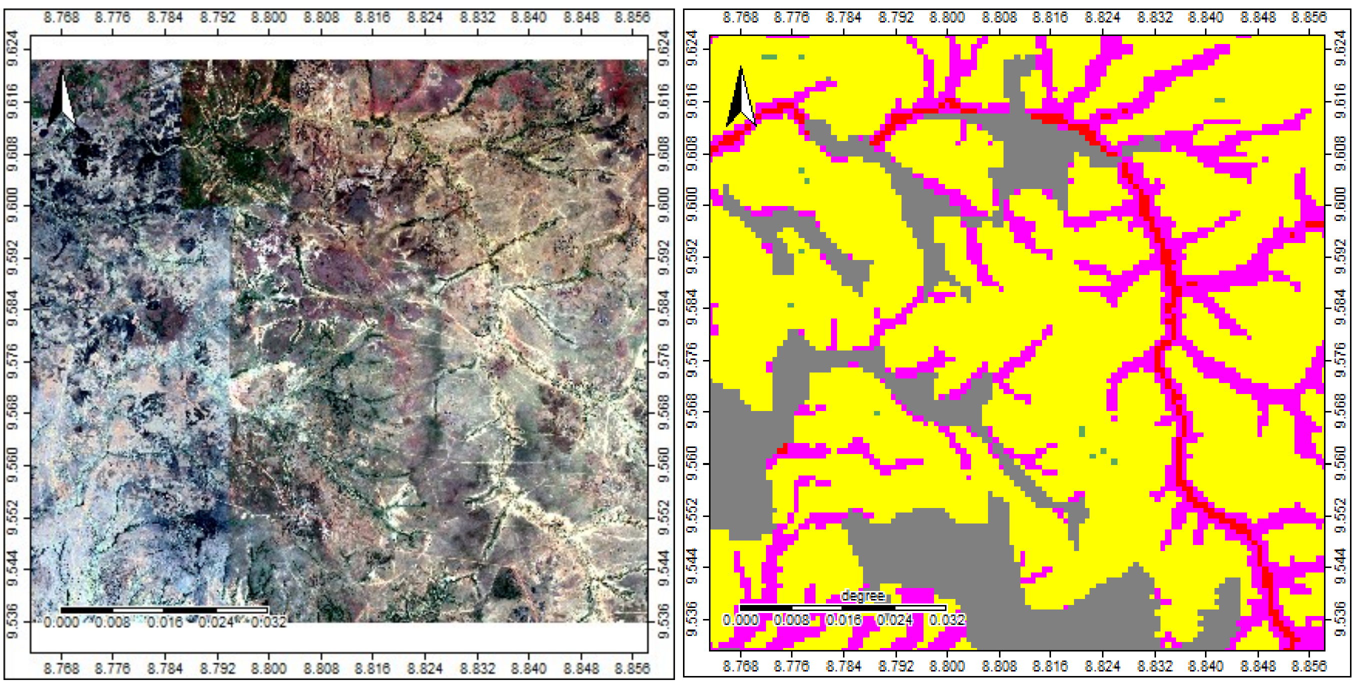

Figure 9: Satellite imagery and actual soil erosion map of Dokku area of the Jos Plateau

Table 1: Erosion Status of Soils on Arable Lands of the Jos Plateau

Description	Annual soil loss (tons/ha/	Percent areal coverage	
		Actual erosion	Potential erosion
None to slight	0 – 30	0.3	0.1
Moderate	30 – 100	4.6	0.2
High	100 – 400	64.4	7.8
Very high	400 – 2000	25.5	71.4
Extremely High	> 2000	5.2	20.6

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