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Mapping and modeling of water erosion in the Revubué river Sub-Basin, Moatize, Mozambique

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Abstract

This study investigated water erosion in the Revubué River Sub-Basin, Moatize, Mozambique, utilizing advanced mapping and modeling techniques. Through detailed land use surveys and application of the Potential Erosion Model (EPM), we identified areas with moderate to severe erosion rates (φ = 0.54), particularly in zones of intensive agriculture (15% of the study area) and mining (1% of the study area). The results highlighted the influence of undulating topography (average slope of 9%) and intensive agricultural practices on erosion rates (0 – 25 ton/ha). Urgent implementation of soil conservation practices, such as contour plowing and terracing, was recommended to mitigate soil loss, improve agricultural productivity, and promote environmental sustainability. Agricultural sustainability was emphasized, focusing on investments in sustainable agricultural practices to preserve long-term soil health. Raising awareness among farmers about the impacts of soil erosion and implementing effective management practices were considered crucial. Extension services were recognized as key agents in disseminating knowledge for promoting eco-friendly agricultural practices.

Keywords

Agriculture, Watershed, Moatize, Mozambique

Introduction

Soil water erosion is widely acknowledged as one of the primary forms of soil degradation in agricultural areas, resulting in significant loss of fertile land and directly impacting agricultural productivity and ecosystem health (Hernani et al., 2002). Anthropogenic activities play a crucial role in erosive processes, influenced by changes in land use, deforestation, and often exacerbated by climate change (Loureiro & Guerra, 2023).

This phenomenon is of great importance due to its rapid onset and significant detrimental effects not only on agricultural exploitation but also on various other economic activities and the environment (Hernani et al., 2002). The magnitude of accelerated erosion relates to soil characteristics, climatic conditions, and the use and management of natural resources.

Hernani et al. (2002) explain that water erosion is characterized by processes occurring in three phases: detachment, transport, and deposition. Precipitation hitting the soil surface initially causes aggregate wetting, reducing their cohesive forces. With continued rainfall and the impact of raindrops, aggregates are broken down into smaller particles.

According to Pruski (2000), the quantity of disintegrated aggregates increases with the kinetic energy of precipitation, which is a function of rainfall intensity, velocity, and drop size. Soil transport begins only when rainfall intensity exceeds the infiltration rate, which tends to decrease over time, both due to soil wetting and the resulting surface sealing effect (Hernani et al., 2002).

Once runoff is established, it moves downhill, potentially concentrating in small depressions but always gaining speed as sediment volume and terrain slope increase. With this, its capacity to generate friction and detachment expands as the runoff moves. Deposition occurs when sediment load exceeds the runoff's transport capacity (Nuernberg, 1998; Pruski, 2000).

Incorrect management is among the leading determinants of erosion and soil degradation (Santos, 2014). The author continues to emphasize that inappropriate practices include indiscriminate deforestation, overuse of land beyond recommended suitability, lack of planning and conservation practices, and finally, inadequate soil preparation.

Intensive soil preparation with disc harrows has been one of the main causes of land degradation in subtropical and tropical environments (Hernani et al., 2002). Its effects are primarily felt through rapid reductions in organic matter content and their consequences on soil productivity loss.

In Mozambique, shifting agriculture, logging, timber harvesting, charcoal production, and uncontrolled burning are considered the main factors contributing to vegetation cover reduction and consequently soil erosion (Matule & Macarringue, 2020).

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Economic Importance of the Moatize District

Moatize, a district located in the province of Tete, Mozambique, plays a prominent role in the regional economic landscape due to its wealth of natural resources, notably coal. Coal mining in Moatize emerges as a substantial factor in the region's economic development (Cebola, 2018).

Coal mining in Moatize has attracted significant investments and driven local economic growth. Prominent companies like Vulcan S.A., an Indian mining company, play a crucial role in this sector. Additionally, the expansion of operations by Vale S.A., a Brazilian mining company, into Mozambique has historically contributed to economic activities in the region.

