Available online at www.worldnewsnaturalsciences.com

World News of Natural Sciences

An International Scientific Journal

WNOFNS 55 (2024) 271-284 EISSN 2543-5426

GIS Based Predictive Analysis of Gully Erosion Sites in Part of Delta State, Nigeria Using Soil Loss Model

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ABSTRACT

Gully erosion presents a significant challenge in developing countries, adversely impacting soil integrity, infrastructure, and community well-being. This study focuses on Delta State, Nigeria, located between Latitudes 6°29'38.563’ N and 5°0'33.342’N and Longitude 4°59'10.59’E and 6°46'6.569’E, with specific attention to the Obomkpa and Jesse Erosion sites. This study centred on the predictive analysis mapping of gully erosion in some parts of Delta State using soil loss model (RUSLE). RUSLE model predicts long term rates of inter-rill erosion from field to different management practices which consists of five (5) parameters. The primary data include coordinates obtained from field survey, AsterDEM, satellite imageries were used to prepare the topographic factors and landuse/landcover factor while the secondary data of annual rainfall, Soil map and land management data were used to prepare rainfall erosivity, soil erodibility and conservation practices layer respectively. The thematic layers prepared were integrated into RUSLE model in ArcGIS to predict the erosion risk map. The results were categorized in their various levels of erosion risks as in low, moderate, high and very high. This comprehensive approach offers insights crucial for effective erosion management and sustainable environmental practices in the region.

***Keywords*:** ArcGIS, Erosion, DEM, RUSLE model, Satellite imagery, erosivity

(Received 09 June 2024; Accepted 01 July 2024; Date of Publication 03 July 2024)

1. INTRODUCTION

The depletion of natural resources, particularly soil, is one of the major issues of the modern era that has emerged in the past ten years (Turner et al., 2016; Wassie, 2020). Degradation of agricultural land by soil erosion is a worldwide phenomenon leading to loss of nutrient rich surface soil, increased runoff from more impermeable subsoil and decreased water availability to plants. Thus, estimation of soil loss and identification of critical area for implementation of best management practice is central to success of a soil conservation program (B.P. Ganasri, H. Ramesh). The total land area subjected to human-induced soil degradation is estimated at about 2 billion hectares. By this, the land area affected by soil degradation due to erosion is estimated at 1100Mha by water erosion and 550Mha by wind erosion (Saha, 2003). Soil erosion may impact soil productivity, surface water sources, their quality, ecological balance, and landscape (Bilotta et al., 2007; Issaka & Ashraf, 2017). Soil erosion is responsible for many challenges in ecological protection and sustainable development, including land degradation, water shortage and destruction of ecosystem service function (Hou et al., 2017; Panagos, 2018). The prediction of soil erosion has been paid much attention, while there were uncertainties and difficulties due to the changing climate and land surface conditions (Bezak et al., 2021; Borrelli et al., 2021).

A gully is characterized as a deep, relatively permanent canal with vertical walls on either side that allow passing water currents for a short period. Gully erosion occurs when rushing surface water erodes a deep channel, removing and transporting the eroded surface soil (Ghorbanzadeh, Blaschke, et al., 2020). Over time, these gullies cause soil erosion, alter the surrounding environment, and accelerate the sedimentation of rivers and dams (Belayneh et al., 2020; Ghorbanzadeh, Blaschke, et al., 2020; Hancock & Evans, 2010). Sediment from eroding gullies does not necessarily go straight to creeks and rivers. Larger soil particles such as sand and silt are readily deposited and move downstream as a series of pulses during larger floods. However, gully erosion from soils with a high percentage of clays—dispersive soils—can produce very small clay particles that remain in suspension and can result in turbid water. (Andebutop et al., 2023).

FAO (1990) recognized three main environmental problems, facing Nigeria: soil degradation and loss, water contamination, and deforestation The presence of gully sites is one of the hazard features that characterize this zone as well as other States that adjoin them. Over the years, tremendous contributions regarding the understanding and behaviour of gully erosion and possible control measures have been documented by many scholars (James et al., 2007; Valentin et al., 2005; Poesen et al., 2003; Marzolff and Poesen, 2009; Li et al., 2003; Casasnovas, 2003).

