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Quantitative Mapping Using a GIS/RUSLE Approach of Water Erosion of Soils and the Resulting Carbon Losses : The Case of the Fatick Region (Senegal)

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Abstract

Water erosion is a complex phenomenon linked to natural and anthropogenic factors. It causes significant damage in terms of soil loss and organic fertilizers. Thus, in the Fatick region, to better understand this problem, this study aimed to map and quantify soil losses linked to water erosion as well as their effects on their carbon content. In this respect, the empirical universal equations of USLE and RUSLE were used. The environmental factors involved in the erosive process (climate, topography, soil, land use) were integrated as an information layer in a Geographic Information System (GIS). The results obtained showed soil losses ranging from 0 to 236 t/ha/year with an average of 50 t/ha/year. The categorization of the results revealed that the levels of "zero" and "very low" soil loss (i.e. < 5 t/ha/year) were the most significant, as they covered 99% of the total area.

The vegetation areas appear more resistant to water erosion. The carbon losses caused by this erosion range from 0 to 0.19 t/ha/year. This study thus highlighted the importance of the RUSLE model in the assessment of water erosion and its impacts. The location of these different levels of soil loss, through mapping, could help to better guide intervention areas for good conservation of these soils.

Keywords: Water erosion, soil, RUSLE, Carbon and Fatick region

Introduction

Water erosion is one of the natural factors that negatively affect soils (Maamar-Kouadri K., et al., 2016). Under the action of rainfall and runoff, it consists of a process of removing the soil layer and its particles, which are transported and deposited along the paths followed by runoff and watercourses. This phenomenon, although favored by natural factors (slope steepness, soil type and structure, high rainfall totals, etc.), accelerates with landscape modifications caused by human activities. These include : deforestation, the conversion of land cover from low-cover to low-cover cover (cultivation of grasslands, etc.), the cultivation of plots on steep slopes, overgrazing, etc. (Antoni V. and Darbous F., 2009).

In Senegal, and more specifically in the peanut basin, landscape changes resulting from deforestation and agricultural expansion, both driven by population growth, have led to soil denudation, which consequently accelerates erosion processes (Vidal & Djiba, 2016). This is compounded by certain farming practices, such as peanut cultivation, which leaves the soil completely bare after harvest. All peanut products are, in fact, sold commercially, including the straw, which is sold as animal feed. This situation exacerbates gully erosion and leads to the loss of the topsoil's fertile layer, resulting in decreased productivity and additional costs for conservation or mitigation (Ndour T., 2001 ; Diallo S. et al., 2017 ; Gerard et al., 2020 ; ENDA/GRAF, 2015). In addition, eroded sediments are generally those richest in clay and fine silt, organic matter, and associated nutrients, particularly carbon, nitrogen, and cations (Roose E. and De Noni G., 2004). Indeed, water erosion is not only considered a factor in stripping soil layers or transporting sediments, but it is also a source of water and nutrient loss.

To address this major soil issue, and given the complexity of the factors involved in the process, several models and methods have been developed and used to assess soil water erosion (USLE, RUSLE, LEAM, PAP/CAR). Among these models, the revised version of the Universal Soil Loss Equation (USLE/RUSLE) by Wischmeir and Smith (1978) remains the most widely used for predicting losses due to water erosion because of its simplicity and flexibility. Its integration into Geographic Information

Systems (GIS) offers several advantages. It allows for the assessment of the average annual erosion rate over large areas, based on a combination of factors responsible for the phenomenon: rainfall, soil type, topography, cropping system, and erosion control practices. Furthermore, it allows for the visualization of results and the representation of the spatial heterogeneity of soil losses related to water erosion.

By applying the RUSLE model to understand the spatial distribution of water erosion in the Fatick region, an administrative unit of the groundnut basin, this study aims to achieve two objectives. The aim is twofold: firstly, to spatially map and quantify the risk of water erosion, and secondly, to assess its consequences on soil carbon losses. This assessment makes it possible to map the areas most vulnerable to erosion and to identify the factors influencing soil degradation.

Materials and Methods

Presentation of the Study Area

The study was conducted in the Fatick region, a locality situated in west-central Senegal, specifically between latitudes 13°36’0’ and 14°42’0 North and longitudes 15°30’0’’ and 16°47’0’’ West (Figure 1). It covers an area of 6848.88 km². The terrain is relatively flat (elevations do not exceed 47 m) and includes depressions fed by the Saloum and Diomboss rivers and their tributaries (Figure 1). The climate is of the northern Sudanian type. It is characterized by a long dry season from November to May and a short rainy season from June to October. The average annual rainfall recorded at the Fatick regional station for the period 1984–2024 is 598.6 mm. The soils of the region are dominated on the plateaus by tropical ferruginous soils, interspersed in places with hydromorphic soils in the valleys (Figure 2). There is also a small presence of ferralitic and poorly developed soils on the plateaus. However, in the amphibious zone, halomorphic soils predominate, followed by poorly developed aeolian soils (Figure 2). The vegetation is quite diverse. In the amphibious zone, it consists of mangrove vegetation, while on the plateaus, it is reduced to patches containing savanna formations, gallery forests, and forest plantations (Figure 2). Agriculture, primarily rainfed, along with livestock farming and fishing, constitute the main activities of the population.

