UJEAS

UNIZIK JOURNAL OF ENGINEERING AND APPLIED SCIENCES

UNIZIK Journal of Engineering and Applied Sciences 5(2), June (2025), 2364-2374
Journal homepage: https://journals.unizik.edu.ng/index.php/ujeas
PRINT ISSN: 2992-4383 || ONLINE ISSN: 2992-4391

Modeling the Impact of Climate Change on Soil Erosion and Flooding Using Remote Sensing and Geographic Information System (GIS)

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Abstract
Climate change significantly impacts soil erosion and flooding in agricultural zones, intensifying environmental degradation. This study models and predicts these effects in the Aguata Agricultural Zone of Anambra State, Nigeria, using Geographic Information System (GIS) and remote sensing techniques. The Revised Universal Soil Loss Equation (RUSLE) and Watershed Erosion Prediction Project (WEPP) were used to develop susceptibility maps. Factors of the rainfall erosivity (R-factor), soil erodibility (K-factor), slope length and steepness (LS-factor), vegetation cover (C-factor), and conservation practices (P-factor) were analyzed. The study reveals a mean soil erosion rate of 0.79 tons per hectare per year, while the soil erosion next ten years' prediction model indicates an increase to 0.82 tons per hectare per year. Likewise, the flood model recorded a total flow accumulation of 2,823,864.50 m², an average flow accumulation of 13.81 m², a current mean flood risk of 10.98 mm, a total flood risk of 2,244,474.11 mm, respectively. However, the flood prediction model reveals a rise to 22.12 mm mean flood risk and 4,523,622.06 mm total flood risk over the next decade due to increased rainfall. Both studies underscore the critical need for effective mitigation strategies, improved drainage systems, and climate adaptation policies to combat soil erosion and flooding. Implementing sustainable conservation measures will be essential in minimizing climate change's adverse effects on agriculture in the region.

Keywords: Climate Change, Soil Erosion, Flooding, Remote Sensing, Hydrological Modeling

1.0 Introduction

Climate change, characterized by long-term shifts in temperature, precipitation, and atmospheric conditions, has intensified environmental challenges, particularly in agriculture (IPCC, 2014). Among the most critical disasters affecting farmlands are soil erosion and flooding, which threaten food security, land productivity, and local economies (Liana and Damien, 2020). Climate change exacerbates these disasters by altering rainfall patterns, increasing storm intensity, and accelerating land degradation (Karolina and Agnieszka, 2023). Soil erosion occurs when topsoil is removed by water, wind, or human activities, reducing soil fertility and making farming difficult (Dede and Thomas, 2020). Increased rainfall intensity and prolonged dry periods accelerate soil degradation, making farmlands vulnerable to loss of productivity. Flooding, often caused by heavy rainfall and rising water levels, further deteriorates soil quality, destroys crops, and displaces farmers (Borrelli et al., 2020). Both disasters form a vicious cycle erosion weakens soil retention, increasing runoff and exacerbating flood risks. If left unchecked, these issues will continue to threaten agricultural zones, necessitating adaptive strategies for resilience (Kirkby et al., 2004).

In Nigeria's Aguata Agricultural Zone (Anambra State), climate change has intensified soil erosion and flooding, severely impacting agriculture (Ofomata, 1985). Heavy rainfall has led to extensive topsoil loss, land degradation, and increased flood risks (Okpala-Okaka and Ogbu, 2019). However, the specific mechanisms linking climate change, soil erosion, and flooding in this region remain poorly understood. The aim of the study is to employ the Geographic Information System (GIS) technology to model climate change's impact on soil erosion and flooding in

Aguata Agricultural Zone. The objective(s) is to provide data to guide policies on land use, climate resilience, and disaster mitigation while helping farmers adapt to changing soil and water conditions (Kang, 2024). By identifying conservation strategies to improve soil retention and flood prevention, the research offers localized data for informed climate response measures. Furthermore, it contributes to Nigeria-specific climate research and disaster management efforts (Ogunbodede et al., 2022).

Assessing climate change's impact on soil erosion and flooding over 30 years (1993–2023), this research will use Python-based GIS models to predict trends for the next decade. The findings will provide critical insights into mitigating climate-induced agricultural disasters and improving resilience in the region.

2.0 Materials and methods

2.1 Study Area - The Aguata Agricultural Zone, one of the four agricultural zones in Anambra State, Nigeria, is situated in a sub-humid climatic region (Ofomata, 1985). It covers an area of approximately 534 square kilometers and includes four local government areas: Nnewi North, Nnewi South, Orumba South, and Orumba North as shown in Figure 1.

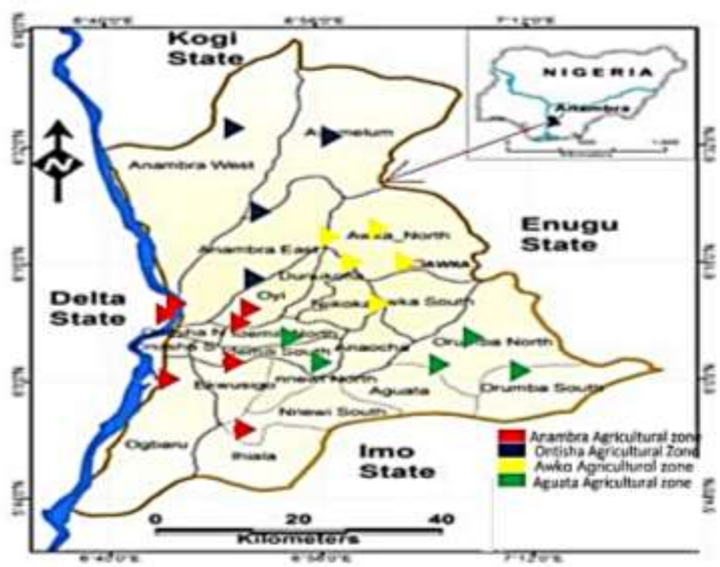

Figure 3.1: Map of Anambra State showing Aguata Agricultural Zone
Source: Ohaturuonye (2022)