The Revised Universal Soil Loss Equation (RUSLE) is the most extensively used empirical soil erosion model. It is the present state of art in soil erosion modeling. It has been modified to give sediment yield as well. Basically RUSLE, which lumps enter-rill and rill erosion together, is a regression equation (Jha Raghunath 2002). RUSLE like its predecessor the Universal Soil loss Equation (USLE) is an erosion prediction model designed to predict the long-term average annual soil loss from specific filed slopes in specified land use and management systems (i.e. crops, rangeland, and recreational areas) (Bagarello et al., 2010).

Geographic Information is today being extensively used in decision-making processes because it has become a fundamental element to provide better understanding about one's surroundings. Sustainable development relies on the control of the consequences of public decisions regarding natural resources, people and the involved interrelationships. This study was aimed at using GIS to map and predict erosion sites of the study areas using RUSLE model to enhance critical decision making in dealing with the problem of erosion in under developed Country especially Nigeria.

2. STUDY AREA

This study was carried out in two different locations in Delta State of Nigeria. The first is in Obomkpa which is located in Aniocha North LGA, with coordinates of Latitude N 6º 23' 6.6'' and Longitude E 6º 28' 58'' with estimated length and depth of 2500m and 6m respectively. The site is located in a densely populated area. The second area is located in Jesse, Ethiope West LGA, with coordinates of Latitude N 5º 51' 45.5'' and Longitude E 5º 43' 4.8''. The area is floodplain located in a densely populated area. Delta state occupies the area on the lower River Niger in the South-South geopolitical zone of Nigeria; and is bounded on the West by the Atlantic Ocean and Ondo State, on the North by the Edo State; and on the East by Anambra State, Imo State and Rivers State, while Bayelsa State bounds it on the South. It covers an area of about 16,842 sq. km; and returned a population figure of about 4,098,291 people with 2,674,306 males and 2,024,085 females during the 2006 Census exercise.

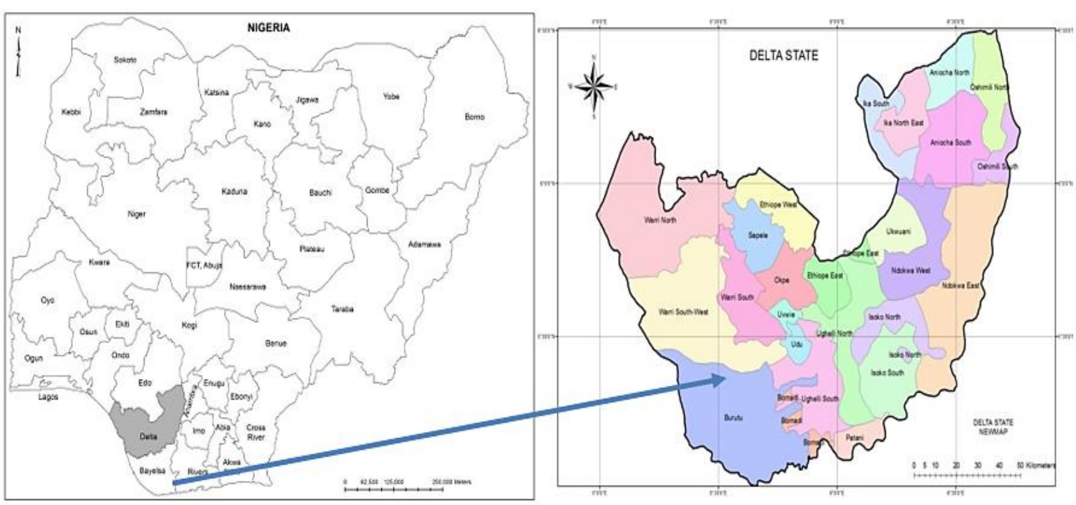

Figure 1. Map showing location of Delta State

3. METHODOLOGY

The advent of Geographical Information System (GIS) technology has allowed the Revised Universal Soil Loss Equation (RUSLE) equation to be used in a spatially distributed manner because each cell in a raster image comes to represent a field-level unit. In this study, the modified RUSLE model by Turner et al., 2016) was adopted. The equation is given below:

A = LS* R* K* C* ………………………………………(1)

where A is the annual soil loss (metric tons ha-1yr-1); R is the rainfall erosivity factor [MJ mm h-1 ha-1 yr-1]; K is soil erodibility factor [metric tons ha-1 MJ –1 mm-1]; LS = slope length factor (dimensionless); C is land cover and management factor (dimensionless, ranging between 0 and 1); and P is conservation practice factor (dimensionless, ranging between 0 and1). Rainfall is the main driving force of soil erosion, and thus the calculation of Re plays a major role in predicting event soil loss (Lee & Heo, 2011; Wang et al., 2014).