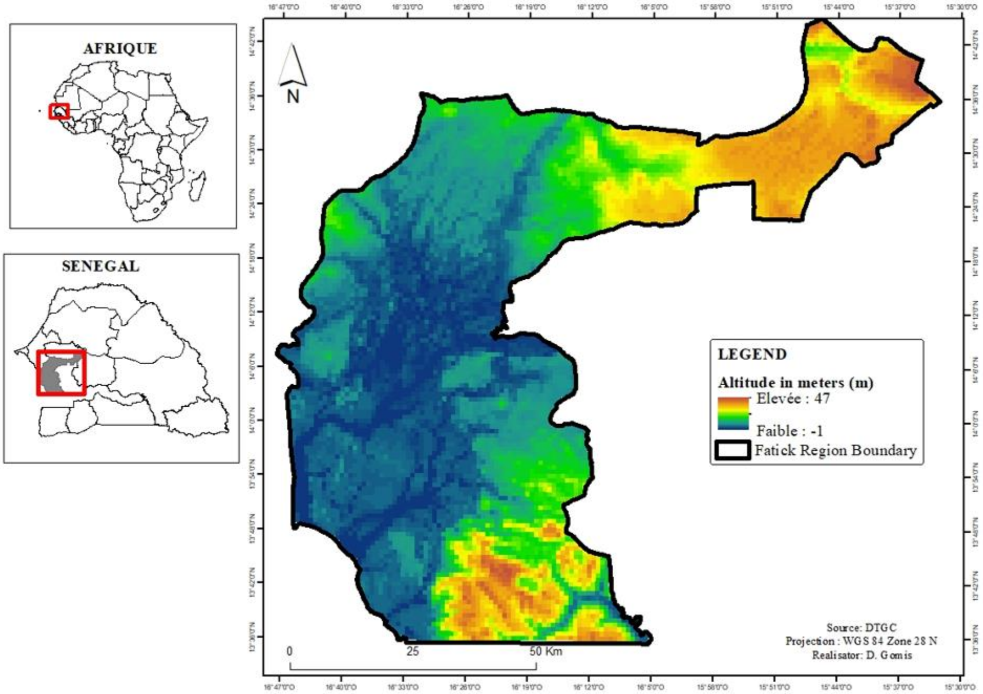


Figure 1 : Geographical location and topography of the Fatick region

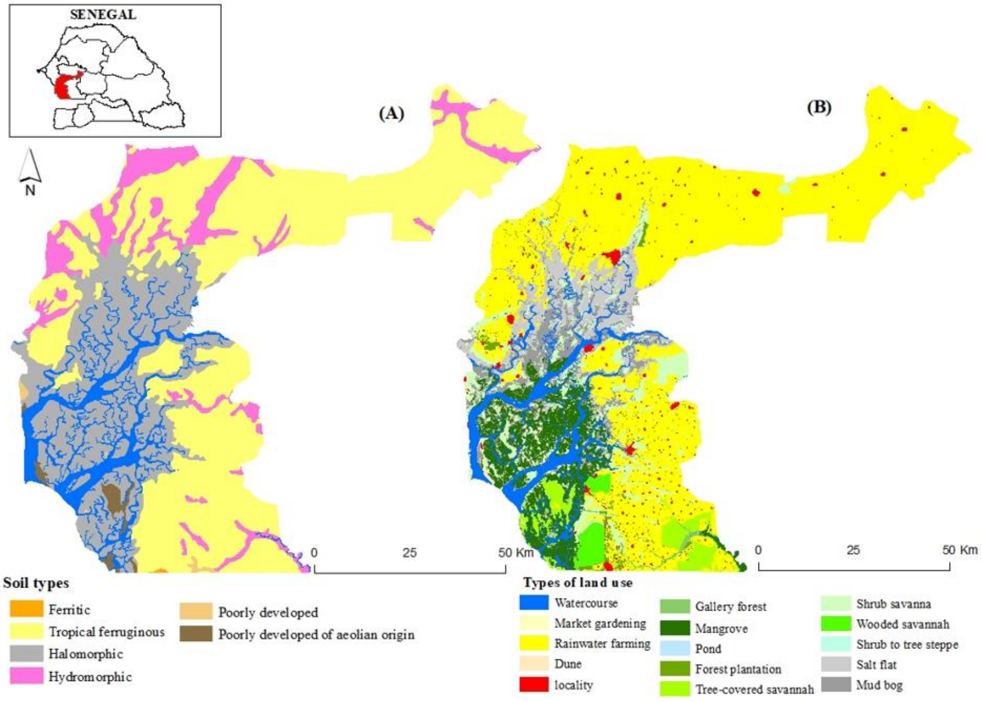


Figure 2 : Soil types (A) and land cover (B) of the Fatick region

Methodology for Evaluating Soil Loss due to Water Erosion

The methodology used in this study is based on the Revised Universal Soil Loss Equation (RUSLE) of Wischmeyer and Smith (1978). This equation is a multiplicative function that combines several factors influencing the rate of water erosion, namely: climatic aggressiveness, soil erodibility, slope angle and length, land use, and erosion control practices. It is defined by the following expression :

$$A = R \times K \times LS \times C \times P$$

Where:
A: Annual soil loss rate in t/ha/yr;
R: Rainfall erosivity factor (MJ·mm/ha·h·yr);
K: Soil erodibility factor (t·ha·h/ha·MJ·mm);
LS: Topography factor (Length × Slope);
C: Land cover factor (unitless dimension);
P: Factor of anti-erosion farming practices (unitless dimension).