Although coal mining has a notable impact, Moatize also hosts other equally relevant economic sectors. Agriculture represents a field with great potential to expand employment and contribute to the region's economic growth. Increasing agricultural productivity is a fundamental recommendation aimed at job creation and strengthening the local economy (Cebola, 2018).

The economic importance of Moatize is intrinsically linked to its geographical location. The Moatize district, located in the Southern Africa region, plays a central role as a regional economic hub. Its strategic location and the presence of valuable natural resources like coal have attracted substantial investments and contributed to the region's economic development.

For effective watershed management, aiming at natural resource sustainability, having spatial information on soil erosion potential and sediment production and transport is crucial. However, modeling soil erosion processes is challenging due to the complex interactions of active and passive factors influencing this process (Durães & Mello, 2016).

The Revised Universal Soil Loss Equation (RUSLE) is widely employed to quantify the amount of soil lost due to water erosion, as evidenced in various studies (Dambrowski & Marenzi, 2023; Ayer et al., 2015; Oliveira et al., 2015; Francisco et al., 2023; Morais & Sales, 2017, among others).

In the Revubué River Sub-Basin, this issue is of crucial relevance due to the importance of agricultural activities in this region and the urgent need to understand and mitigate the effects of water erosion.

This study aims to deepen the understanding of water erosion in the Revubué River Sub-Basin, employing mapping and modeling techniques. Analyzing these processes is crucial to identify areas most susceptible to erosion and understand the interactions between land use for agricultural activities and water erosion potential.

To achieve this goal, detailed land use surveys were conducted and modeling techniques were applied using the potential erosion method. Integrating this information allows not only the identification of areas at higher risk of erosion but also the proposal of appropriate management strategies to mitigate negative impacts, promoting more sustainable agricultural practices and preserving the integrity of natural resources in the Revubué River Sub-Basin. This study significantly contributes by providing relevant insights for decision-making in land use policies and more conscious agricultural practices, aiming at soil conservation and environmental sustainability in this specific region. It represents a comprehensive analysis of water erosion in agricultural areas of the Revubué River Sub-Basin, offering valuable information for the proper management of these natural resources and the development of environmental preservation strategies.

Materials and methods

Study Area

The hydrographic sub-basin of the Revubué River, with an approximate area of 3,000 square kilometers, is located in the central part of the Tete province, Mozambique (Figure 1). This territory encompasses the districts of Moatize, Angónia, and Tsangano, being referred to as the Máue River in the latter region.

The characterization of the sub-basin stands out for a predominance of rural characteristics, housing approximately 150,000 inhabitants. Predominant economic activities include agriculture, mining, and forestry. The Revubué River, vital for the region, plays crucial roles as a water source for irrigation, human consumption, and industrial activities, besides being a significant fishing resource for the local population. However, the sub-basin faces challenges such as deforestation, soil erosion, and pollution, threatening the sustainability of its natural resources.

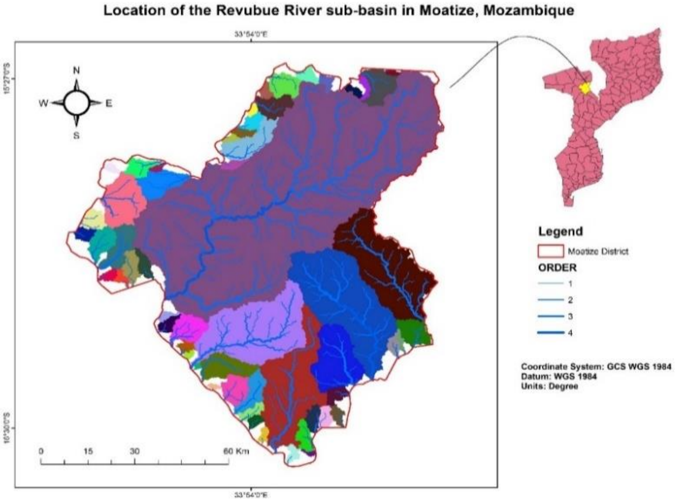

Figure 1. Geographic Location of the Revubué River Sub-Basin in the Moatize District, Mozambique (Source: Author, 2024).

