



Research Article

Quantification of Soil Erosion Using Remote Sensing and GIS: The Case of the Anguededou Watershed

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Abstract

The Anguededou watershed belongs to the Anguededou river hydrographic system. It is located in the Abidjan district in southern Côte d’Ivoire. The present study aims to quantify water erosion of soils in the Anguededou watershed using remote sensing and GIS. The USLE (Universal Soil Loss Equation) model was chosen to quantify and spatialize water erosion processes at the watershed scale. This model, already implemented in different environments and at different scales, takes into account five determining factors in erosion processes, including: the aggressiveness of rainfall, the erodibility of soils, the inclination and length of the slope, as well as the vegetation cover and the means put in place to combat soil erosion. This study is part of a sustainable management approach for peri-urban watersheds. The result from the combination of the different factors indicates a soil loss on the Anguededou watershed which varies from 0 to 250 t/ha/year with an average of 41.27t/ha/year. The results obtained allow the identification of areas at the basin scale where interventions are needed to limit soil degradation processes. Soil loss from upstream to downstream of the catchment area could contribute in the long term to pollution and silting of the lagoon, thus causing a drastic reduction in the water surface area.

Keywords

Erosion, Remote Sensing, GIS, USLE, Anguededou, Côte d’Ivoire

1. Introduction

Soil is a fundamental natural resource, providing the biophysical support for the functioning of terrestrial ecosystems [1, 2]. It makes a decisive contribution to the provision of a wide range of ecosystem services that are essential to human societies, including food production, water cycle regulation, carbon storage, nutrient recycling and biodiversity conservation [3-5]. Thus, soil represents a strategic lever for the sustainability of socio-ecological systems and resilience to global

change (Wu et al., 2011). Soil erosion is one of the most worrying phenomena for watershed management. This phenomenon is linked to natural and human-induced factors that are difficult to control over time and space [6]. Demographic pressure, the expansion of various human activities and urbanisation, combined with the amplifying effects of climate change, have led to land exposure to runoff and soil degradation through water erosion [7-9]. Changes linked to the development of societies and human activities cause soil denudation,

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which in turn accelerates erosion processes [10].

In Ivory Coast, the excessive exploitation of forest resources for agricultural and urbanization purposes is the cause of significant soil loss [11, 12]. In the Anguédédou watershed, located on the northwestern outskirts of the city of Abidjan, this problem takes on a particular dimension due to increasing demographic pressure, the anarchic expansion of urban areas, and the progressive disappearance of protective vegetation cover [13]. These environmental changes accentuate rainwater runoff, thus promoting the triggering of more intense and frequent erosion processes.

Quantifying soil erosion in this watershed is therefore a major issue for urban planning, natural resource conservation, and sustainable environmental management. It not only identifies the most vulnerable areas, but also suggests appropriate anti-erosion measures. In this context, the use of spatial modelling tools, such as the Universal Soil Loss Equation (USLE) model coupled with Geographic Information Systems (GIS), offers an effective approach to estimating soil loss [14, 15] and guide land use planning decisions. This empirical soil erosion

model has been revised (Revised Universal Soil Equation, RUSLE) [14].

The present study aims to quantify water erosion in the Anguédédou watershed, highlighting the determining factors of this dynamic and identifying areas at risk. It is part of an integrated soil resource management approach in a context of high anthropogenic pressure.

2. Materials and Methodology

Geographically, the Anguédédou watershed is located in the district of Abidjan in southern Ivory Coast between longitudes 4°4'30" and 4°9'30" West and latitudes 5°18'0" and 5°27'30" North (Figure 1). It covers an area of 87 km² with a perimeter of 65 km. The climate is classified as a transitional equatorial regime. Average annual rainfall was around 1500 mm in 2500 mm in 2017 [16]. The population surrounding the basin increased from 4 707 404 inhabitants in 2014 to 6 321 017 inhabitants in 2021 [17].