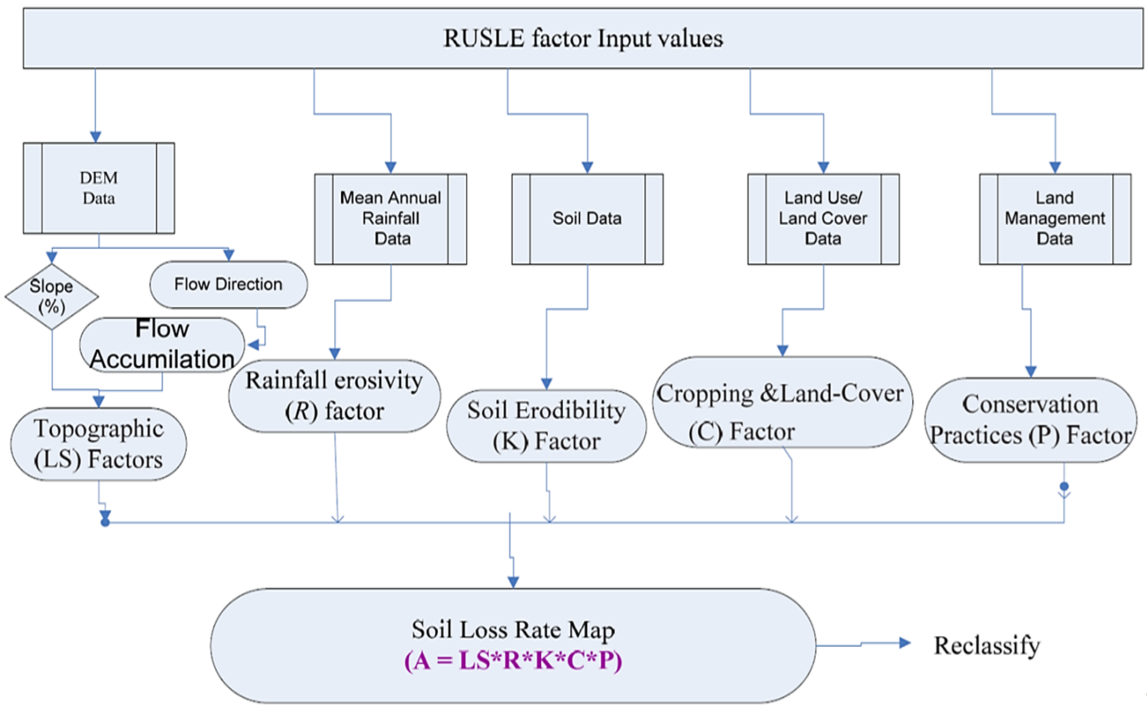

Figure 2. RUSLE Implementation Model Flowchart

Individual GIS files relevant for the RUSLE model were built for each parameter and combined on a cell by cell-grid modeling procedure in ArcGIS 10.4 to predict soil loss in a spatial domain.

3. 1. TOPOGRAPHIC (L AND S) FACTORS

The influence of topography on erosion is complex. The local slope gradient (S sub-factor) influences flow velocity and thus the rate of erosion. Slope length (L sub-factor) describes the distance between the origin and termination of inter-rill processes. Termination is either the result of the initiation of depositional processes or the concentration of flow into rills. In RUSLE, the LS factor represents a ratio of soil loss under given conditions to that at a site with the 'standard' slope steepness of 9% and slope length of 22mplot (Robert, et al.,2000). The steeper and longer the slope, the higher is the erosion. The Equation for Calculation of LS:

$$LS = [0.065 + 0.0456(slope) + 0.006541(slope)^2] \times (slope\_length \div const)^{NN} \ldots\ldots\ldots(2)$$

where: slope = slope steepness (%)
slope length = length of slope (m)
constant = 72.5 Imperial or 22.1 metric
NN = See Table 1.0 below

Table 1. NN Values

S	< 1	Slope	Slope	**≥ 5**
NN	0.2	0.3	0.4	0.5

3. 2. PRECIPITATION DATA AND RAINFALL EROSIVITY (R) FACTOR

Rainfall erosivity is a term that is used to describe the potential for soil to wash off disturbed, de-vegetated areas and into surface waters during storms. Rainfall data were acquired from Nigeria Meteorological Agency (NIMET) for stations covering the country, including Benin and Warri through temporal space spanning from 1980 to 2015 which were used to calculate the rainfall erosivity Factor (R-value). The mean annual precipitation surface was interpolated to determine the value of each cell based on the values of nearby cells.