The climate is tropical, with a raining season starting from April to October and a dry season starting from November to March. Annual rainfall ranges between 1,500 mm and 2,000 mm, supporting rainfed agriculture, though climate variability can cause water stress (Odekunle, 2004). The temperature averages between 25°C and 32°C, contributing to high evapotranspiration rates, which affect soil moisture retention and necessitate irrigation during the dry season (Adedokun et al., 1989). The region is water-rich, with tributaries of the Niger River and the Anambra River, which support irrigation, fisheries, and domestic water use (Ezenwaji et al., 2016). The topography includes a mix of lowland plains and undulating terrains, with fertile alluvial soils along riverbanks that support diverse crops such as rice, cassava, maize, and vegetables. However, soil erosion and leaching are concerns in the region, requiring soil management practices (Igbokwe et al., 2008).

2.2 Data Collection and Processing - The study utilized two datasets which includes the Geographical Information System (GIS) and climate dataset. The Geographical Information System (GIS) dataset comprises the

Digital Elevation Model (DEM); this was sourced from the USGS, 30m resolution and was used for the terrain analysis, watershed delineation, and hydrological modeling. It was processed through conversion, projection (WGS 1984 UTM Zone 32N), resampling, and sink filling.

Satellite Imagery: The satellite imagery used was obtained from the Landsat 8 with a 30m resolution. It was used for land cover and vegetation analysis, with preprocessing steps including conversion, radiometric correction, NDVI and EVI calculation, and alignment.

Land Cover: the land cover was obtained from the USGS NLCD, with a 30m resolution: Processed for spatial alignment, resampling, and accuracy verification using satellite imagery and field observations.
Soil Type: the soil type was sourced from the USDA SSURGO, with a 30m resolution. The soil type was processed through conversion, projection, resampling, and validation against field data for soil erosion modeling.
Secondly, the climate dataset which comprises the Rainfall Data was sourced from the Nigerian Meteorological Agency (NiMet). The rainfall data was processed into a raster format, re-projected, resampled, and validated against historical records for accuracy in hydrological modeling.

2.3 Development of Soil Erosion Model - The soil erosion model was developed to predict soil erosion of Aguata Agricultural Zone. The comprehensive model was constructed following a systematic sequence of steps, including Modeling Framework, Algorithm Development, and implementation within a GIS environment as detailed below.
Modeling Framework: The modeling framework was based on established principles and equations from the Revised Universal Soil Loss Equation (RUSLE) and the Watershed Erosion Prediction Project (WEPP). These models are widely used for predicting soil erosion rates and understanding runoff and sediment dynamics.
Algorithm Development and Testing: Algorithms were developed to automate the computation of critical parameters in the RUSLE and WEPP models. Python programming language was employed for spatial analysis and the development of raster-based processing algorithms for each erosion and flood models.

Erosion and flood Modeling Parameters: The following parameters were calculated and integrated into the model. The R-Factor (Rainfall Intensity and Erosivity Factor), which was calculated using rainfall data representing the volume and intensity of rainfall contributing to flooding. The SCS Curve Number (Soil Runoff Potential Factor) was derived from soil type and land use data to estimate runoff potential. The LS-Factor (Slope Length and Steepness Factor) was computed from the DEM, quantifying the impact of terrain on water flow and accumulation. The C-Factor (Vegetation Cover Factor) was based on vegetation indices such as NDVI and EVI, representing the effect of vegetation in reducing runoff. Additionally, the Drainage Density Factor was calculated using hydrological data to assess the efficiency of drainage networks in mitigating flooding. Likewise, the K-Factor (Soil Erodibility Factor) was derived from soil type data indicating soil susceptibility to detachment and transport. The models were implemented using ArcGIS software, a robust platform for spatial analysis, raster processing, and hydrological modeling. A Python programming language was employed for scripting, automating workflows, and performing advanced computations.

For flood and erosion susceptibility analysis, raster layers representing each factor (R, SCS, LS, C, Drainage Density for flooding; R, K, LS, C, P for erosion) were computed and combined to generate susceptibility maps. Vector layers, including watershed boundaries and stream networks, were integrated to enhance spatial analysis and visualization. Overlay analysis using GIS tools was performed to compute the overall flood and erosion susceptibility maps, ensuring a spatially explicit representation of risk areas. Hydrological tools were employed to analyze flow direction and flow accumulation, identifying areas with concentrated runoff and potential flooding or erosion hotspots. Hence, integrating these factors, the models effectively highlight areas at risk, supporting better decision-making for flood and erosion management.

3.0 Result and Discussion

The soil erosion and flood models developed as well as the next ten years' prediction model was based on the effect of climate change on environmental disasters such as erosion and flood in aguata agricultural zones of Anambra State. Four (4) different results stages is presented and discussed, namely; the terrain analysis, the morphometric parameters, the hypsometric analysis, the soil erosion and flood modeling and prediction, respectively.

