GIS-based estimation of soil erosion rates and identification of critical areas in Anambra sub-basin, Nigeria

Babatunde J. Fagbohun¹ · Adeleye Y. B. Anifowose¹ · Chris Odeyemi² · Olabanji O. Aladejana¹ · Adegoke I. Aladeboyeje³

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Abstract Estimation of soil loss through water erosion is an essential exercise which can help decision makers and planners determine the severity of soil loss through rill and sheet erosion and also curtail the development of further gullies in an area already ravaged by gully erosion. While Universal Soil Loss Equation (USLE) is the most commonly adopted model because it provides a straight forward approach for qualitative estimation of soil loss, however its rainfall erosivity component is found incompetent in most parts of the world. To overcome this deficiency, the Revised Universal Soil Loss Equation (RUSLE) was implemented using rainfall erosivity (R) values peculiar to tropical environment of the Anambra area of Nigeria. Rainfall erosivity (R-factor), soil erodibility (K-factor), slope factor (LS-factor), and cover management (C-factor) were generated in GIS environment and then integrated based on RUSLE equation to estimate the rate of soil erosion. The study indicated that about 1804.39 km² (39.49 %) of the study area have slight erosion rate of 0–10 t ha⁻¹ year⁻¹, while the rates of erosion in 746.60 km² (16.34 %), 1025.38 km² (22.44 %), 659.55 km² (14.43 %), 287.08 km² (6.28 %), and 46.59 km² (1.02 %) of the study area are 10.6–85.3, 85.4–235.2, 235.3–608, 608.1–2200 and >2200.1 t ha⁻¹ year⁻¹ respectively. The

study revealed that high rainfall erosivity combined with moderate to high slope factor and decreasing vegetal cover are the major factors driving soil loss in the area.

Keywords Soil erosion · Geographical information system · Remote sensing · Revised universal soil loss equation model

Introduction

Erosion is the process of detachment and transportation of soil particles by an erosive force. Such erosive force can be wind, ice or water in form of raindrop impact and surface runoff. The development of erosion occurs as a result of interplay between numbers of geo-environmental and geotechnical factors which are better considered together. A major purpose of the soil-loss equation is to guide the making of methodical decisions in conservation planning as the equation enables the planner to predict the average rate of soil erosion for each of the various alternative combinations of cropping systems, management technique and erosion control practices on any particular site (Renard et al. 1997).

It is still a challenge to find a model that sufficiently estimates soil loss through all forms of erosion from a particular site. There are a number of parametric model used in estimating soil erosion, these include the Universal Soil Loss Equation (USLE), Modified Universal Soil Loss Equation (MUSLE), Revised Universal Soil Loss Equation (RUSLE), Water Erosion Prediction Project (WEPP), Limberg Soil Erosion Model (LISEM) and Soil Loss Estimation Model for Southern Africa (SLEMSA). The USLE (Wischmeier and Smith 1978) was formerly accepted as the most suitable equation for estimation of soil

✉ Babatunde J. Fagbohun
jfahb328@gmail.com

¹ Department of Remote Sensing and Geoscience Information System, Federal University of Technology, P. M. B 704, Akure, Nigeria

² Department of Surveying and Geoinformatics, The Federal Polytechnic, P. M. B 5351, Ado-Ekiti, Nigeria

³ Department of Physics, Olabisi Onabanjo University, Ago-Iwoye, Ogun State, Nigeria

loss because of its simplicity and robustness (Desmet and Govers 1996), but its application in other parts of the world other than the United States of America proves it to be insufficient due to disparity in soil types and rainfall patterns experienced in these parts of the world.