Rainfall Erosivity Factor (R)

The erosivity factor R characterizes the erosive power of rainfall intensity on the soil. It was determined using the Nguyen equation (1996) due to its simplicity and robustness, having been validated based on 54 years of observations at several meteorological stations. It is expressed by the following function:

$$R = 0.548 * P – 59.9$$

R = the rainfall aggressiveness index and P is the annual rainfall;

The rainfall data used for this purpose were collected from the database of the National Civil Aviation and Meteorology Agency (ANACIM). The average rainfall for the period from 1984 to 2024 for all stations in Senegal was calculated using Excel. The R factor was then calculated from the average rainfall for each station. The results were entered into a GIS (ArcGIS) and spatialized using the IDW interpolation method. This method was chosen because of its suitability to field conditions, unlike other methods which are generally more sensitive to variations (Khali Issa et al., 2016). The IDW method is a local deterministic interpolation technique that calculates the value of a point by averaging the values of points located in the neighborhood, weighted by the inverse of the distance to the calculated point: the closer the points, the stronger the weighting.

Soil erodibility factor K

The soil erodibility factor K expresses its susceptibility to water erosion and depends on its intrinsic properties, namely its texture, structure, and permeability. In this study, the EPIC model equation was used to determine this factor (Williams, 1995). The data used to perform this equation are the proportions of sand, silt, clay, and organic carbon in the soil of the study area. This data was collected from the analysis of 762 soil samples taken by the National Institute of Soil Science (INP) in the study area and entered into the INP database. After calculating the EPIC model in Excel, the results were imported into ArcGIS and interpolated using the IDW method to obtain the K factor raster.

$$K = 0{,}1317[0{,}2+0{,}3\exp[-0{,}0256SAN^{\left(1-\frac{SIL}{100}\right)\left(1-\frac{SIL}{100}\right)}]] \times \left[\frac{SIL}{CLA+SIL}\right]^{0{,}3} \left.\frac{SIL}{CLA+SIL}\right]^{0{,}3} \times [1- \left.\frac{0{,}25C}{C+\exp(3{,}72-2{,}95C)}\right]\left.\frac{0{,}25C}{C+\exp(3{,}72-2{,}95C)}\right] \times \left.\frac{0{,}75SN1}{[SN1+\exp(-5{,}51+22{,}9SN1)}\right]\left.\frac{0{,}75SN1}{SN1+\exp(-5{,}51+22{,}9SN1)}\right]$$

Where SN1 = 1 - (SAN/100); SAN = Sand (%); SIL = Silt (%); Clay = Clay (%) and C = Organic Carbon (%)

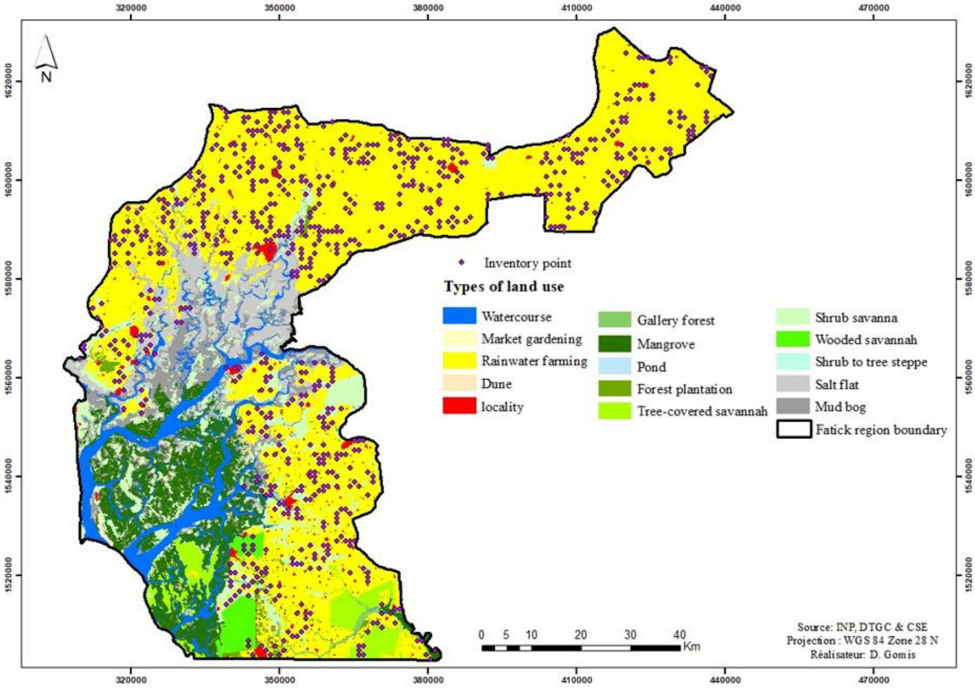


Figure 3: Distribution of soil sampling points (Source: INP)

Topographic Factor (LS)