3.1 Terrain analysis -

3.1.1 The Digital Elevation Model (DEM): The terrain analysis of the Aguata Agricultural Zone was conducted using a Digital Elevation Model (DEM), which provided insights into elevation range, slope variations, and overall terrain patterns. The study revealed that the minimum elevation in the area is 50 meters, representing low-lying features such as valleys, plains, or gully erosion sites, while the maximum elevation reaches 236 meters, indicating the presence of hills, ridges, or elevated plateaus (Figure 2). The mean elevation was found to be 100.91 meters, suggesting a moderately elevated landscape, though it is slightly skewed by extreme values. The median elevation was recorded at 94 meters, slightly lower than the mean, indicating a terrain distribution with more land closer to lower elevations.

The elevation variation within the study area was calculated as 186 meters, suggesting moderate topographic relief characterized by rolling hills or foothills. The difference between the mean and median elevations reflects a positively skewed distribution, meaning that while much of the terrain is closer to the lower elevation levels, a few high points elevate the overall average, this finding supports the research of (Pike and Wilson, 2021). This terrain analysis is crucial for understanding factors such as erosion risks, water flow patterns, and agricultural suitability in the region.

3.1.2 *Slope analysis*: The slope analysis of the Aguata Agricultural Zone quantifies the steepness of the terrain, providing essential insights for hydrology, geomorphology, land use planning, and hazard assessment. The study revealed that the mean slope is 58.36 degrees, indicating a generally steep landscape typical of hilly or mountainous regions. However, the averaging process may obscure significant variations in slope across different areas. The median slope, recorded at 63.43 degrees, suggests that half of the terrain is steeper than this value, while the other half is less steep as shown in Figure 3. Since the median is slightly higher than the mean, the slope distribution may be negatively skewed, with fewer gentle slopes affecting the average value. The standard deviation of 16.55 degrees reflects a moderate level of variability, indicating a mix of steep and gentle slopes within the study area. The high mean and median slope values suggest that the region is predominantly steep, which can influence factors such as accessibility, vegetation patterns, and water flow dynamics, this finding support the study of Sharma *et al*., 2016. The presence of steep slopes may also contribute to erosion and potential geomorphological changes, while gentler slopes are more likely to be found in valley floors or plateau-like areas.

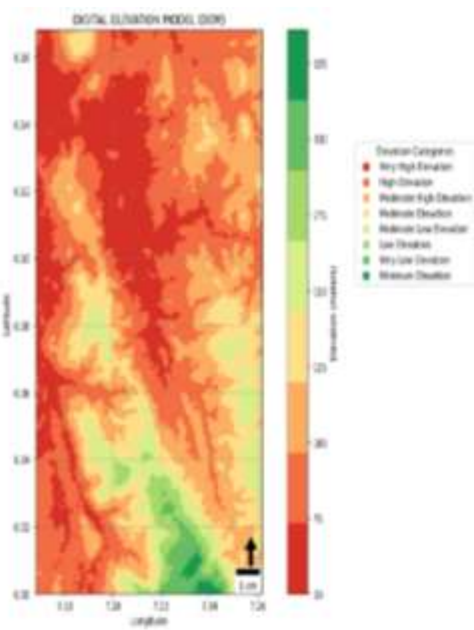

Figure 2: The Digital Elevation Model

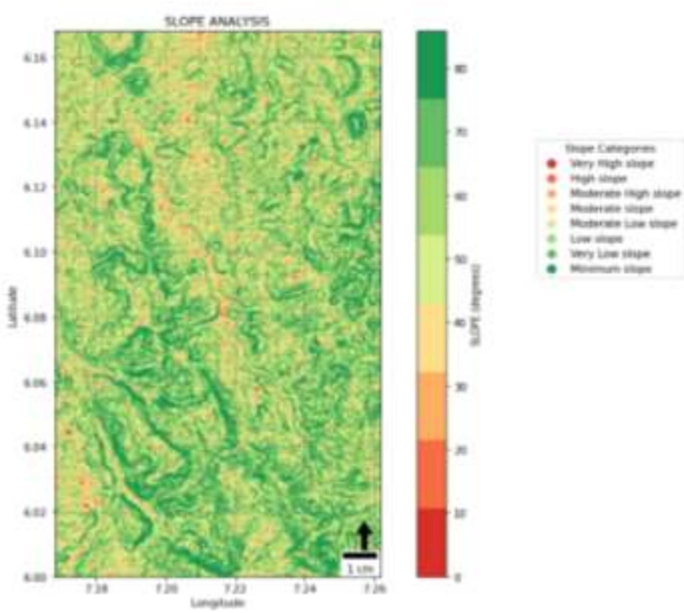

Figure 3: The slope analysis

3.1.3 *Aspect Analysis:* The aspect analysis of the Aguata Agricultural Zone examines the direction slopes face, which influences solar radiation exposure, microclimate variations, vegetation distribution, and land use suitability. The study found that the mean aspect of the terrain is 175.03°, indicating an overall southward slope orientation as shown in Figure 4. However, due to the circular nature of aspect data, the mean alone may not fully capture the distribution of slope directions. The median aspect of 180° confirms that at least half of the slopes in the study area face directly south, suggesting a predominant south-facing terrain orientation. A high standard deviation of 107.46° reflects significant variability in slope directions, indicating that slopes face multiple orientations rather than being concentrated in a single direction. This suggests a complex and rugged landscape with ridges, valleys, and irregular terrain features, this study confirm the study of Hughes *et al.*, 2019. The predominance of south-facing slopes has important implications for solar radiation exposure, potentially affecting microclimates, vegetation patterns, and hydrological processes such as snowmelt and water retention. However, the high variability in aspect values highlights the diverse nature of the terrain, where different slope directions contribute to a heterogeneous environmental and agricultural landscape.