The Revised Universal Soil Loss Equation (RUSLE) has instead replaced the USLE. Although the RUSLE is not capable of estimating soil loss through gully erosion, it offers a way to identify potential areas for gully development which can aid development of plans to prevent gully initiation. The RUSLE has improved the effects of soil roughness and the effects of local weather in the prediction of soil loss and sediment yield (Gaffney and Lake Jr 2005). An alternative regression equation was developed for volcanic tropical soils and a correction was developed for rock fragments in soil profile (Renard et al. 1997). The RUSLE followed the same formula as USLE but has several improvements in estimation of factors and broader application to different conditions including forest, rangelands and disturbed areas (Gitas et al. 2009). Several studies has been carried out in different parts of the world in recent years using RUSLE (Adediji et al. 2010; Gitas et al. 2009; Khosrowpanah et al. 2007; Lu et al. 2004; Nangia et al. 2010; Sajaul et al. 2012). This justifies the suitability of the method in regions of diverse climatic conditions and varying soil properties.

RUSLE is an erosion model designed to predict the long-time average annual soil loss carried by runoff from a specific field slopes and with appropriate selection of its factor values, RUSLE will compute the average soil loss (Renard et al. 1997). The soil loss predicted by RUSLE is that produced by sheet and rill erosion. Sheet erosion is first stage of water erosion; it involves the removal of a layer of soil from the land surface by the action of rainfall and runoff. Rills on the other hand occur more on croplands and are usually associated with farming operations.

This study aims at developing an erosion potential model to estimates the amount of soil loss through sheet and rill erosion, and identify zones of high soil loss which are susceptible to development of gully erosion in a part of Anambra Basin by applying the RUSLE.

Study area and data description

Anambra lies between Latitudes 5°40'N and 6°35'N, and Longitudes 7°10'E and 7°20'E. It falls within the Anambra Basin which is underlain by sedimentary rocks. The geology of the area has an influence on erosion process with the occurrence of weak unconsolidated sandy formations which has higher erosional susceptibility (Ofomata 1981).

The evolution of the basin is linked with Santonian folding and uplift of the Abakaliki region resulting in the

dislocation of the depocentre into Anambra platform and Afikpo region (Obboh-Ikuenobe et al. 2005). Prior to folding and uplift, the Asu River Group, Eze Aku Group and Agbani Sandstone/Awgu Shale constitute the lithologies in the Abakaliki region. The evolution of Anambra Basin resulted in the deposition of Nkporo Group during the Campano-Maastrichtian, followed by Mamu and Ajali Formations during the Maastrichtian, Nsukka and Imo Formation during the Palaeocene, Ameki Group during the Eocene, and finally Ogwashi–Asaba Formation during the Oligocene (Nwajide 1990).

Nkporo Group consists of Nkporo Shale, Oweli Sandstone and Enugu Shale. It is overlain by Mamu Formation which consists of shale, coal and sandy shale while Ajali Formation which overlies Mamu Formation is a thick, friable, poorly sorted white sandstone (Gideon et al. 2014; Reymont 1965).

The Nsukka Formation overlying Ajali Sandstone graduates from coarse to medium grained sandstones at the base to a sequence of well-bedded blue clays, fine-grained sandstones and carbonaceous shale with limestone at the top while the overlying Imo Formation consist of blue-grey clays, shale and black shales with bands of calcareous sandstone, marl and limestone (Obboh-Ikuenobe et al. 2005; Reymont 1965).

The Ameki Group consists of Nanka Sands, Nsugbe Formation and Ameki Formation. The Ameki Formation is an alternating sequence of shale, sandy shale, clayey sandstone, and fine-grained fossiliferous sandstone with thin limestone bands (Obboh-Ikuenobe et al. 2005; Reymont 1965).

The Ogwashi–Asaba Formation comprises of alternating coarse-grained sandstone, lignite seams, and light coloured clays of continental origin (Obboh-Ikuenobe et al. 2005).

Anambra area has tropical climatic condition with rainy and dry seasons. The rainy season spans between March and September with full commencement in April. Rainfall stops around October but few showers are sometimes experienced in November and early December. The dry season extends from November to February and it is characterized by harmattan winds. The annual rainfall ranges from 1400 mm in the northern part to around 2500 mm in the southern part, while average annual temperature is about 33 °C (Onwuka et al. 2012).