The LS factor represents the effect of topography on water erosion. It combines the length (L) and the slope angle (S), which are among the factors that significantly influence soil water erosion. The LS factor was calculated using the equations below, proposed by McCool et al. (1989) and Liu et al. (2015). A 90 m resolution digital elevation model was used to develop these equations. This model was downloaded from the BaseGéo Senegal platform. (https://www.geosenegal.gouv.sn).

$$m = \begin{cases} 0.2 & si\ \theta < 1\% \\ 0.3 & si\ 1\% \leq \theta \leq 3\% \\ 0.4 & si\ 3\% \leq \theta \leq 5\% \\ 0.5 & si\ \theta \geq 5\% \end{cases}$$

$L=(\lambda/22.13)^{m}$

$$m = \begin{cases} 0.2 & si\ \theta < 1\% \\ 0.3 & si\ 1\% \leq \theta \leq 3\% \\ 0.4 & si\ 3\% \leq \theta \leq 5\% \\ 0.5 & si\ \theta \geq 5\% \end{cases}$$

$$S = \begin{cases} 10.8 \sin\theta + 0.03 & si\ \theta < 5° \\ 16.8 \sin\theta - 0.05 & si\ 5° \leq \theta \leq 14° \\ 21.91 \sin\theta - 0.96 & si\ \theta > 14° \end{cases}$$

Where: λ = The slope length in meters; θ = The slope angle in degrees; m = The factor established as a function of the slope

Land cover factor C

The C factor is based on the density and height of the vegetation cover on the soil surface (Wischmeier and Smith 1978). Vegetation cover protects the soil and cushions raindrops, slowing runoff and infiltration. C values range from 0 for fully covered land to 1 for fallow land (Wischmeier and Smith, 1978). Essentially, it assesses the protection offered to the soil by vegetation cover against rainfall, an estimate based primarily on land use during the rainy season. Therefore, for this study, the 2018 land cover database from the Centre de Suivi Ecologique (CSE) was used. The study area was extracted from this database. The erosion sensitivity values assigned to the different land cover types are recorded in the table below.

Table 1 : Land Cover Coefficient C as a function of land cover type

Land Cover Types	Factor C
Watercourse	0
Market gardening	0,5
Rainwater farming	0,8
Dune	1
Gallery forest	0,1
locality	1
Mangrove	0
Pond	0
Forest plantation	0,1
Tree-covered savannah	0,25
Shrub savanna	0,4
Wooded savannah	0,25
Shrub to tree steppe	0,4
Salt flat	1
Mud bog	0

Anti-erosion practices factor P

The P factor describes the human actions used to conserve soils and counteract water erosion. These actions include: contour plowing, hilling, ridge tillage, stone bunds, grass strips, etc. The value of the P factor ranges from 0 to 1. A value of 1 represents areas where erosion control practices are absent. However, given the lack of available data on erosion control measures, a value of 1 was assigned to the P factor across the entire study area.

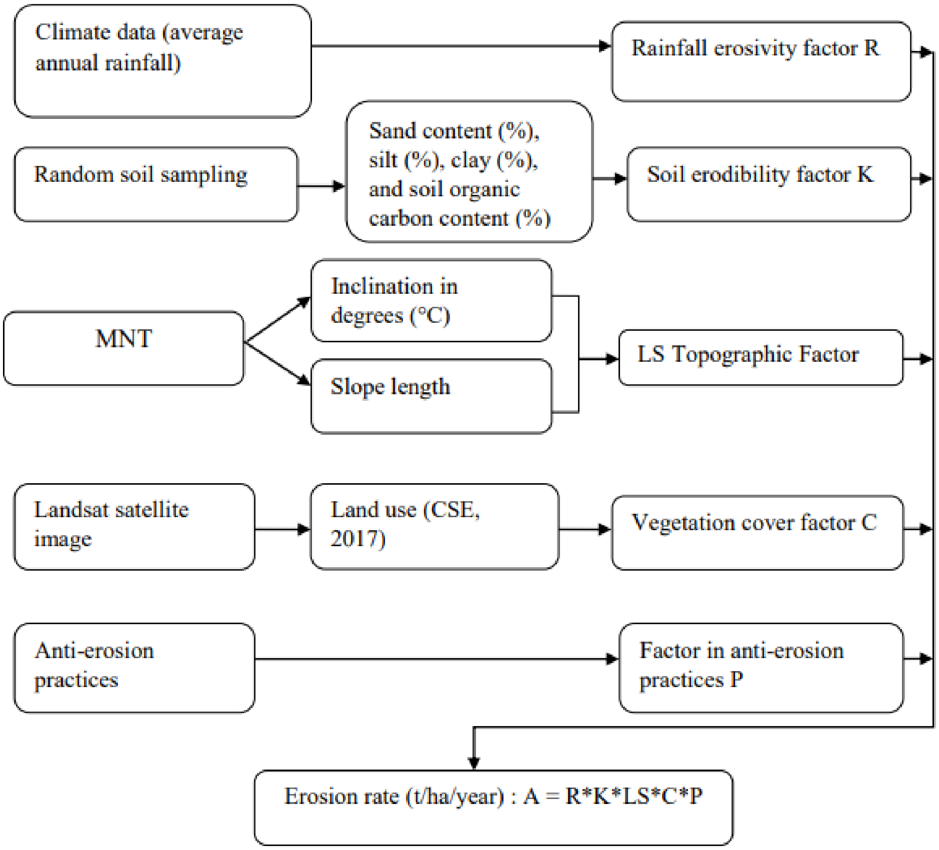


Figure 4 : Methodological flowchart of the applied RUSLE model

3.1 Results

3.1.1 Spatial Distribution of RUSLE Model Factors

The spatial representation of the RUSLE model factors highlighted the geographic distribution of each parameter.