3.1.4 Landform Analysis: Landform Analysis: The landform analysis of the Aguata Agricultural Zone classifies key geomorphological features, including valleys, hills, and plateaus, which impact hydrology, biodiversity, and land use planning. The study identified 2,694 valleys, 99,415 hills, and 1,029 plateaus as shown in Figure 5. The high hill count indicates a rugged, elevated landscape shaped by erosion and tectonic processes, while the lower valley and plateau counts suggest limited flat and low-lying areas. This terrain influences water flow, sediment transport, and habitat diversity. Hills create microclimatic variations, while valleys serve as drainage pathways, highlighting the region's complex geomorphological dynamics and environmental implications.

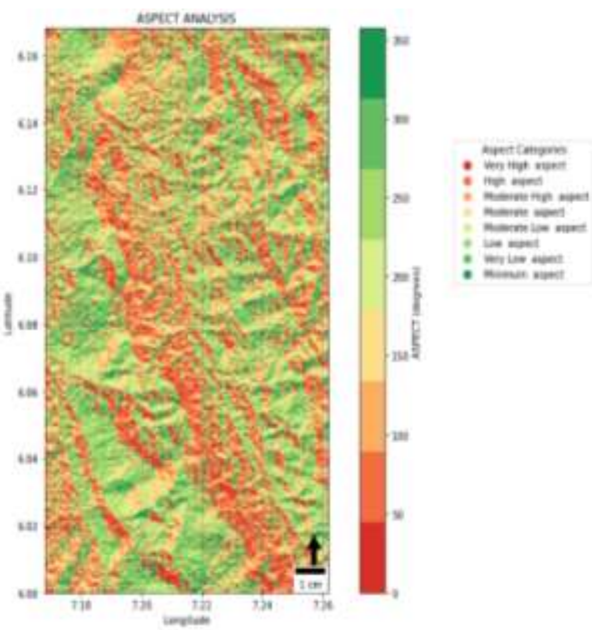

Figure 4: The Study Area Aspect Analysis

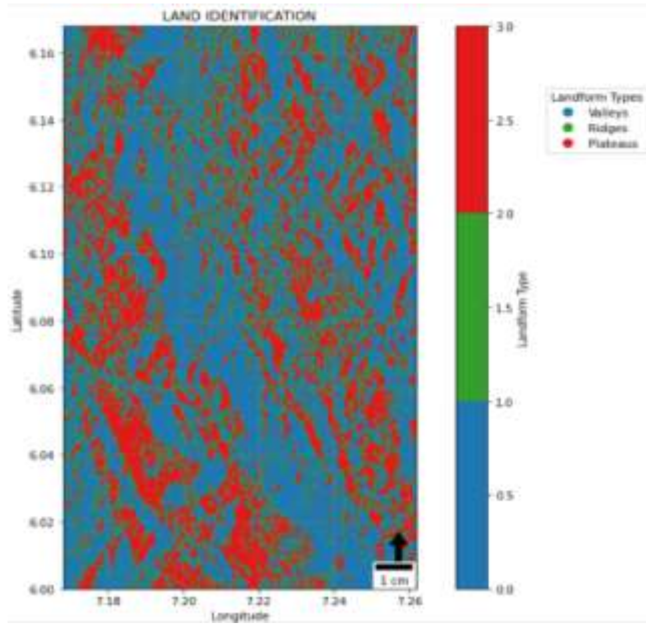

Figure 5: The Landform Analysis of the Study

3.1.5 Curvature Statistics: The curvature analysis quantifies changes in slope and aspect, highlighting geomorphological processes like erosion and water flow. The study found a mean curvature of 0.0013, a median of 0.0, and a standard deviation of 1.69 as shown in Figure 6. A mean close to zero suggests a balanced terrain, while a slight positive value indicates rounded hilltops. The median of zero reflects an equal distribution of concave and convex areas, and the high standard deviation suggests significant variability. This indicates a dynamic landscape where convex areas may face erosion, while concave regions accumulate sediments, shaping the hydrological and geomorphological characteristics of the terrain, this finding agree with the study of Zhang and Montgomery (2024).

Hillshade: The hillshade analysis simulates terrain illumination by calculating light interaction based on slope and aspect. The study found a mean hillshade value of 3.44 and a standard deviation of 158.56 (Figure 7). The low mean suggests most of the terrain is shadowed, likely due to steep slopes or unfavorable light alignment. The high standard deviation indicates a mix of bright and dark areas, reflecting a rugged landscape with sharp elevation changes. Shadowed areas may retain moisture longer, affecting drainage and vegetation. This highlights the terrain's complexity, where valleys and steep slopes create uneven light distribution and varied microclimatic conditions. The findings on the hillshade align with the study of Wang*et al.,2021.*

3.2 Morphometric Parameters - The morphometric analysis quantifies the terrain's geometry and hydrological properties, highlighting its susceptibility to soil erosion, particularly under climate change. The study reveals a watershed area of 0.0086 m^2 with a high perimeter-to-area ratio, indicating an irregular shape that promotes uneven runoff distribution and localized erosion. A low circularity value of 0.0671 suggests an elongated watershed prone to increased flow velocity and concentrated erosion pathways. The high drainage density of 3600.0000 m^{-1}, and stream frequency of 115.8705 m^{-2} indicate an extensive stream network, leading to rapid runoff and heightened erosion risks.