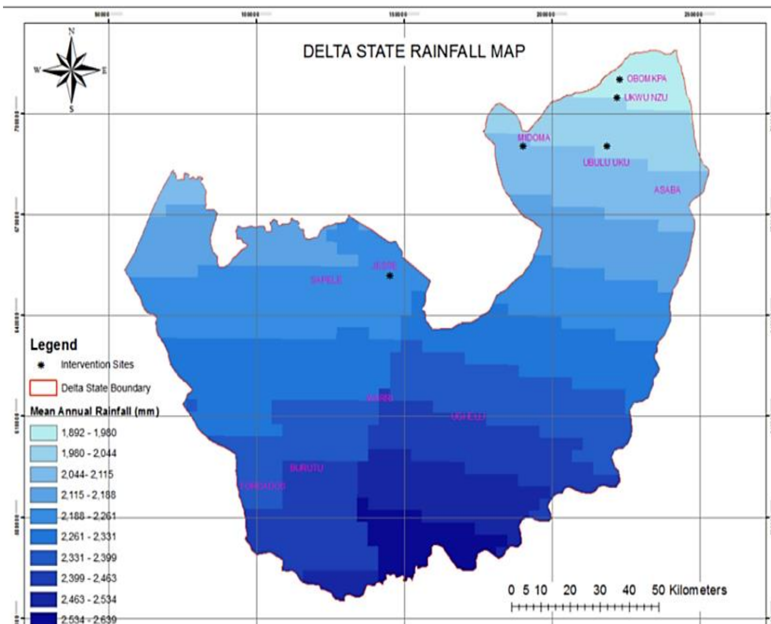

Figure 3. Rainfall distribution

Within the RUSLE parameters, rainfall erosivity is estimated using the EI30 measurement (Renard et al., 1997), that means R is the average annual sum of the event rainfall-runoff (erosivity) factor when this factor is given by the product of the kinetic energy

of the rainstorm E and the maximum 30 minutes rainfall intensity I30.
In this study, Hurni's empirical equation (Hurni, 1985) that estimates R-value annual total rainfall was used. It is given as:

$$R = -8.12 + 0.562P \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where R is the rainfall erosivity factor and P is the mean annual rainfall (mm).

3. 3. SOIL DATA AND SOIL ERODIBILITY (K) FACTOR

The soil data for this study was obtained from the soil map of Nigeria produced in the Department of Geoinformatics and Surveying, University of Nigeria Nsukka. This map was used for analyzing the soil erodability factor (K-value). The erodibility of a soil is an expression of its inherent resistance to particle detachment and transport by rainfall. Erodibility depends essentially on the amount of organic matter in the soil, the texture of the soil especially sand of 100-2000 μ and silt of 2-100 μ, the profile, the structure of the surface horizon and permeability (Kim. 2006, Ganasri, 2016) In this study, K- values estimated by (Kim. 2006, Robert, 2000) was used and the vector data were first rasterized and each raster (grid-cell) was assigned K-values (See Table 2.0 below).

Table 2. K Factor Data (Organic Matter Content)

Textural Class	Average	Less than 2 %	More than 2 %
Clay	0.22	0.24	0.21
Clay Loam	0.3	0.33	0.28
Coarse Sandy Loam	0.07	--	0.07
Fine Sand	0.08	0.09	0.06
Fine Sandy Loam	0.18	0.22	0.17
Heavy Clay	0.17	0.19	0.15
Loam	0.3	0.34	0.26
Loamy Fine Sand	0.11	0.15	0.09
Loamy Sand	0.04	0.05	0.04
Loamy Very Fine Sand	0.39	0.44	0.25
Sand	0.02	0.03	0.01
Sandy Clay Loam	0.2	-	0.2
Sandy Loam	0.13	0.14	0.12
Silt Loam	0.38	0.41	0.37
Silty Clay	0.26	0.27	0.26
Silty Clay Loam	0.32	0.35	0.3
Very Fine Sand	0.43	0.46	0.37
Very Fine Sandy Loam	0.35	0.41	0.33