The terrain is generally varied with highland of moderate elevation in the south and low plains lying to the east, west and north. The plains are almost featureless, except for occasional broad undulations which rise above the flood plains. The effect of high relief of the highlands is well reflected by numerous gullies which are generally located on either the scarp face or dip slopes of the highlands as a result of continuous incision of the highlands by headwaters of the main river systems. Virtually all severe erosion

gullies in the area are located on moderate to very gently dipping poorly consolidated sandstones associated with local or regional highlands. The major highlands, plateau and their precipitous escarpments are formed by sandstone bedrocks of Ajali sandstones and Nanka sands, while the lower slopes and plains are underlain by mainly shaly units of Imo, Mamu, Nsukka and Ameki Formations (Akpokodje et al. 2010). Previous studies in the area indicate that most gullies begin as rills over bare soils and then graduate into gullies by cutting near-vertical walls in poorly cemented soils and/or formations (Akpokodje et al. 2010; Hudec et al. 2005). Hudec et al. (2005) emphasize the progressive widening and deepening of rills with successive rainfall events.

The drainage pattern in the study area is dendritic, with most rivers emptying into River Niger in western part of the area (Fig. 1).

Erosion potential modeling

A detailed erosion potential modeling using RUSLE requires the following geoenvironmental variables as inputs: rainfall erosivity, slope length, slope steepness, soil

erodibility, cover management and support practise. In order to derive these geoenvironmental variables, the following data were processed: Isoerodent map, SRTM with spatial resolution of 30.86 m (1 Arc-Second), soil map, and Landsat 8 with 30 m spatial resolution. The SRTM and Landsat 8 were downloaded from <http://earthexplorer.usgs.gov/>.

Study method

The approach adopted in this study is the RUSLE. The RUSLE is an empirical equation which computes the combined amount of soil loss through sheet, rill and inter-rill erosion as influenced by four major factors affecting erosion. These factors are: climatic erosivity, Soil erodibility, topography and land use and management (McCool et al. 1995). RUSLE is designed to predict the long-time average annual soil loss (A) carried off by runoff from specific field slopes in specified cropping and management systems as well as from rangeland (Renard et al. 1997). Although the basic USLE structure is retained, the algorithms used to calculate individual factors have changed

Fig. 1 Drainage map of the study area

significantly in RUSLE (McCool et al. 1995). The RUSLE is given as:

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

where A is the computed soil loss, R is the rainfall-runoff erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the cover management factor, while P is the support practice factor.

Rainfall erosivity (R -factor)

The rainfall erosivity data used in this study is derived from rainfall erosivity map developed by Salako (2010). The rainfall erosivity maps were developed from daily rainfall amount collected from 17 meteorological stations covering all the ecological zones in Nigeria within 10–33 years period. The daily rainfall was used to calculate rainfall erosivity using the power law relationships developed by Salako (2006, 2008) expressed as:

$$\text{Erosivity Index} = a A^b \quad (2)$$

where Erosivity index is either $EI_{30}\text{-WS}$ ($\text{MJ mm ha}^{-1} \text{h}^{-1}$), product of rainfall kinetic energy (E) based on Wischmeier and Smith (1978) equation (Renard et al. 1997) and maximum 30-min intensity (I_{30}) or $EI_{15}\text{-BF}$ ($\text{MJ mm ha}^{-1} \text{h}^{-1}$), product of rainfall kinetic energy (E) based on Brown and Foster (1987) equation (Renard et al. 1997) and maximum 15-min intensity (I_{15}). A is daily rainfall amount (mm), a and b are parameters with different values for the sub-humid and humid regions (Salako 2010).