Geomorphology of the Revubué River Sub-Basin in the Moatize District

The sub-basin has an average slope of 9% (Figure 2 - Slope (%)), characterized as an Undulating relief, following the classification by Santos et al. (2013). The soil types identified in the area include Chromi-Profondic Acrisols (ACf), Petric Calcisols (CLp), Eutri-Leptic Cambisols (CMe), Rhodi-Acric Ferralsols (FRr), Eutric Leptosols (LPe), Ferric Lixisols (LXf), Rhodic Lixisols (LXh), and Pelli-Calcic Vertisols (VRe) (Figure 2 - Soil Types), according to the World Reference Base for Soil Resources [WBR (2020)].

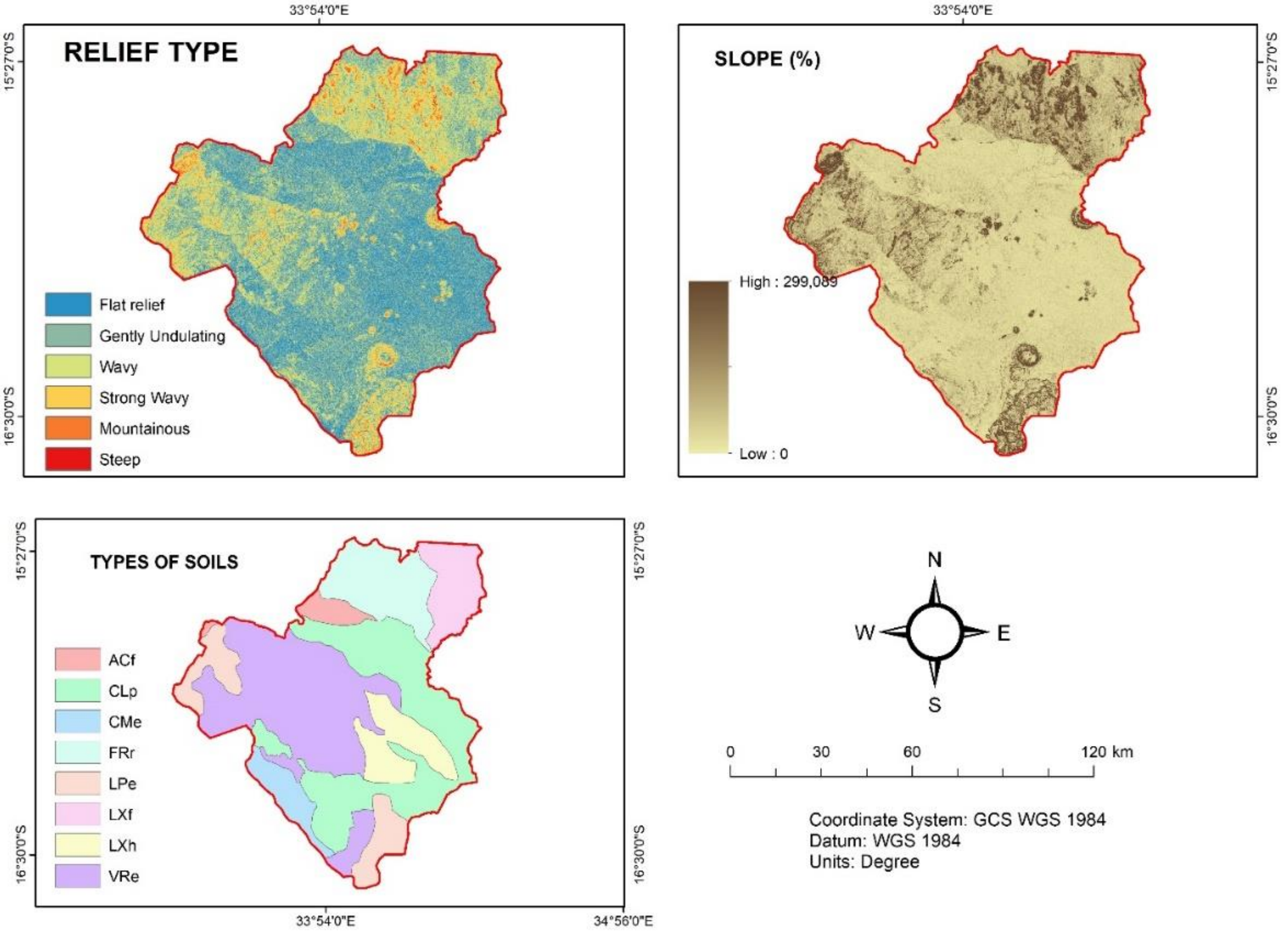

Figure 2. Geomorphology of the Revubué River Sub-Basin in the Moatize District, Mozambique (Source: USGS (2024) and WBR (2020), adapted by the author)

Climate, Land Use, and Land Cover

The Revubué River sub-basin has an average temperature of 24°C and an annual precipitation of approximately 1500 mm. Regarding land use and land cover, the Moatize district is characterized by native vegetation, including areas with sparse vegetation and patches of dense vegetation, along with agricultural, urban, mining, and water bodies (Figure 3).

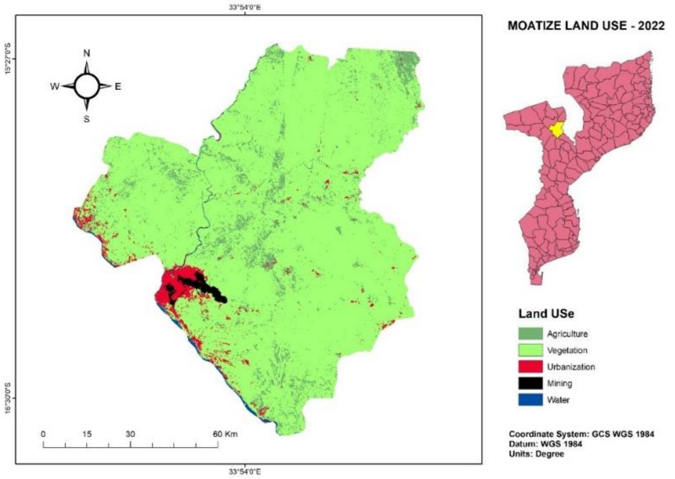

Figure 3. Land Use and Land Cover in the Revubué River Hydrographic Sub-Basin, Moatize, Mozambique (Author, 2024).

Data and Processing

The Digital Elevation Model (DEM), acquired from the United States Geological Survey (USGS) Shuttle Radar Topography Mission (STRM) with a spatial resolution of 30 meters, was used to delineate the sub-basin using SAGA GIS software. Using ARCGIS 10.8, the classification of slope and terrain type was calculated based on the classes suggested by Santos et al. (2013). Sentinel-2A satellite images for the year 2022 were specifically used, with the combination of RGB432 bands, where band 4 is assigned to the red channel (R), band 3 to the green channel (G) and band 2 to the blue channel, along with soil data from the World Reference Base for Soil Resources. Climate data were obtained from the NASA Powerec platform.

Potential Erosion Model

The Potential Erosion Model (EPM) is an essential tool in assessing and predicting soil erosion potential. Developed based on erosion measurements over 40 years in the Morava River watershed in Serbia (Lense, 2020; Dragičević et al., 2019) and adapted for tropical conditions by Sakuno et al. (2020), the model incorporates climatic variables, geological factors, soil properties, topography, land use and the degree of watershed erosion (Gavrilovic, 1988).