3. 4. LAND USE/COVER DATA AND CROP MANAGEMENT (C-VALUES) FACTOR

The cover management factor (C-values) reflects the effect of cropping and management practices on the soil erosion rate. It is used to determine the relative effectiveness of soil and crop management systems in preventing soil loss. The C-value is a ratio comparing the soil loss from land under a specific crop and management system to the corresponding loss from continuously fallow and tilled land.

To determine the C-values and-use/ land-cover map of the study area was used. A land-use and land-cover map of each intervention site watershed was prepared from Landsat ETM+ imagery acquired from Global Land Cover Facility (GLCF). Supervised digital image classification technique was employed and was complemented with field surveys that provided on-the-ground information about the types of land use and land-cover classes. Six land-use and land-cover classes were recognized. These include Tree Forest, Shrub Forest or bush, grass land, agricultural or farm land and bare land and built-up areas. Based on the land cover classification map, the analysis of crop management factor (C-value) was made. The crop and management factor (C-value) corresponding to each crop/vegetation cover was estimated from Table 3. below. After changing the coverage to grid, a corresponding C-value was assigned to each land-use class using the 'reclass' method in ArcGIS.

Table 3. Cropping and land-cover C-values.

Land-use and land-cover type	C factor value
Forest	0.02
Grassland	0.01
Cultivated land (cereals/pulses)	0.17
Bare land	0.6
Shrub	0.014

3. 5. DETERMINING CONSERVATION PRACTICES (P-VALUES)

The conservation practices factor (p-values) reflects the effects of practices that will reduce the amount and rate of the water runoff and thus reduce the amount of erosion. It depends on the type of conservation measures implemented, and requires mapping of conserved areas for it to be quantified. The P-value ranges from 0 to 1 depending on the soil management activities employed in the specific plot of land. In Delta State, there are few areas that have been treated with terracing through the agricultural extension programme of the government, and these are poorly maintained as implementation was performed without participation of the local people. The traditional conservation measure is a drainage ditch which is meant to drain excess runoff from croplands during rainstorms, and in some areas such as Ubulu Uku, rain water harvesting is practiced. As data were lacking on permanent management factors and there were no defined management practices, we used the P-values suggested by Bewket, et al., (2009) that consider only two types of land uses (agricultural and non-agricultural) and land slopes. Thus, the agricultural lands are classified into six slope categories and assigned P-values; while all non-agricultural lands are assigned a P-value of

1.00. A corresponding P-value was assigned to each land use type using the re-class method in GIS.

Table 4. Conservation practices factor (P-value)

Land use type	Slope (%)	P factor
Agricultural land	0-5	0.11
	5-10	0.12
	10-20	0.14
	20-30	0.22
	30-50	0.31
	50-100	0.43
Other land	all	1.00

Source: Adapted from Wischmeier & Smith (1978) & Bewket and Tefer 2009)