The compactness coefficient of 3.8598 and shape factor of 0.0053 confirm a highly elongated watershed, which enhances concentrated flow and erosion. The very high elongation ratio of 377.3733 further suggests rapid water movement, increasing erosion vulnerability, especially with intensifying rainfall due to climate change. High stream frequency implies continuous soil displacement, exacerbating land degradation. These characteristics suggest a fragile watershed with limited infiltration capacity, making it prone to severe erosion, land degradation, and soil fertility loss, this study agree with the study of Biswas and Pani, 2015. To mitigate these effects, conservation practices such as contour farming, terracing, reforestation, and check dams are recommended. Managing the existing stream network and increasing vegetation cover will help reduce runoff speed and minimize soil erosion risks.

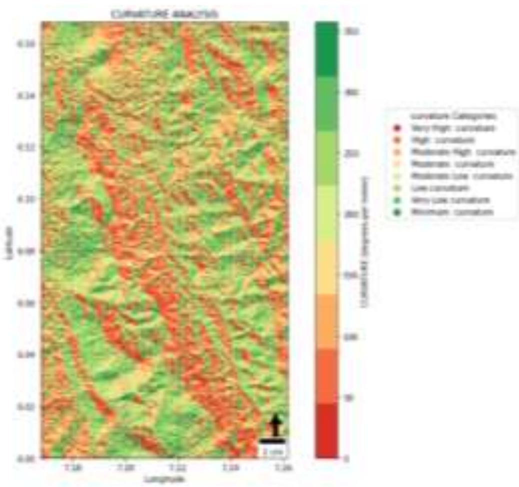

Figure 6: Curvature Descriptive Analysis

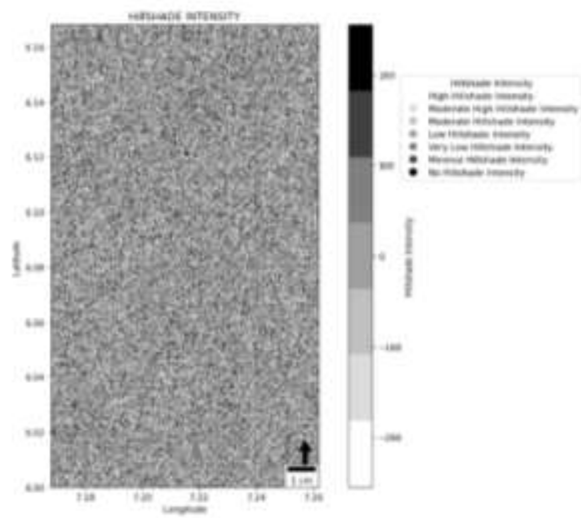

Figure 7: Curvature Descriptive Analysis

3.3 Hypsometric Analysis - Hypsometric analysis assesses elevation distribution within a landscape, revealing its erosional stage and geomorphological characteristics. The study results show a hypsometric integral (HI) of 0.7403, mean elevation of 97.46 m, elevation range of 173.00 m, and relief of 173.00 m as shown in Figure 8. An HI of 0.7403 suggests a youthful erosional stage, with steep slopes and active geomorphic processes. This implies a high potential for erosion, particularly under increased rainfall due to climate change. The mean elevation of 97.46 m indicates a relatively low-lying area. Lower elevations can be prone to erosion if steep slopes exist within this range. Additionally, low-lying areas are more susceptible to flooding, particularly during heavy rainfall events. While the elevation range of 173.00 m suggests moderate topographic variation, meaning both steep and flat areas exist. Steeper slopes are more prone to erosion, while flatter areas may experience sediment accumulation and water pooling, thi study findings supports the study of Chen and Li, 2018. Increased rainfall can intensify these effects, leading to higher erosion in elevated areas and flooding in lower regions. However, a relief of 173.00 m indicates a mix of high and low elevations. Steep areas are vulnerable to erosion, while low-lying regions are at higher risk of flooding, particularly if the terrain lacks sufficient drainage infrastructure.

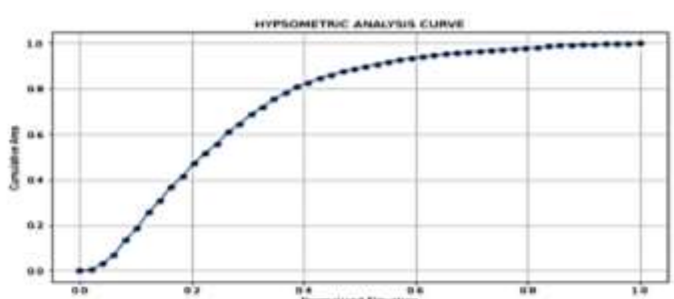

Figure 9: Hypsometric Analysis Curve of the Study

3.4 Soil Erosion and Flood Modeling

3.4.1 Soil Erosion Model

3.4.1.1 Soil Erosion Factors/Parameters: The soil erosion parameters (Figure 9) of R-Factor, was calculated as 8.80 in the Aguata Agricultural Zone, indicates moderate-to-high rainfall erosivity, suggesting vulnerability to soil erosion and flooding. High rainfall intensity in the region contributes significantly to soil degradation, increasing runoff and flood risks. The K-Factor of 0.396 reflects moderate soil erodibility, making the area prone to erosion, especially under intense rainfall. This can impact agricultural productivity and infrastructure, with sediment clogging drainage systems. Likewise, The LS-Factor of 1.25 highlights moderate topographic influence on erosion, with steep, long slopes accelerating runoff and increasing erosion risks. The C-Factor of 0.262 shows that land cover offers moderate protection against erosion, with partial vegetation cover providing some mitigation. The P-Factor of 0.39 suggests moderate implementation of erosion control measures, indicating room for improvement in soil conservation practices. Together, these factors emphasize the need for enhanced erosion control and flood management strategies in the region, especially with climate change intensifying rainfall and runoff.