The model takes into account climate-dependent factors, surface geology, soil properties, topographic characteristics, type and distribution of land use, and the degree of watershed erosion (Gavrilovic, 1988).

Equation 1 (Table 1) mathematically describes the model, where the erosion coefficient (Z) indicates the intensity of the erosive process in a specific area. The closer it is to 0, the lower the severity of water erosion (Pinto et al., 2020; Sakuno et al., 2020). The calculation of Z considers the average slope of the soil (Isr) and tabulated values (Y, Xa, φ). The erosion resistance coefficient (Y), associated with the soil's parent material and the area's geology, varies from 0.25 to 2.0 (Pinto et al., 2020; Sakuno et al., 2020). The land use and management coefficient (Xa) are determined by land use and its vegetation cover. Values close to zero indicate higher vegetation density, while values close to 1.0 characterize areas with exposed soil. Field-observed erosion (φ) reflects the occurrence of erosive features associated with land use, ranging from 0.01 for weak sheet erosion to 1.0 for severe erosion (Gavrilovic, 1988). The parameters Y, Xa, φ (Tables 2, 3, and 4) were determined from tabulated values according to Sakuno et al. (2020).

Table 1. Equations and descriptions of parameters used for estimating soil losses in the Potential Erosion Method.

Eq. 1	$W_{yr} = T * H_{yr} * \pi * \sqrt[2]{Z^3 * F}$	Wyr = Annual Erosion (ton/ha/year) T = Temperature coefficient (dimensionless) Hyr = Average rainfall (mm/year) Z = Erosion coefficient (dimensionless) F = Study area (km^2) Ds = Soil density (kg/dm)
Eq. 2	$G_{yr} = W_{yr} * R_u$	G_{yr} = Actual soil loss (Mg/ano) R_u= Retention coefficient (dimensionless)
Eq 3	$T = \sqrt[2]{\frac{t_o}{10}}+0,1$	t_o = Average air temperature (°C/ano)
Eq 4	$Z = Y * X_a * \left(\varphi + \sqrt[2]{I_{sr}}\right)$	Y = Erosion resistance coefficient (Adm) X_a = Land use and management (Adm) φ = Observed field erosion (Adm) I_{sr} = Average slope (%)

Notes: Eq = Equation; Adm = Dimensionless; Source: Gavrilovic (1988); Pinto et al. (2020).

Table 2. Average soil resistance coefficient to water erosion (Y).

Parenting Material	**Originated Soils (SiBCS [1])**	**Y**
Rocky outcrops	-	0.25
Alluvial sediments	Fluvic Neosols, Gleisols, Organosols, Planosols	0.50
Basic and ultrabasic rocks, amphibolites, mudstones, shales	Chernosols, Oxisols	0.60
	Argisols, Nitisols, Plintisols	0.70
Granites, Gneisses and Migmatites	Argisols*, Oxisols*, Luvisols*, Nitisols*, Planosols*.	0.80
	Humic Cambisols, Luvisols*, Plintisols*.	0.90
Quartz sandstones, siltstones and quartzites	Spodosols, Vertisols	1.20
	Cambisols, Regolithic Neosols	1.50
	Cambisols*, Litholic Neosols*, Luvisols*	2.00

[1] Brazilian Soil Classification System. *Presence of quartz sand. Source: Adapted from Sakuno et al. (2020).

Table 3. Values of the soil use and management coefficient (Xa).

Use and management	Xa
Woods	0.05 – 0.30
Pasture	0.30 – 0.40
Degraded pasture	0.40 – 0.50
Permanent crops with conservation management	0.50 – 0.60
Permanent crops with conventional management	0.60 – 0.70
Temporary crops with conservation management	0.70 – 0.80
Temporary crops with conventional management	0.80 – 0.90
Exposed soil	0.90 – 1.00

Source: Adapted from Gavrilovic (1962) and Sakuno et al. (2020).

Table 4 - Erosive features and coefficient that expresses the erosion observed in the field (φ).