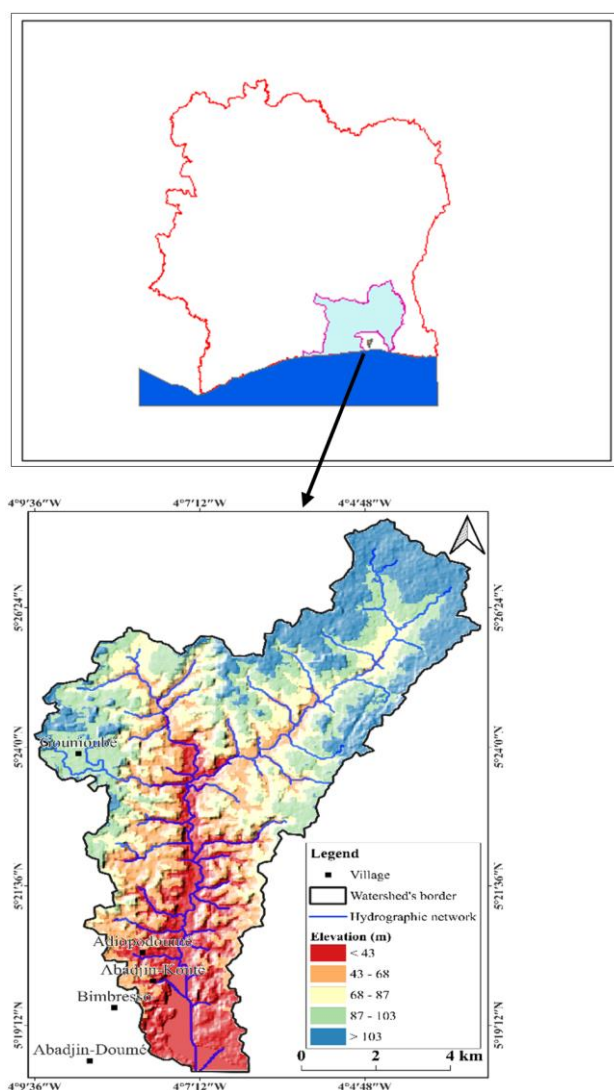


Figure 1. Location of the Anguédédou watershed in the Abidjan district.

Several methods are generally used to assess soil erosion, with varying degrees of complexity. The empirical model developed by [18] was used to estimate the soil loss rate (USLE) in the watershed. This is best-known and most widely used mathematical model for estimating water erosion. According to this model, erosion is a multiplicative function of the five factors that control water erosion: climate aggressiveness, soil erodibility, slope inclination and length, land use and anti-erosion practices. This equation, which is well suited to GIS [19], has been used by several researchers around the world to assess erosion [11, 19-22]. The RUSLE formula is as follows:

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

Where:

A: expressing the average annual soil losses possible in the long term (t.ha. year).

R: expressing the rainfall erosivity index (MJ. mm/ha.h.an). In the absence of data on rainfall intensity, the formula developed by [23], based on monthly and annual precipitation is used to calculate this factor. It is expressed as follows:

$$R = \sum_{n=1}^{12} \frac{p^2}{p}$$

With:

P: Monthly rainfall (mm) and *P*: Annual rainfall (mm). Based on the erosion values obtained, an erosion map is produced using kriging with rainfall data from six (06) stations (Abidjan-Cocody, Adiopodoume-ORSTOM, Azaguie-IRFA, Niekya's banana plantation, Banco and Kossi-Houan) over the period 1994-2024, i.e. 30 years.