The rainfall erosivity map, synthesized from the spatial representation of the hydrological stations, shows that the values of the R factor vary from 174.3 to 332.5 MJ.mm/ha.h.yr. They increase along a north-south gradient, proportionally to rainfall, the abundance of which follows the same pattern (Figure 5a).

The values of the K factor, ranging from 0.008 to 0.024 t.ha.h/ha.MJ.mm, show heterogeneity in the spatial distribution of soil erodibility (Figure 5b). This factor, which depends on soil texture, also varies according to farming practices. According to Roose (1989-1990), K increases rapidly 6 years after clearing, especially in the case of leached tropical ferruginous soils.

The LS factor shows the importance of slope angle and length in the erosion process. It is influenced by the relatively flat topography of the area, resulting in fairly low LS values ranging from 0 to 53 (Figure 5c). The highest values are found in areas with the steepest slopes.

Finally, for the C factor, Figure 5d shows values varying between 0 and 1. This factor reveals the sensitivity of different land cover types to erosion processes. Heavily vegetated areas, such as gallery forests and plantations, were associated with the lowest coefficient (0.1). This coefficient becomes more significant for wooded savanna, tree savanna (0.25), and shrub savanna (0.4) due to bushfires and human pressures that degrade vegetation cover and accelerate the savannaization process. High susceptibility to erosion was associated with bare soils (1), which remain the most vulnerable land cover type, followed by rainfed agricultural areas (0.8).

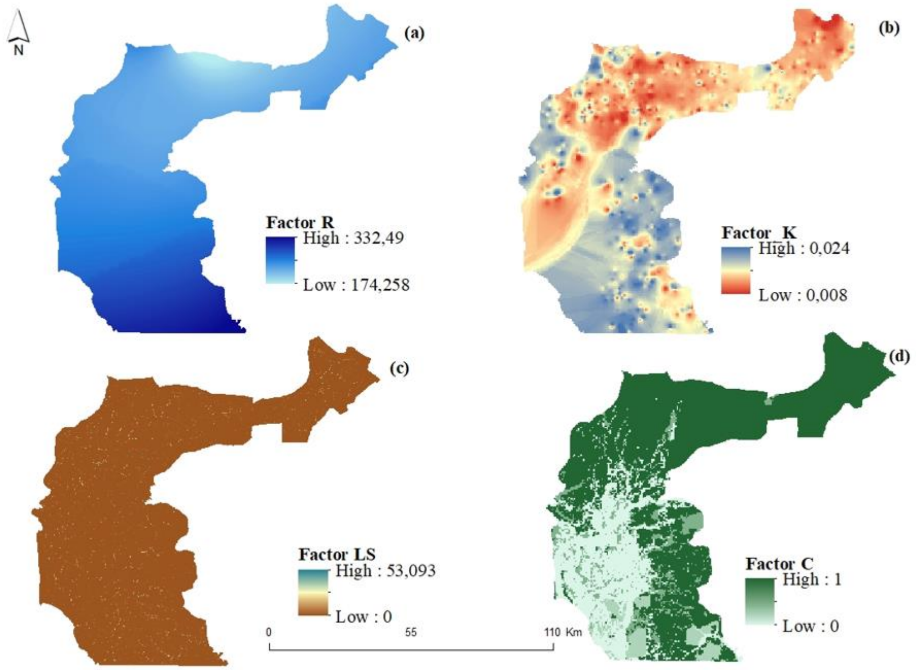


Figure 5 : Spatial distribution of the factors in the RUSLE model

Soil Losses Due to Water Erosion

The soil loss map, created by combining the maps corresponding to the four factors described above using a GIS, shows that the Fatick region exhibits significant variability in terms of soil erosion (Figure 6). Recorded soil losses range from 0 to 236 t/ha/year, with an average of 50 t/ha/year. This overview map provides concise information on the nature, intensity, and spatial distribution of the phenomenon, and thus allows for the identification of the areas most affected by water erosion.