Type of erosion	φ
Area with severe erosion (gully, heavy furrow erosion)	1.00
Intense furrow erosion	0.90
Average furrow erosion	0.80
Intense laminar erosion	0.70
Laminar erosion without visible signs	0.60
Medium laminar erosion	0.50
Light laminar erosion	0.30
Areas with erosion on the banks of watercourses	0.20
Agricultural areas under non-apparent erosion	0.15
Areas covered by native vegetation	0.10

Source: Adapted from Gavrilovic (1962), Spalevic (2011) and Sakuno et al. (2020).

Results and discussion

The sub-basin features extensive coverage of native vegetation, followed by agricultural areas, predominantly cultivated under rainfed conditions, and small irrigated plots (Table 5). The phenomenon of urbanization is growing, driven by immigration to large-scale mining exploration projects, concentrated especially near the district capital (Figure 3). The average climatic conditions in the sub-basin, with an average air temperature (t_o) of 24 °C and average annual precipitation (Hyr) of 1,500 mm, resulted in a temperature coefficient (t) of 1.58. The soil resistance coefficient (Y) was calculated as 0.67, indicating moderate to good soil resistance to erosion. The predominant use of Vertisols (Eutri-Pellic Vertisols) in the sub-basin, with an average density of 1.63 kg/dm³, was observed (Guedes et al., 2020).

Table 5. Areas Occupied by Land Use and Land Cover Classes in the Revubué River Sub-Basin, Moatize, Mozambique.

Classes	Areas	
	Km²	%
Agriculture	1317	15%
Vegetation	7048	79%
Urbanization	384	4%
Mining	79	1%
Water	52	1%
Total	**8881**	**100**

Source: Author (2024), research result.

The land use and management coefficient (Xa) is 0.54, suggesting a significant presence of vegetation compared to exposed soil, mitigating the impact of water erosion. The degree of erosive features (φ) was assessed at 0.54, indicating predominantly moderate sheet erosion (Gavrilovic, 1988; Sakuno et al., 2020).

The erosion intensity coefficient (Z) ranged from 0.0001 to 1.73, with an average of 0.09. According to Gavrilovic's classification (1988), the sub-basin predominantly exhibits weak-intensity water erosion. In agricultural areas, the average Z was 0.68, indicating moderate erosion, while in mining areas, Z ranged from 0.72 to 1.73, representing strong to severe erosion.

Mining activities contribute to increased erosion due to the removal of vegetation for mining operations, exposing the soil to erosive agents, the risk of sedimentation in water bodies and contamination by toxic elements (Silva et al., 2018). Mining is identified as one of the main causes of erosion in watersheds (Filho & Quadros, 2017).

The estimated total erosion (Wyr) varied from 0.0001 ton/ha to 231.904 ton/ha, with an average of 5.95 ton/ha, indicating values above 1 ton/ha/year, common in tropical climates (FAO, 2015). In comparison, soil formation areas are around 1 ton/ha/year (Tavares, 2017).

Based on Figure 3, which relates to different land uses and undulating terrain with an average slope of approximately 9%, some relationships can be inferred:

Undulating terrain with an average slope of 9% can be considered moderately inclined. This inclination can increase the potential for water erosion, as rainwater tends to flow more rapidly on inclined terrain, increasing soil erosion. Miguel et al. (2023), mapping soil erodibility and potential erosion in a hillside watershed, state that slope areas with higher forest cover tend to reduce soil loss in these areas, which have a higher potential for erosive processes. This creates a more favourable soil conservation configuration and lower sediment production along the basin, especially in sloping areas (Didoné et al., 2014; Ten Caten et al., 2012).

In areas with undulating terrain and an average slope of 9%, the higher soil loss results in agricultural and mining areas may be explained by the vulnerability of these areas to erosive processes (Table 6). Agriculture in this region often involves intensive practices that expose the soil to higher erosion risks and the inclined terrain can exacerbate this problem. Santos & Rosa (2019) report that in the state of Amazonas, the slope varies very little throughout the state. The steeper the slope, the higher the erodibility and natural vulnerability of the area to soil erosion.