4. RESULTS AND ANALYSIS

4. 1. OBOMKPA WATERSHED EROSION RISK MAP

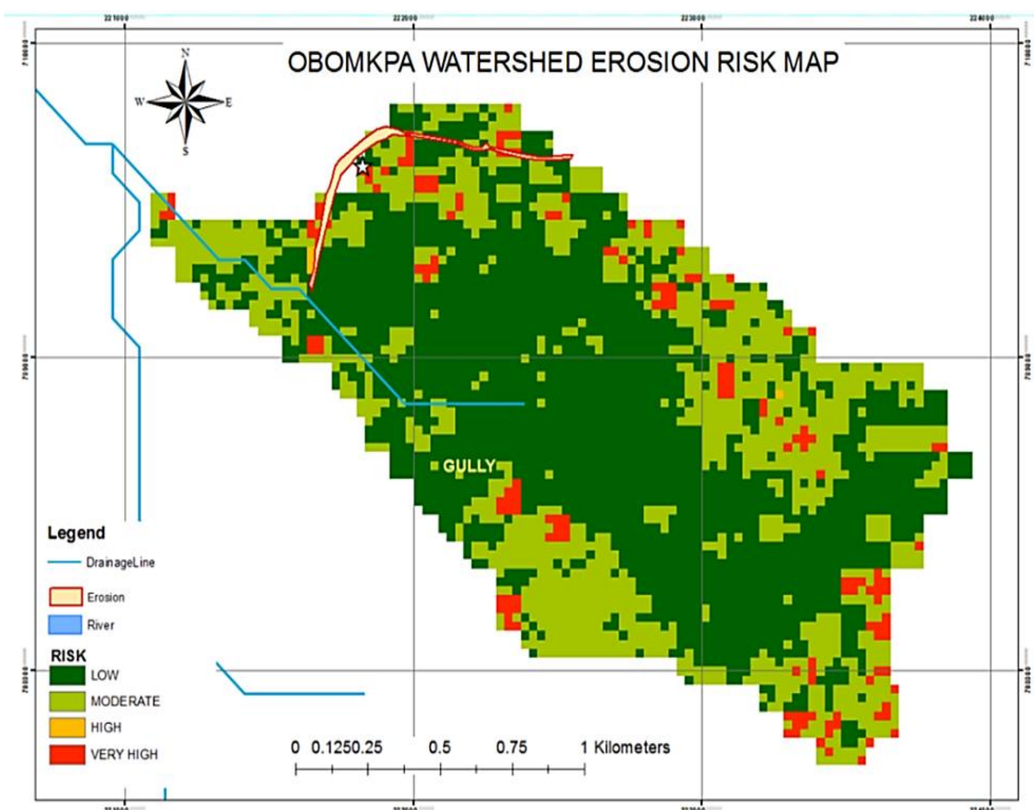

Figure 4. Obomkpa Watershed Erosion Risk Map

Table 5. Potential erosion classes of Obomkpa

Erosion Class	Erosion Area (m^2)
Low	2615588.907
Moderate	3582469.886
High	137004.600
Very High	292423.6003

Table 5 shows the area of different potential erosion classes in the watershed. The table shows that nearly 292423.6003m2 of lands within the watershed has very high erosion potential which constitutes 4% of the study area see fig 1.6, while 2615588.907m2 areas of land records the lowest erosion risk class. Fig 5 shows that the 54% of the study area has low risk of erosion.

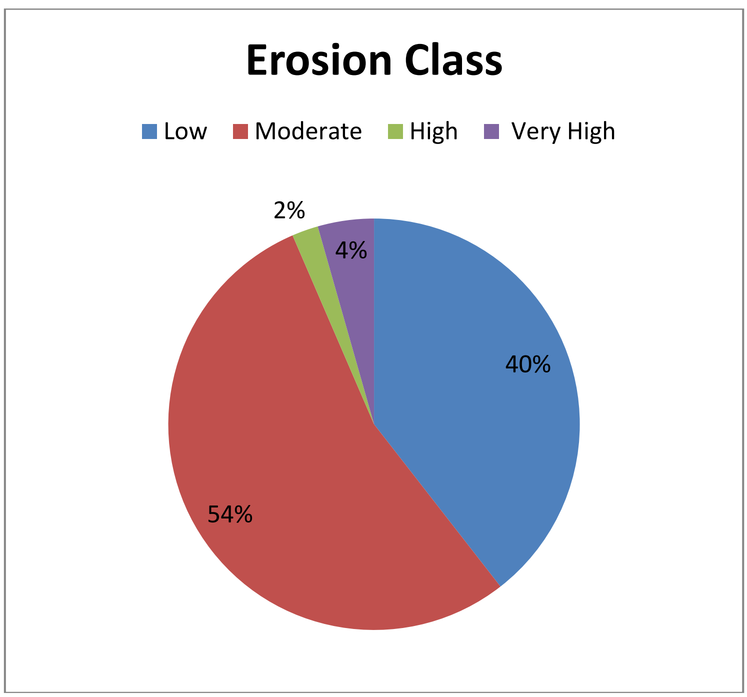

Figure 5. Obomkpa Watershed Erosion Risk Map

Figure 6 shows the overlay result of the erosion risk with the satellite imagery covering Obomkpa in order to assess areas that should be treated as the erosion risk zones especially areas with very high risk with residential buildings. It is shown that there is need for erosion management practice measures be adopted in these areas to prevent further erosion and possible flooding especially buildings within the very high erosion risk zones to avoid severe damages of property and even loss of lives mainly children.