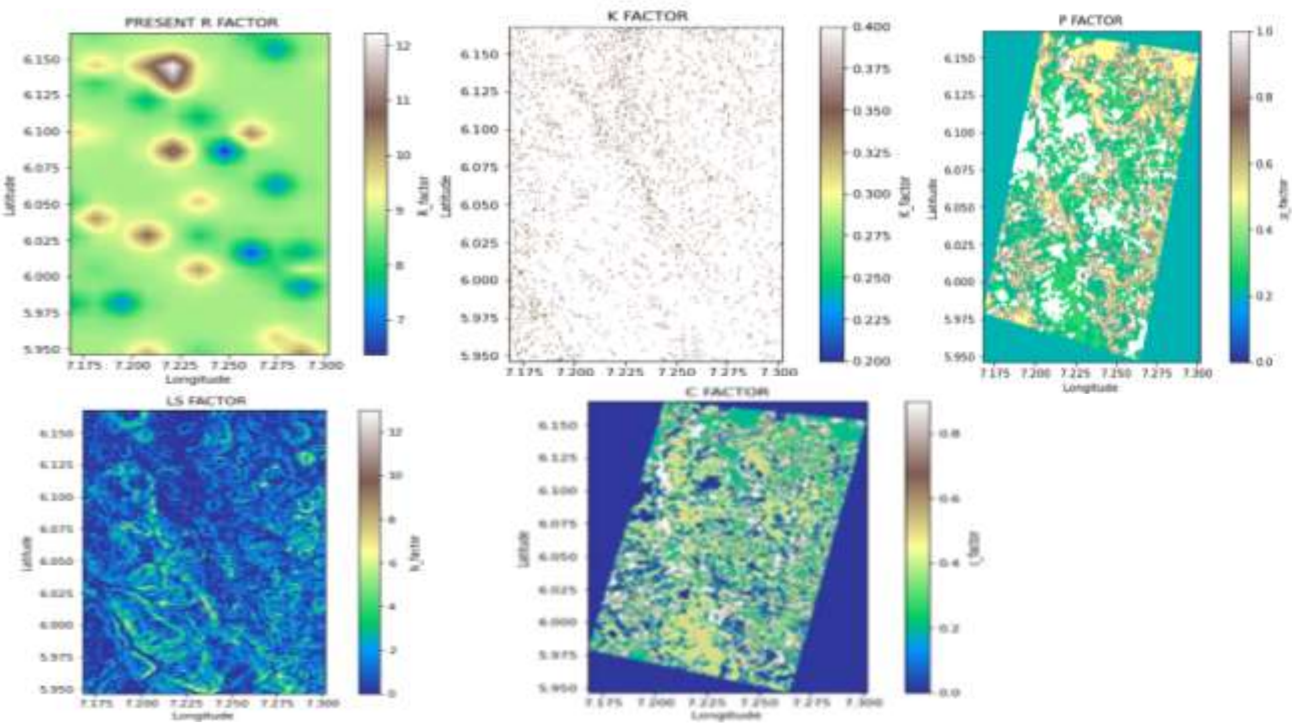

Figure 9: Soil Erosion Factor Model Map of the Study Area

3.4.1.2 Present and Predicted Soil Erosion Model: The developed soil erosion model shows that the mean soil erosion rate in the Aguata Agricultural Zone is 0.79 tons per hectare per year as shown in Figure 10, representing a low to moderate level of soil loss. This suggests that while the soil loss is manageable, it still poses a risk to soil fertility, agricultural productivity, and increases the likelihood of flooding due to sediment deposition in waterways. Climate change, with its effects on rainfall variability and storm intensity, could further exacerbate these erosions and flooding risks. this is in agreement with the study of Akanbi, O. A., and Adepoju, K. A. (2017) who in their studies highlights how moderate soil erosion in agricultural zones contributes to sediment deposition in rivers, increasing flood risks and infrastructure vulnerabilities.

Looking ahead, the next 10-year soil erosion model predicts a slight increase in the erosion rate to 0.82 tons per hectare per year as shown in figure 11, totaling 13.20 tons of soil loss over the decade. This reflects the growing impact of climate change, including more intense rainfall and land use changes like deforestation, which increase soil exposure and erosion. Such erosion will likely reduce agricultural yields, increase sedimentation in rivers, and heighten flood risks, making soil management and conservation practices critical for the region's sustainability.