Urbanized areas can also be affected by undulating terrain. Impermeable structures, roads, and built surfaces on inclined areas can increase surface runoff, resulting in greater erosion in urban areas with this type of terrain. Vasconcelos et al. (2023), applying an erosion vulnerability index in the state of Amazonas, obtained higher vulnerability in punctual areas of deforestation, pasture formation, grassland vegetation and urbanization, with no data along the main river courses.

Areas with vegetation cover and near water bodies may have lower average soil losses, even with undulating terrain (Table 3). The presence of vegetation can help stabilize the soil, reducing surface runoff and, consequently, erosion. Areas near water may be less susceptible to erosion due to the natural tendency of water to accumulate in flatter areas. Vasconcelos et al. (2023) in their study report reductions of 68.0% to 97.4% in the depth of surface runoff and 98.0% to 99.9% in soil loss compared to bare land under erosive rainfall events.

Table 6. Average values of erosion per hectare of soil lost by water erosion.

Land Use	**Average Erosion (ton/ha)**
Agriculture	9.89
Vegetation	4.75
Urbanization	6.99
Mining	43.47
Water	5.52

Source: Author (2024).

Soil erosion poses a significant challenge to agriculture, directly impacting the productivity and sustainability of agricultural systems (Figure 4). Analyzing average soil losses due to water erosion in different agricultural areas reveals substantial implications that require attention and strategic actions to preserve soil health and the viability of agricultural production (Figure 5).

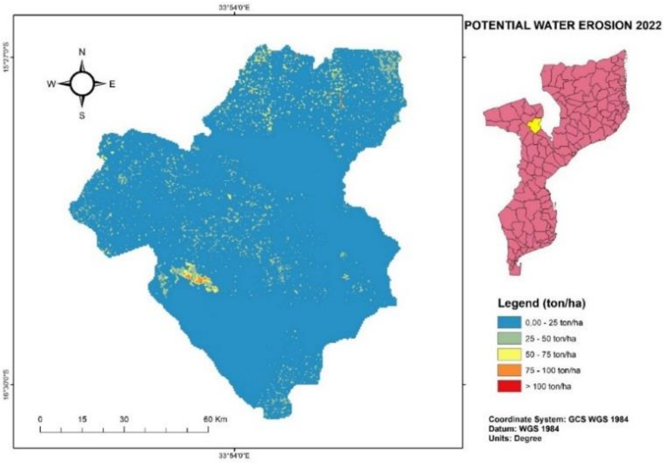

Figure 4. Potential Water Erosion in the Revubué River sub-basin, Moatize, Mozambique (Author, 2024).

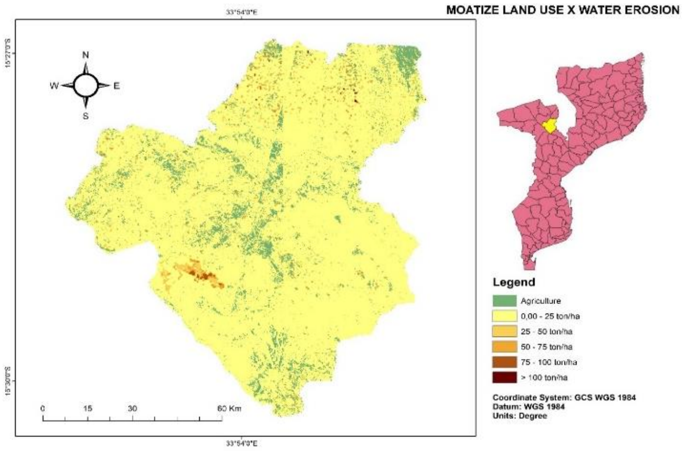

Figure 5. Land use in the Revubué River sub-basin in the Moatize district, Mozambique, and its relationship with water erosion (Author, 2024).