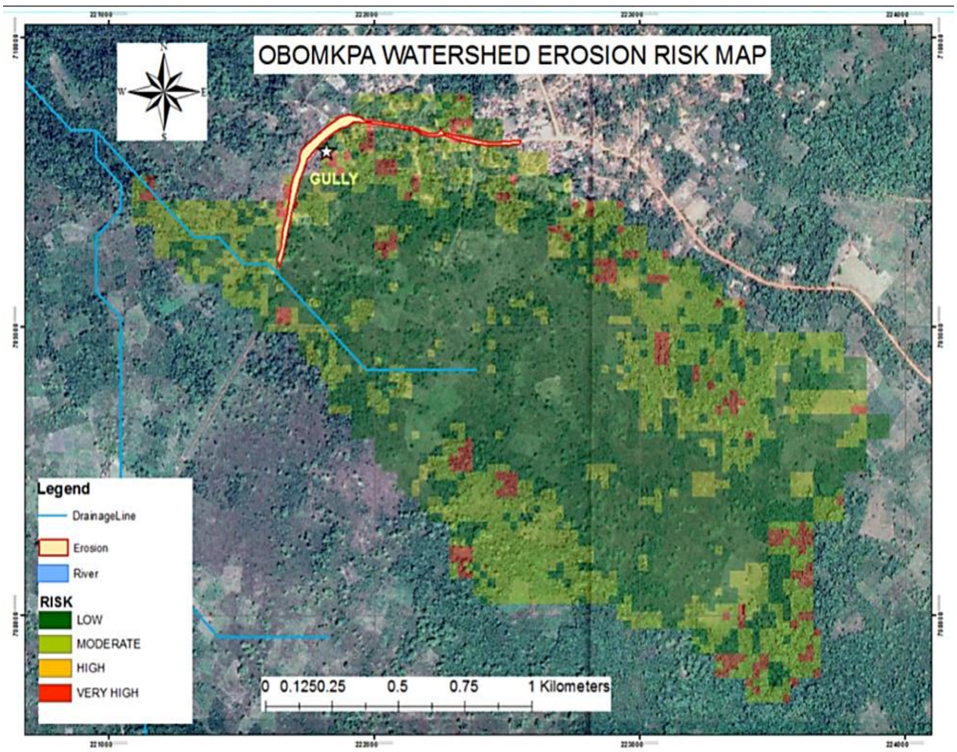

Figure 6. Obomkpa Erosion Class

4. 2. WATERSHED EROSION MAP FOR JESSE

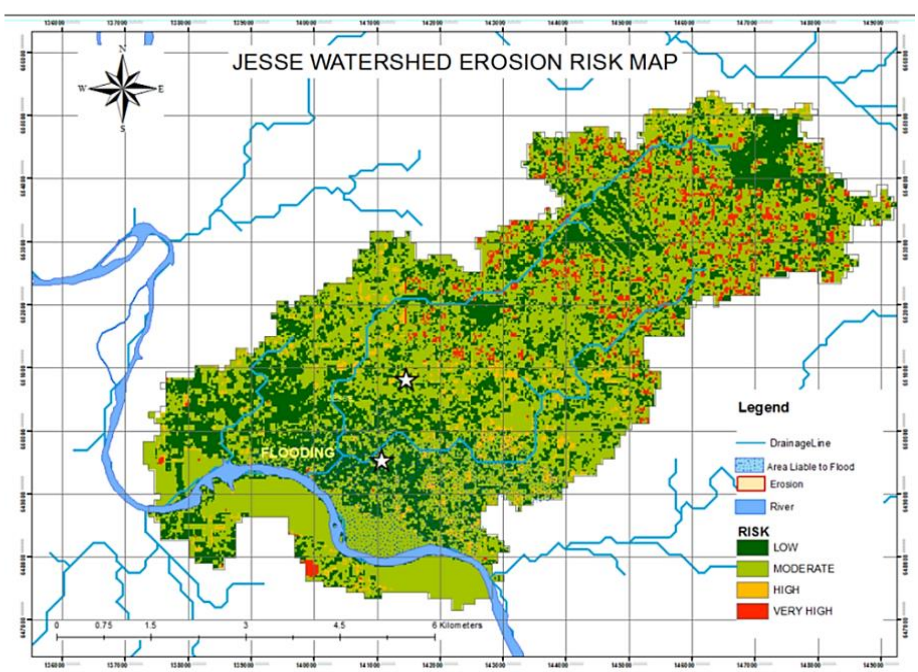

Figure 7. Watershed Erosion Map for Jesse

Table 6 shows the area of different potential erosion classes in the catchment. It is shown that about 12% of land within the watershed has very high erosion potential. These areas should be treated as the erosion hazards and the watershed management practices should be adopted in this area to prevent erosion.