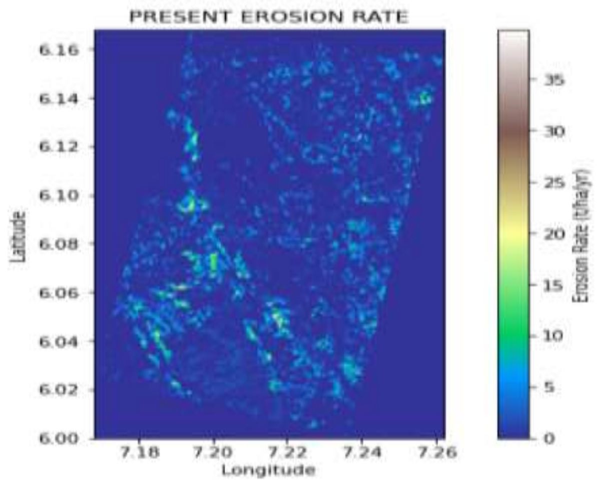

Figure 10: Present Soil Erosion Model

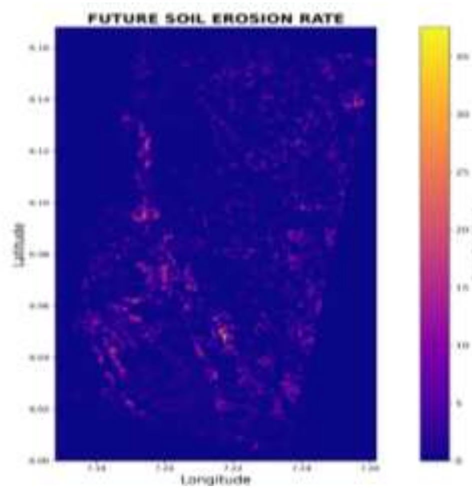

Figure 11: 10-year Predicted Soil Erosion Model

3.4.2 Flood and Flood Prediction Models –

3.4.2.1 Water flow accumulation model: The flood modeling results reveals a significant water flow accumulation, with a total of 2,823,864.50 m² and an average of 13.81 m² as shown in Figure 12. These metrics are crucial in assessing water movement, erosion, and flooding risks. Areas with latitude and longitude above 6.6 show higher flow accumulation, indicating potential hotspots for soil erosion and gully formation. Climate change-driven intense rainfall increases runoff, leading to concentrated water flow and reduced infiltration, aligning with studies by Egboka and Okpoko (1984) and Obiefuna and Orazulike (2011). The well-developed runoff pathways suggest that topography and human activities, such as deforestation and land-use changes, influence water movement. Increasing rainfall intensity exacerbates soil degradation, affecting agricultural productivity. Areas with high flow accumulation are prone to waterlogging and severe flooding, threatening infrastructure and livelihoods. Reduced infiltration due to compacted or degraded soils further worsens flooding impacts, making effective flood and land management strategies essential.

3.4.2.2 Flood Risk Model: The flood risk analysis model highlights the Aguata Agricultural Zone's vulnerability to climate-induced disasters like soil erosion and flooding. With a mean flood risk of 10.98 mm and a total flood risk of 2,244,474.11 mm, the study reveals significant water accumulation and inundation potential (Figure 13). Climate change has intensified rainfall patterns, increasing flood risks. The mean flood risk suggests potential waterlogging, nutrient leaching, and soil destabilization, while the total flood risk indicates large-scale inundation. Heavy rainfall accelerates soil erosion by increasing runoff and topsoil destabilization, leading to gully formation and land fragmentation. Higher runoff volumes transport sediment, reducing soil fertility and agricultural productivity. Persistent flooding disrupts farming activities, damages crops, and threatens infrastructure and settlements, particularly in low-lying areas. These findings emphasize the need for effective flood management and erosion control strategies to protect agricultural land, infrastructure, and livelihoods in the region.

3.4.2.3 Next 10-Year Predicted Flood Risk Model: The 10-year flood risk prediction for Aguata Agricultural Zone reveals a significant increase in flood hazards due to climate change. Figure 14 shows that the future mean flood risk of 22.12 mm and total flood risk of 4,523,622.06 mm represent a 101.46% and 101.54% increase, respectively, indicating intensified flood events and prolonged inundation. This surge in flood depth and volume will accelerate surface runoff, leading to severe soil erosion, topsoil loss, and reduced agricultural productivity. Steeper slopes and high-flow accumulation areas face heightened risks of gully formation and sediment displacement. Increased flooding threatens farmlands, infrastructure, and settlements, disrupting transportation and escalating recovery costs. Additionally, flood-prone zones may expand, affecting previously unaffected areas and demanding urgent mitigation efforts. Proactive planning is essential to manage these risks and protect livelihoods, emphasizing the need for adaptive flood management strategies to counter the growing impacts of climate variability in the region.

3.4.2.4 Sensitivity of flood risk to rainfall intensity: The sensitivity of flood risk to rainfall intensity in the Aguata Agricultural Zone highlights the impact of climate change on hydrological hazards. As shown in Figure 15, increased rainfall intensity leads to higher flood risks and soil erosion, threatening agriculture, infrastructure, and communities. When rainfall exceeds the soil's infiltration capacity, surface runoff increases, accumulating in low-lying areas and causing deeper, more widespread flooding. In Aguata, soil types and land use constraints further elevate flood risks. Intense rainfall also generates powerful runoff, detaching soil particles, deepening gullies, and accelerating erosion. Sediment-laden floodwaters contribute to siltation in downstream water bodies, reducing their capacity to handle future runoff. Repeated exposure to heavy rainfall compacts soil, decreases permeability, and increases runoff severity. Additionally, vegetation loss from flooding weakens the land's ability to absorb water, perpetuating a cycle of rising flood vulnerability. Effective mitigation strategies are essential to manage these escalating risks.