Salako (2006, 2008) showed that the coefficients of determination obtained for the relationship of R with rainfall amount were better using daily rather than annual values for sub-humid and humid zones of Nigeria. The two indices above ($EI_{30}\text{-WS}$ and $EI_{15}\text{-BF}$) were used to compute monthly and annual isoerodent maps. Although similar trend of decrease from the southern to the northern part of the country was observed in resulting monthly and annual isoerodent maps obtained by application of the two indices, monthly values of erosivity were recommended for conservation planning because the use of annual time-scale for the assessment of erosivity can obscure information on potential erosivity of few rainfall events that occur in the relatively dry regions (Salako 2010). Additionally, even though the overall means of EI_{30} and EI_{15} were similar, EI_{15} was found to be 1.7 times greater than EI_{30} due to the difference between intensity (I_{30} and I_{15}) components (Salako 2010). He further recommended the use of monthly EI_{15} (Fig. 2) for seasonal and annual soil loss computations because short-term intensities reveal rainfall erosivity better in the tropics. The rainfall erosivity value ranges from $1000 \text{ MJ mm ha}^{-1} \text{h}^{-1}$ in the northern part to $6000 \text{ MJ mm ha}^{-1} \text{h}^{-1}$ in the southern part of the country. Similar high rainfall erosivity associated with arid/semi-arid tropics to humid tropics have been observed in other parts of the world (Hoyos et al. 2005; Mannaerts and Gabriels 2000; Xie et al. 2016).

Isoerodent lines in EI_{15} monthly isoerodent map (Fig. 2) were digitized and converted to an isoerodent map using Topo to Raster interpolation tool in ArcGIS. A subset of the study area was subsequently extracted from the interpolated isoerodent map covering Nigeria.

Fig. 2 Isoerodent map of Nigeria with mean monthly values of EI_{15} ($\text{MJ mm ha}^{-1} \text{h}^{-1}$) index during the rainy season of May–October (Modified after Salako 2010). Study area is outlined in red

Slope length factor (*L*-factor)

Erosion increases as slope length increases (McCool et al. 1997). Slope length is a dimensionless factor calculated as a ratio of the horizontal length of the actual plot divided by the unit plot length raised to exponent m . It is defined as the distance from the point of origin of the overland flow to the point where either slope length decreases sufficiently enough for deposition to begin or to where the flow links to a river (Wischmeier and Smith 1978). It is calculated as.

$$L = \left(\frac{\lambda}{72.6ft} \right)^m \quad (3)$$

where λ is the horizontal projection of slope length, 72.6 ft is the standard unit plot length, while m is a variable slope length component (McCool et al. 1997). The exponent m is related to the ratio of rill erosion (caused by the flow) to inter-rill erosion principally caused by raindrop impact (McCool et al. 1997).

Slope steepness factor (*S*-factor)

Soil loss increases more rapidly with slope steepness than it does with slope length (McCool et al. 1997). Soil erosion occur more rapidly on steep slopes due increase in the

velocity of overland flow and increase in the potential energy that is associated with the soil mass being elevated above the reference point (Khosrowpanah et al. 2007). The slope steepness factor as estimated by McCool et al. (1987) and is given as

$$S = 10.8 \sin \theta + 0.03 \quad s < 9\% \quad (4)$$

$$S = 16.8 \sin \theta - 0.50 \quad s \geq 9\% \quad (5)$$

The L and S are fundamentally related and are generally grouped together in the RUSLE calculations. The effect of topography on erosion in the RUSLE is accounted for by the LS factor. The slope map (Fig. 3) of the study area was generated from the SRTM DEM. LS factor was then computed by combining Eqs. 3, 4 and 5 using the slope map of the study area.

Soil erodibility (*K*-factor)

Soil erodibility factor is a parameter that represents the integrated average annual value of the total soil and soil profile reaction to a large number of erosion and hydrologic processes such as detachment and transport by raindrop impact, surface flow, localized deposition due to topography, tillage induced roughness and rainwater infiltration into the soil profile (Römkens et al. 1997).

Fig. 3 Slope map of the study area

Fig. 4 Soil map of the study area (adapted from FDLAR 1990)

Soil erodibility can be best obtained by direct measurement on the natural rough of plot, however this approach is restricted by time and economic factor (Römken et al. 1997). Derivation of K -factor can be achieved either by empirical computation (Römken et al. 1997) or extracted from a nomograph (Wischmeier and Johnson 1971). Due to the complexity of deriving K values by empirical approach through soil sampling for a large area as in the case of this study area and the susceptibility of the result to inaccuracies due to improper estimation of any of the parameters used in deriving the values, therefore a soil map (Fig. 4) produced by the Soil Division of Federal Department of Agricultural Land Resources in 1990 served as the source of information for soil types and descriptions. Based on the description of each soil type and comparison with erodibility derived for soils in parts of the study area by Ezeabasili et al. (2014) appropriate K values were assigned to each soil type using a nomograph.