K: expressing the soil erodibility index (t.ha.h/ha.MJ.mm). It depends on the texture, organic matter content, and permeability of the soil [24].). The *K* factor was calculated using a series of equations that mimic and translate the nomogram developed by [18].), instead of the classic equation, which has limitations and is responsible for more than 50% of prediction errors [25]. It is presented as follows:

$$K = 2,77 \times 10^{-5} \times ((f_{li} + f_{sf}) (100 - f_{arg})) 1,14 \times (12 - f_{MO}) / 10 + (0,043 \times (S - 2) \times 0,033 \times (P - 3))$$

With *K* expressed in [(t.ha.h) / (h.MJ.mm)] in the International System of Units (SI). *f_{li}* + *f_{sf}*: Fraction of silt and fine sand; *f_{arg}*: Fraction of clay; *f_{MO}*: Fraction of organic matter; *S*: Soil structure; *P*: Soil permeability

Once the resistance of each soil type has been calculated, a new field containing the calculated values is added to the vector file containing the polygons corresponding to the different soil types, which allows this factor to be spatialised and a soil erodibility map to be obtained.

LS: expressing the slope factor (dimension less). There are many different equations available for calculating the *LS* factor. [26] presented that slope length and slope inclination can be used in a single index, which expresses the ratio between soil loss as defined by [18]. As shown below:

$$LS = (X/22,13)^m (0,065 + 0,045S + 0,0065S^2)$$

Where:

X: slope length (m);

S: slope gradient (%)

The values of *X* and *Y* can be obtained from the digital elevation model (DEM). To calculate the value of *X*, the flow accumulation was derived from the DEM after conducting flow direction and filling processes in ArcGIS.

$$X = (\text{flow accumulation} * \text{resolution})$$

Substituting the value of *X*, the *LS* equation will be:

$$LS = (\text{runoff accumulation} * \text{resolution} / 22,13)^m (0,065 + 0,045S + 0,0065S^2)$$

(*m* = Constant equal to 0.5 for *S* > 5%; 0.4 for 3.5 < *S* < 5%; 0.3 for 1 < *S* < 3.5%, and 0.2 for *S* > 1%).

C: expressing the vegetation factor (dimension less). It allows the soil's capacity to mitigate the effect of raindrops to be estimated [27]. This factor was determined based on the land use map. Table 1 shows the type of vegetation cover existing in the study area and the assigned *C* value.

Table 1. Land use coefficient *C* according to land use type.

Land use type	Factor <i>C</i>
Bare ground	1
Scrubland or mosaic of crops	0,5
Built-up area	0,2
Reforested area	0,18
Dense forest	0,001
Water body	0

P: expressing the support practice factor (dimension less). The *P* factor describes human actions to conserve soil that are practised to counter water erosion [28]. It generally varies from 0 to 1, depending on the practice adopted and the slope. However, given that no anti-erosion practices have been adopted throughout the study area, this factor has been considered a unit value equal to 1.

The organizational chart below (Figure 2) presents the methodology adopted to estimate and map potential erosion. It aims to develop a soil loss map for the Anguededou catchment area. This map takes into account most of the factors included in the Wischmeier and Smith equation (1978), which are themselves expressed in the form of thematic maps. By cross-referencing these digital maps using GIS, we were able

to estimate the rate of soil loss at the watershed scale.

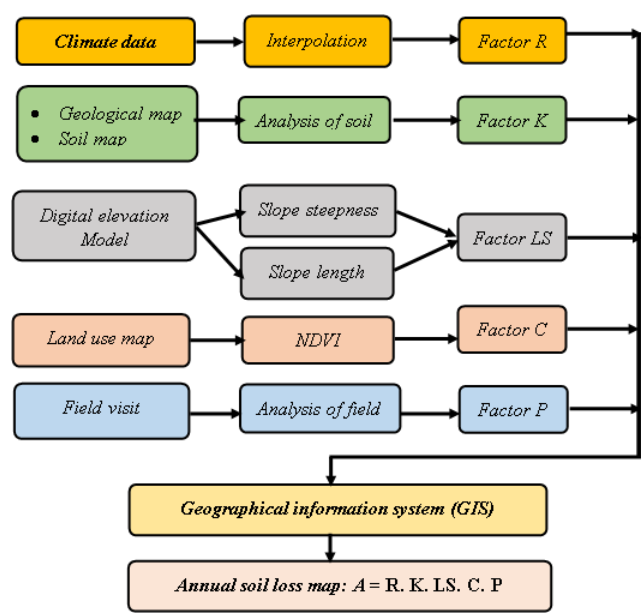


Figure 2. Methodology used to produce the water erosion map for the Anguedou catchment area.