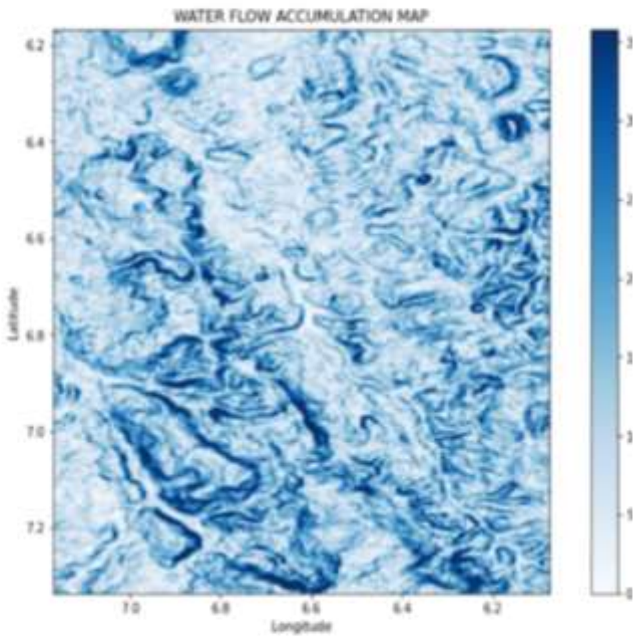

Figure 12: Flood Accumulation Map Model

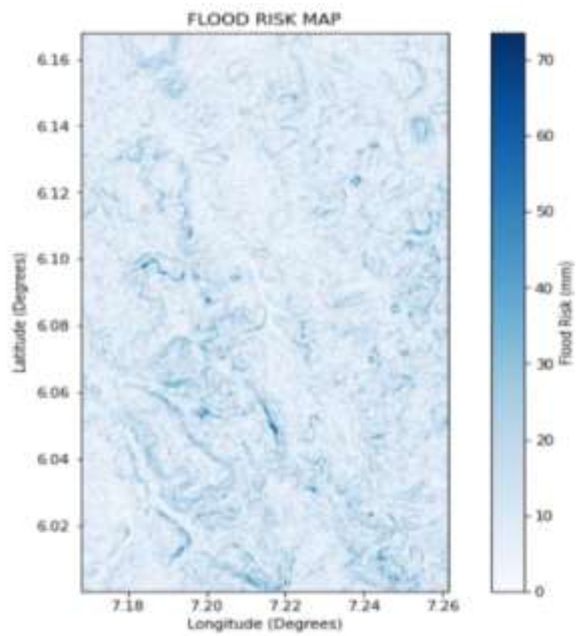

Figure 13: Flood Risk Map Model

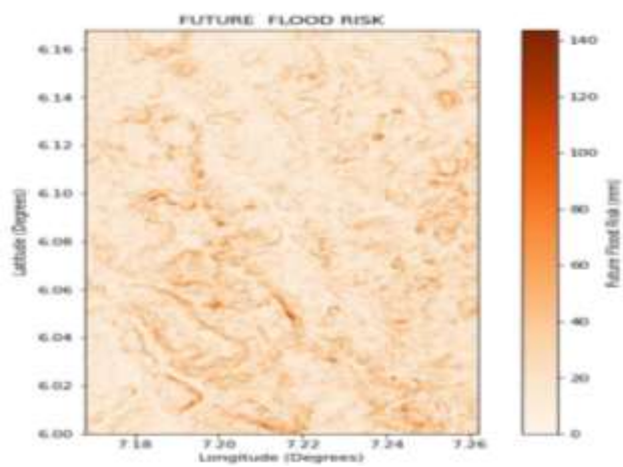

Figure 14: A Ten Year Predicted Flood Map Model

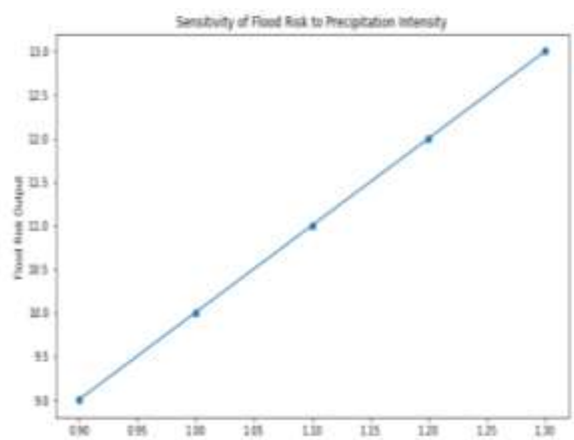

Figure 15: Sensitivity of Flood Risk to Rainfall Intensity

3.5 Conclussion

The study highlights the significant impact of climate change on soil erosion and flooding in Aguata Agricultural Zone, emphasizing increased soil erosion and flood risks due to changing rainfall patterns and topographical factors.

GIS-based modeling provided insights into terrain characteristics, hydrological dynamics, and future flood susceptibility, revealing a projected rise in flood risk over the next decade. Findings indicate that intensified rainfall will exacerbate erosion, soil degradation, and agricultural losses, threatening local livelihoods. Effective flood management strategies, including improved drainage, afforestation, and soil conservation, are crucial for mitigating these impacts. The study underscores the importance of climate adaptation policies to enhance agricultural resilience and sustainability in the region. Future research should refine predictive models and explore community-based adaptation measures for long-term flood mitigation.

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