Cover management factor (C -factor)

The C -factor represents the effect of land cover on erosion. It relates to the percentage of vegetation cover for a particular area, and is perhaps the most important USLE/RUSLE factor because it represents conditions that can

most easily be managed to reduce erosion (McCool et al. 1995). The C -factor in RUSLE is computed using empirical equations on field measurements of ground cover. However the availability of satellite images which provide up to date information on land cover has resulted in their use for derivation of C -factor (Lin et al. 2002; Machiwal and Katara 2015; Warren et al. 2005). In this study, cloud-free Landsat 8 images acquired in December 2014 were used to generate cover factor. Normalized Difference Vegetation Index (NDVI) was used to estimate the amount of vegetation cover; this approach was adopted simply because classification of the image and assigning values to each class usually do not account for variation in the amount of cover between pixels in a single landcover class.

Considering that NDVI ranges from -1 to 1 , with 1 representing full vegetation cover whereas C -factor ranges from 0 – 1 with 1 representing no cover conditions, a reversal linear transformation established by Lin et al. (2002) was subsequently used to transform NDVI values to cover information. Detailed examination reveals that NDVI values below 0.175 are related to water bodies, hence these values were masked out before transformation and were subsequently assigned 0 value (Machiwal and Katara 2015) in the C -factor after transformation.

Fig. 5 Rainfall erosivity map of the study area

Fig. 6 Combined slope length and slope steepness of the study area

Support practise (*P*-factor)

The *P*-factor represents broad, general effects of practices such as contouring. It accounts for how surface conditions affect flow paths and flow hydraulics. Currently, no major erosion control/support practices are used in the area, hence the *P*-factor was assigned a value of 1.0 such that it had no effect on the calculation of soil loss.

Results and discussion

Rainfall erosivity (*R*-factor)

Rainfall erosivity of the study area was obtained by interpolation of isoerodent lines. The maximum value is $4510 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$ while the minimum is $3894 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$. The mean and standard deviation are 4209.75 and $147.18 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$ respectively. The highest values occur in the southern part of the study area

and decreases gradually toward the northern part. The rainfall erosivity map (Fig. 5) shows that rainfall distribution varies within the study area and the use of a single *R* value cannot sufficiently capture the rainfall variability in the area.

Slope length and steepness (*LS*-factor)

The computed slope length and steepness factor ranges from 0 to 193.5 (Fig. 6). The mean is 1.64 while the standard deviation is 5.60. Examination of the histogram of *LS*-factor shows that 98 % of the area has values less than 15. The higher values occur mainly along the slopes of highlands in the south while low plains lying to the east, west and north generally have low values.

Although previous studies suggest that slope lengths are usually less than 120 m and generally do not exceed 300 m (McCool et al. 1997), however the validity of this is yet to be confirmed in mountainous and complex landscapes (van Remortel et al. 2001).

Fig. 7 Spatial distribution of soil erodibility in the study area

Soil erodibility (*K*-factor)

Erodibility values were assigned to each soil type based on soil description and information available in literature. The spatial distribution of the *K*-factor within the study area is shown in Fig. 7. Considering that shale and sandstone are the dominant lithologies in the study area, the soils derived from these rock types are generally rich in sand and clay having very little silt. The *K*-factor varies from 0.08 to 0.19. The soil type with the highest *K*-value (0.19) is a loamy sand/sandy loam soil which has been described as having the highest silt/clay ratio (Ezeabasili et al. 2014), and covers 114.75 km² (2.51 %) of the study area. Soil having erodibility value of 0.15 covers 2387.21 km² (52.17 %) representing the soil with the highest percentage of area covered. Poorly drained loamy sand with *K*-value of 0.12 covers an area of 92.28 km² (2.02 %), while deep imperfectly drained loamy sand to sandy loam with *K*-value of 0.10 covers an area of 1348.5 km² (29.47 %). Well drained loamy sand to sandy loam with erodibility value of 0.09 covers 621.55 km² (13.58 %). The soil with the lowest *K*-value (0.08) which is a well-drained sandy loam to loamy sand and sometimes gravelly soils covers the smallest part of the study area 11.25 km² (0.25 %).