Caten et al. (2012), in his work titled "Deintensification of Land Use and Its Relationship with Soil Erosion," reports that the average soil losses from water erosion, particularly in agricultural areas, raise fundamental concerns for crop productivity. These losses diminish the topsoil layer, depleting essential nutrients and compromising its ability to support the healthy growth of plants. Consequently, this affects crop productivity, leading to lower yields and reduced quality of agricultural products.

According to Flores & Alba (2015), the concavity or convexity of the slope modifies the erosive power of runoff and influences the direction of water movement within the soil. Under identical climatic and vegetative cover conditions, soils in concave positions, due to the convergence of water flows, are wetter than those in convex positions.

Higher averages of soil losses may be correlated with intensive agricultural practices that expose the soil to higher erosion risks. Inadequate soil management during seeding and lack of vegetative cover are factors increasing soil vulnerability to erosion, especially in areas with undulating terrain and significant slopes (Panachuki et al., 2005).

Effective soil management practices are crucial to mitigate soil losses due to water erosion (Caten et al., 2012). Strategies such as contour planting, terracing, cover crops, and crop rotation are essential to reduce soil exposure to erosive agents and maintain consistent vegetative cover, thus protecting soil integrity.

Comparing conventional, minimum tillage, and no-till planting systems, Barcelos et al. (1999) note that the start of runoff was shorter in no-till planting due to its smoother surface compared to the others. Conventional and minimum tillage practices induce surface roughness, promoting greater surface water retention.

Investing in sustainable agricultural practices is imperative for long-term soil health preservation. Besides reducing soil losses, these practices contribute to soil fertility conservation, water retention, and erosion mitigation, fostering more resilient and sustainable agricultural systems.

Guimaraes et al. (2014) report that conservation management leads to lower losses of water, soil, C, and N compared to conventional management, attributed to increased vegetative cover. Conservation and conventional systems showed average reductions in TOC content of 33.3% and 42.0%, respectively, in the 0-10 cm depth compared to the forest. For NT (no-till), the average reductions at the same depth were 18.4% for conservation systems and 43.1% for conventional systems compared to the forest.

Raising awareness among farmers about the impacts of soil erosion and implementing effective soil management practices are fundamental. Continuous education, training in soil conservation techniques, and encouraging the adoption of sustainable agricultural practices are essential for promoting an integrated approach to soil management.

Mucavele & Artur (2021) emphasize the crucial role of Extension Services in overall agricultural development, not only for increased agricultural productivity but also for building or strengthening other capacities (health, nutrition, seed production, market linkages, cooperatives, etc.).

Conclusions

This study examines the significant implications of soil water erosion in agricultural areas, emphasizing its detrimental effects on agricultural productivity and ecosystem health. Anthropogenic activities such as changes in land use and deforestation, along with climate change, exacerbate erosive processes.

Water erosion occurs in three phases: detachment, transport, and deposition, influenced by factors such as precipitation intensity and soil management. Inadequate practices, including deforestation and intensive soil preparation, contribute to erosion and soil degradation. In Mozambique, various activities such as shifting agriculture and uncontrolled burning exacerbate soil erosion.

The economic importance of the Moatize District, driven by coal mining and agriculture, underscores the need for sustainable land management. Modeling erosion processes using techniques such as the Revised Universal Soil Loss Equation aids in understanding and mitigating the effects of erosion.

The most susceptible areas to erosion are Mining (43.47 tons/ha/year), Agriculture (9.89 tons/ha/year), Urbanization (6.99 tons/ha/year), Water (5.52 tons/ha/year), and Vegetation (4.75 tons/ha/year).

Effective soil management practices, including contour planting and cover crops, are vital for erosion mitigation and soil health preservation. Promoting sustainable agricultural practices through education and extension services is crucial for fostering resilient agricultural systems and environmental sustainability.

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