Table 6. Potential erosion classes of Jesse

Erosion Class	Erosion Area (Ha)	Percentage %
Low	781.609	25
Moderate	1709.257	54
High	312.831	10
Very High	378.564	12

The agriculture land on more than 100 slope has higher erosion potential and gully located at Obomkpa increased the flow of water. Areas within the built areas with poor drainage system should be identified and agricultural lands should be converted to agro-forestry farming, agro-management practice measures to minimize the erosion and other mechanical approach be adopted to prevent further expansion of gullies.

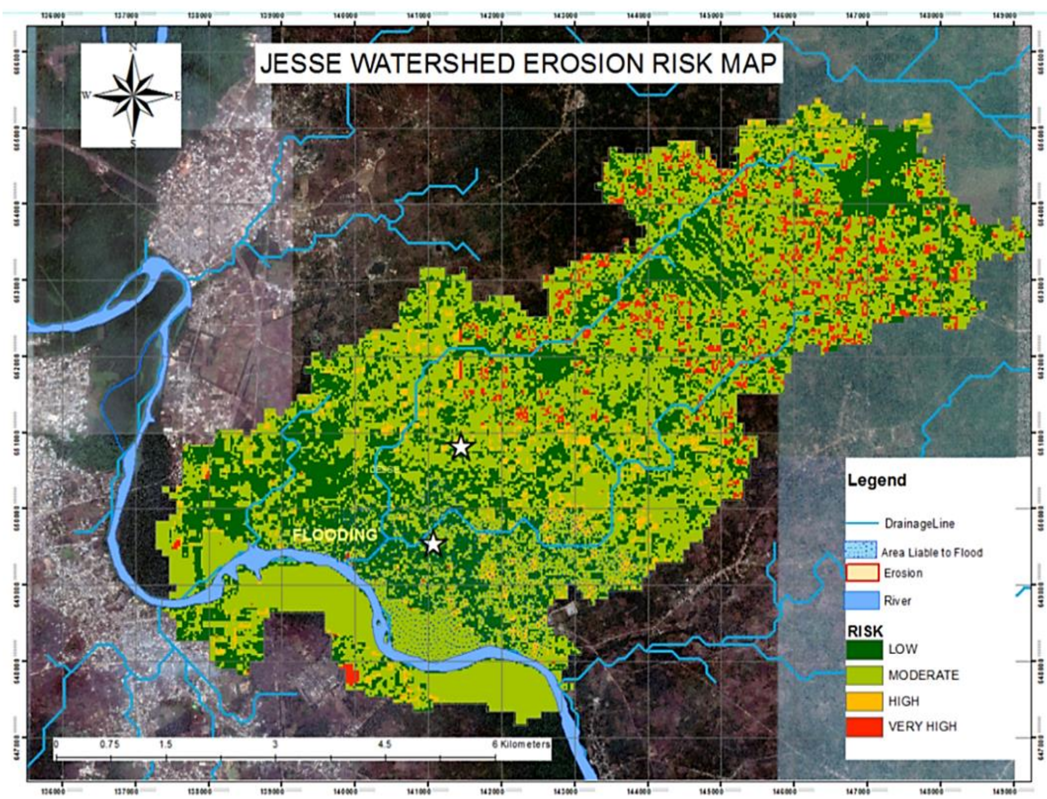

Figure 8. Watershed Erosion Map for Jesse

5. CONCLUSION

It is evident from this study that proactive measures should be taken against the human activities that encourage or promote the risk of erosion expansion in the study areas. It also shows the need for government or its agency to periodically map these watershed areas in order to monitor, make precise and productive decision in the management of erosion. This study has demonstrated that the applications of GIS techniques are useful tools in generating spatial and quantitative information on soil erosion and risk assessment mapping.

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