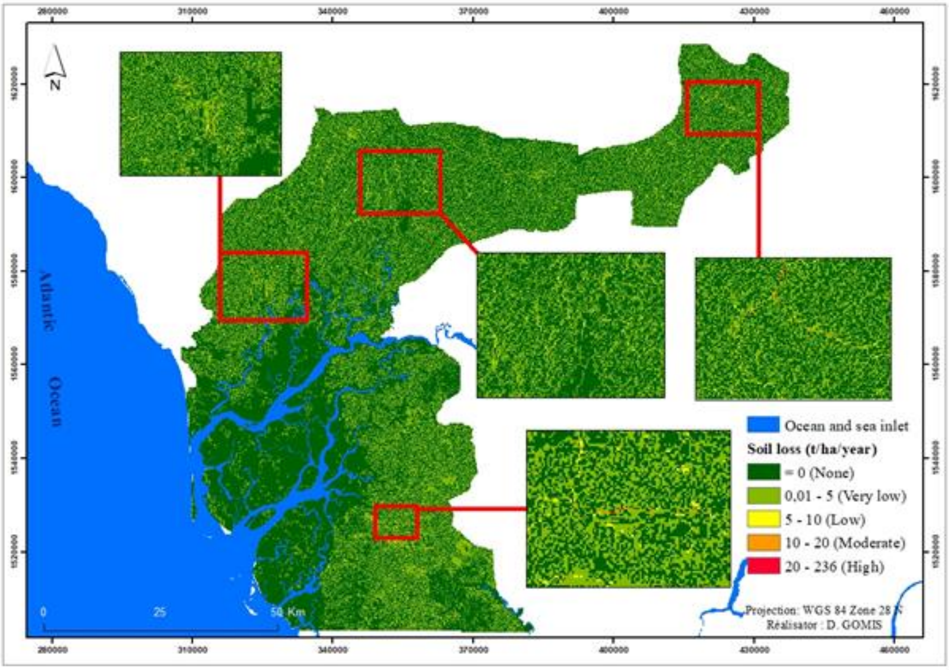


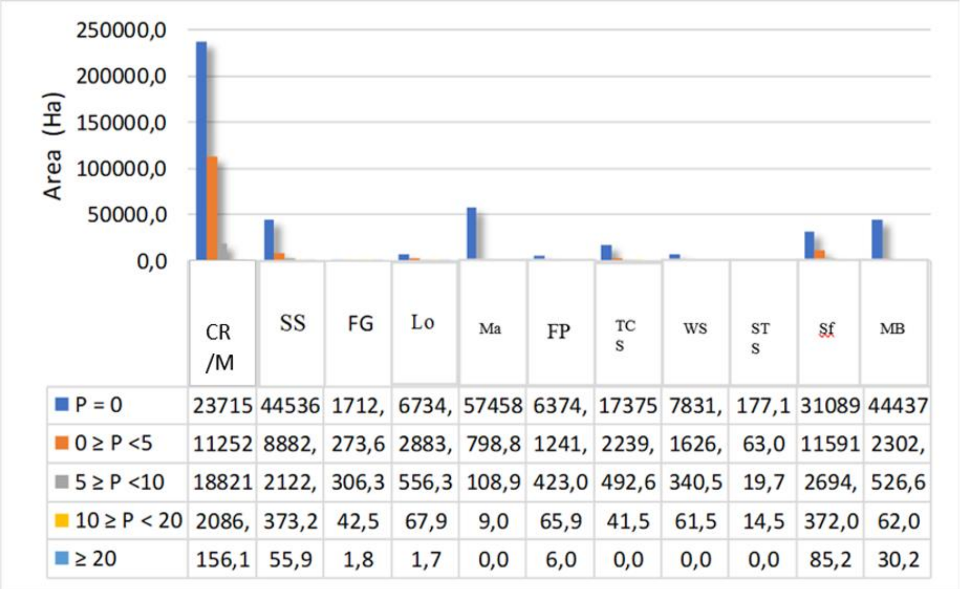
Figure 6 : Hazard Map of Annual Soil Losses from Water Erosion

Based on the classification criteria suggested by Sharma (2010), soil losses were classified into five categories: zero (equal to zero); very low (0 > Loss < 5); low (5 ≥ Loss < 10); moderate (10 ≥ Loss < 20); and high (≥ 20) (Table 2). According to this classification, soil losses are zero for 72.61% of the study area (Table 2). The "very low" soil loss category is the most representative, covering 26.4% of the total area. This is followed by the "low" and "moderate" categories, representing 0.8% and 0.2% of the total area, respectively (Table 2). Finally, high soil losses affect a very small portion, namely 0.03%, of the entire study area (Table 2).

Table 2 : Classification of soil losses (T/ha/year)

Soil Loss (T/ha/year)	Classes	Area (ha)	Percentage (%)
P = 0	None	491248,0	72,61
0 ≥ P <5	Very Low	178777,5	26,42
5 ≥ P <10	Low	5190,4	0,77
10 ≥ P < 20	Moderate	1135,9	0,17
≥ 20	High	227,9	0,03

Based on land cover units, the lowest levels of soil loss were most localized in agricultural areas, followed in descending order by : salt flats and dunes, shrub savanna, settlements, and wooded savanna (Figure 7). For all other soil loss categories, agricultural areas, followed by salt flats, dunes, and shrub savanna, were the most affected (Figure 7). The highest levels of soil loss were not observed in mangroves, wooded savanna, forested savanna, or shrub-to-tree savanna (Figure 7).