Cover management factor (*C*-factor)

Vegetation and land use/cover are important factors in erosion process. The cover management factor describes the effect of land use/cover on erosion. The amount of vegetation cover has significant influence on the rate of erosion. By estimating the amount of vegetation cover through NDVI and subsequently transforming the values, *C* values between 0 and 0.5 were obtained (Fig. 8). The highest *C* values correspond to sand deposits occurring along the banks of River Niger on the west while value of 0 is assigned to the river body.

Soil loss in study area

The average annual soil erosion (*A*) is estimated by implementing Eq. 1 which involves multiplying the factors developed as raster data. The map of average annual soil loss is shown in Fig. 9a. The mean value of the estimated soil loss is 214.82 t ha⁻¹ year⁻¹. The estimated soil erosion is further classified into six (Table 1) in order to reveal the severity of soil loss. The classification shows that about 1804.39 km² (39.49 %) has erosion rate of 0–10 t ha⁻¹ year⁻¹ which can be considered as slight rate of erosion, while about 746.60 km² (16.34 %) experience moderate soil loss between 10.6–85.3 t ha⁻¹ year⁻¹. The areas under classes of high, very high, severe and very severe are

Fig. 8 Spatial distribution of cover and management factor of the study area

1025.38, 659.55, 287.08, and 46.59 km² corresponding to 22.44, 14.43, 6.28, 1.02 % respectively.

The highest erosion rates were found to occur in areas where slope is greater than 15°. The study shows that rainfall and slope factors are the crucial factors driving soil erosion in the area. High rainfall erosivity combined with moderate to high LS factor and low cover result in high rate of soil loss. Southern Nigeria is a high rainfall region, good vegetation cover and heavy plant residues would be expected to protect the soil surface throughout most part of the year. However with rapid increase in population, the demand for more agricultural lands has significantly increased, and marginal lands have been cleared up for farming. The soil is no longer adequately protected by vegetation cover, thereby exposing the soil to heavy tropical storms. The greatest erosion will therefore occur when rain storms fall on bare or poorly covered soils.

Conclusions

This study focused on estimating soil loss potential and identifying critical areas for soil conservation measures. The RUSLE has been the most widely used method to estimate soil loss due to water erosion at any point in a

Fig. 9 **a** Spatial distribution of average annual soil loss **b** Histogram of classes of average annual soil loss and corresponding area

Table 1 Average annual soil loss classes

Soil erosion rate (t ha ⁻¹ year ⁻¹)	Area (Km ²)	Area (%)	Degree of erosion
0–10.5	1804.39	39.49	Slight
10.6–85.3	746.60	16.34	Moderate
85.4–235.2	1025.38	22.44	High
235.3–608	659.55	14.43	Very high
608.1–2200	287.08	6.28	Severe
>2200.1	46.59	1.02	Very severe

landscape where erosion is active because it is conceptually simple to understand and easy to implement.

Implementation of RUSLE reveals that larger part of the study area has slight to moderate soil loss; however, a considerable portion shows severe soil loss which requires conservation measures. It is obvious that large quantities of soil get eroded from the study area annually. The high rainfall erosivity associated with frequent short-interval intensity rainfall in the region plays a significant role on the amount of soil erosion.

Remote sensing provides a means to calculate some of the major factors controlling soil erosion. The

implementation of RUSLE by combining data from remote sensing and other sources in a GIS environment offers a rapid and cost-effective approach for estimating the average annual soil erosion particularly in ungauged catchments. It must be emphasized that comparison between estimated soil loss and measured soil loss could not be achieved; it is therefore imperative that future studies will compare estimated soil loss to measured soil loss. The soil loss estimate obtained in this study might not necessarily correspond to the actual rate of soil loss; however, the method adopted in this study provides qualitative assessment of soil loss which is beneficial for identifying critical

areas of soil erosion that require proper planning and conservation strategies.

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