	CR /M	SS	FG	Lo	Ma	FP	TC S	WS	ST S	Sf	MB
■ P = 0	23715	44536	1712,	6734,	57458	6374,	17375	7831,	177,1	31089	44437
■ 0 ≥ P <5	11252	8882,	273,6	2883,	798,8	1241,	2239,	1626,	63,0	11591	2302,
■ 5 ≥ P <10	18821	2122,	306,3	556,3	108,9	423,0	492,6	340,5	19,7	2694,	526,6
■ 10 ≥ P < 20	2086,	373,2	42,5	67,9	9,0	65,9	41,5	61,5	14,5	372,0	62,0
■ ≥ 20	156,1	55,9	1,8	1,7	0,0	6,0	0,0	0,0	0,0	85,2	30,2

Figure 7 : Distribution of soil loss according to land cover units (ZC = Cultivated Rainwater and market garden areas ; Ss = Shrub savanna; Ma= Mangrove ; FG = Gallery forest; TCS = Tree-couvered savannah ; WS = Wooded savanna ; STS = Shrub-to-tree savanna) ; Sf = Salt flat ; MB = Mud Blog

Soil Carbon Spatialization

Based on available data (a total of 762 samples taken in the region), soil carbon content was spatially mapped by interpolation (Figure 8). According to the results, these soil carbon contents vary between 0.079 and 1.4 Cg/100 g of soil (Figure 7). It should be noted, however, that the carbon data received, while substantial in number, were not sufficiently representative for all units, especially for the mangrove.

Loss of Soil Carbon Content due to Water Erosion

The results for soil carbon losses due to water erosion show a range of values from 0.002 to 0.19 $TC.ha^{-1},yr^{-1}$ (Figure 9). The extent and distribution of these losses remain highly variable in space, which would certainly be a function of the level of erosion and the carbon content of the soil.

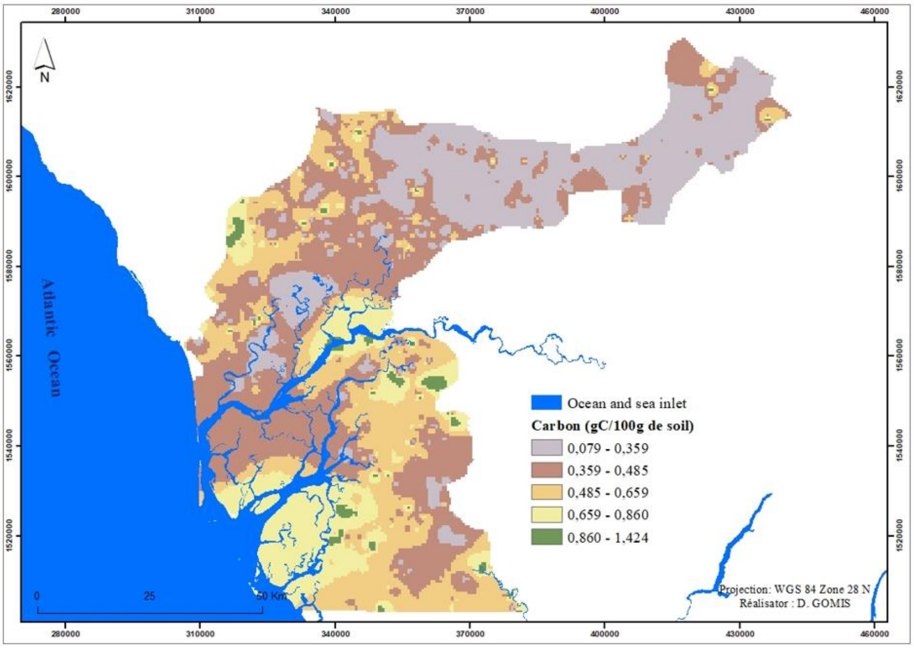


Figure 8 : Soil carbon content per g/100 g of soil

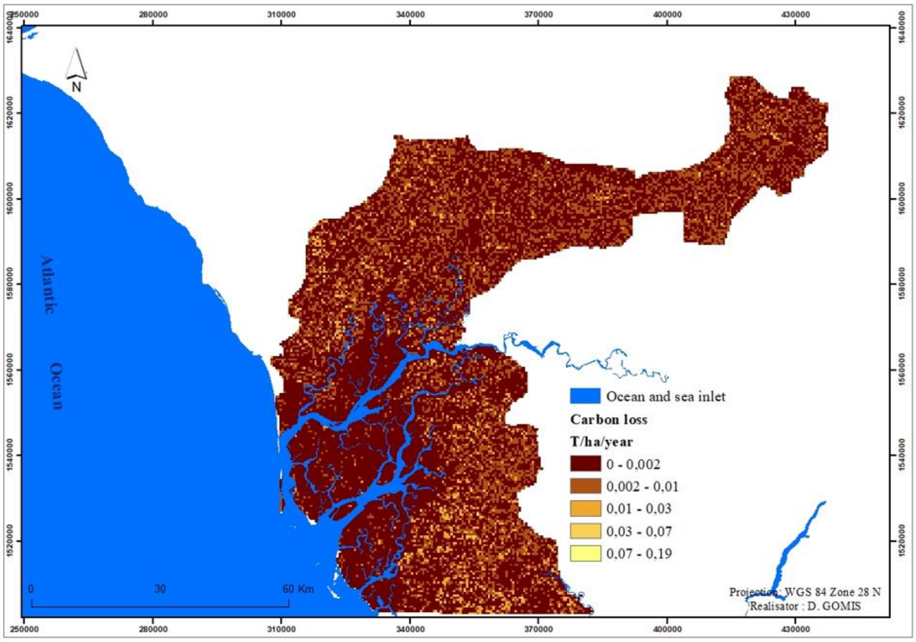


Figure 9 : Soil carbon loss per ton/ha/year

The assessment of carbon loss levels based on surface area yielded five classes (Table 3). Near-zero (0–0.002) and very low (0.002–0.01 TC/ha/year) soil carbon losses were the most representative of the study area, accounting for 73.9% and 21.6% of the total area, respectively.

These were followed by low (0.01–0.03 TC/ha/year), moderate (0.03–0.07 TC/ha/year), and high (≥ 0.07 TC/ha/year) levels, representing 4%, 0.5%, and 0.05% of the total area, respectively.

Table 3 : Categorization of annual soil carbon losses due to water erosion

Soil Loss (T/ha/year)	Classes	Area (ha)	Percentage (%)
[0 - 0,002[	None	498838,0	73,91
[0,002 - 0,01[	Very Low	145842,2	21,61
[0,01 - 0,03[	Low	26708,6	3,96
[0,03 - 0,07[	Moderate	3233,9	0,48
≥ 0,07	High	348,0	0,05

Discussion

This study quantifying and modeling soil water erosion in the Fatick region involved integrating geospatial data on topography, pedology, land use, and climate into a geographic information system. Combining these data using the RUSLE multiplication function allowed for the creation of a synthetic map of soil loss. Categorizing the results revealed that, despite a range of erosion rates from 0 to 236 t/ha/year, the erosion level is virtually zero for a significant portion of the territory (73%). For the remaining 27% of the territory, the most significant erosion rate falls within the very low category, defined as less than 5 t/ha/year, encompassing 26.4% of the total area. This category, together with the "low" erosion category, represents 27.2% of the total territory. The area most affected by erosion represents 0.2% of the study area. Vegetation areas, especially mangroves, gallery forests, and wooded and arboreal savannas, remain the most resistant to erosion. This is due to the fact that vegetation cover stabilizes the soil and increases its protection by intercepting some of the rainfall (El Hage Hassan et al., 2015). However, this soil protection provided by vegetation cover decreases with the loss of its density. Therefore, apart from the aforementioned vegetation areas, virtually all other units in the study area, including shrub savanna zones, and especially areas devoid of vegetation such as agricultural areas, salt flats, and settlements, suffer the most significant soil losses due to water erosion. This is also exacerbated by the dominance of tropical ferruginous soils in the area, which are highly susceptible to erosion. Indeed, as Payet et al. (2011) indicate, once soils are denuded, their alteration is accelerated by harsh climate, soil fragility, and the rapid mineralization of organic matter; all these processes combined lead to accelerated soil loss. Topography also plays a significant role, as the levels of soil loss in the "moderate" and "high" categories are mostly found on slopes and in low-lying runoff areas. This observation is corroborated by the work of Byizigiro et al. (2020) and Noma et al. (2022), who found that losses are greater in areas with steep slopes.

Compared to other studies, the soil loss results obtained (0 to 236 t/ha/yr) are higher than those estimated in the Saraya Department (0.01 to 134.64 t/ha/yr), which has an average of 33.46 t/ha/yr, although it is also characterized by steeper slopes than our study area, reaching 61.57% of its length (Boisy et al., 2022). This could be explained by the significant vegetation cover in the Saraya Department.

This situation contrasts sharply with that of our study area, which is located in the peanut basin, a predominantly agricultural region where high population density and agricultural pressure have pushed vegetation to its extreme limits. However, soil losses recorded in the study area are lower than those observed on the Thiès plateau, ranging from 0 to 17,652 t/ha/yr, with an average of 3,487 t/ha/yr (Diédhiou et al., 2018). Unlike the study area, which has a relatively flat topography, the significant soil losses recorded on the Thiès plateau are, according to the author, due to the high elevation and the degradation of plant resources. This confirms the assertions that areas at high risk of erosion are located on hills and slopes characterized by steep inclines and favorable substrates (Briss and Brahim, 2018).

The effects of erosion were observed here through the resulting losses in soil carbon content. These losses depend on the volume eroded and the carbon content of the top ten centimeters of soil. They reflect the detrimental consequences of erosion, leading to soil depletion of organic matter and a reduction in its capacity to store atmospheric carbon. Faced with this reality, to maintain soil quality, farmers have a strong incentive to develop cropping systems that reduce losses of organic matter and nutrients through erosion, improve aggregate stability, and progressively increase carbon stocks in the topsoil.

Regarding the RUSLE model used, it is certainly subject to debate. Furthermore, it only assesses losses and does not incorporate gains, thus preventing comprehensive assessments. Despite these limitations, it remains an effective tool for quantifying soil losses and locating areas at risk of water erosion. However, it could be supplemented by field surveys.

Conclusion

This study presents the results of mapping work based on the overlay of the main factors of the Universal Soil Loss Equation (USLE) by Wischmeir and Smith, integrated into a GIS. The results obtained revealed the heterogeneity of soil losses due to water erosion. These losses are more prevalent at very low and low levels and have negative impacts on soil quality through carbon loss. Furthermore, it illustrates the importance of vegetation cover in combating water erosion, as it is at this level that the greatest amount of soil loss is found.

Overall, it can be concluded that the study area is not highly subject to intensive erosion. However, the losses of vegetation cover linked to agricultural expansion and farming practices related to peanut cultivation, which leave soils completely bare after harvest, do not bode well for the future of combating this phenomenon.

Conflict of Interest: The authors reported no conflict of interest.

Data Availability: All data are included in the content of the paper.

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