3. Results and Discussion

3.1. Results

3.1.1. R. Factor

The rainfall erosivity map was estimated based on rainfall levels at two rain gauge stations over a 30-year period (1994-2024). In the watershed, the R factor ranges from 389 in the south-east to 452 in the north, with a value of 422.46 in the centre (Figure 3 and Table 2). High rainfall aggressiveness values are observed in the North of the catchment area. The impact of rainfall intensity is manifested in the processes of sediment detachment and transport. Given the very low variability but high values, it can be concluded that the R factor could only cause slight variability in erosion; however, it could accentuate linear erosion and therefore high values of solid transport.

Table 2. Rainfall erosion statistics.

Soil erodibility statistics	
Min	389
Max	452
Average	422,46
Standard deviation	17,39

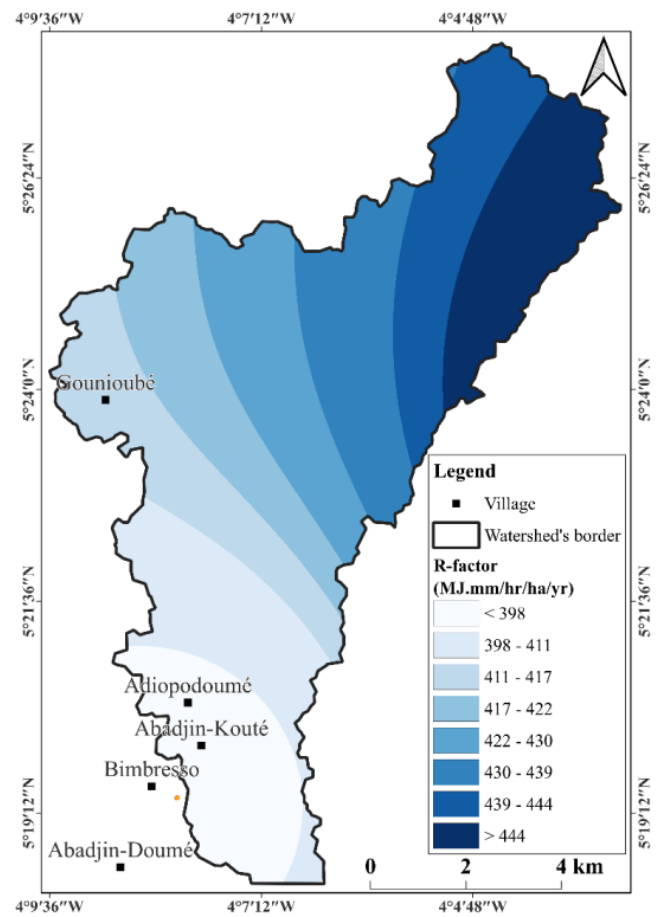


Figure 3. Map of the R climate factor the Anguedou watershed.

3.1.2. K. Factor

Lithology influences the erosion process in terms of the substrate and surface formations. To understand the degree of resistance of lithological substrates to erosion, a classification is made based on the degree of erodibility of the rocks. This varies from a minimum value of 0.013 for soft rocks to a maximum value of 0.019 for resistant substrates (Figure 4 and Table 3). Approximately 95% of the catchment area is characterized by a K factor of less than 0.010, and 5% by a K factor of more than 0.010. This shows the fragility of the soils and their susceptibility to erosion.

Table 3. Soil erodibility factor statistics.

Soil erodibility statistics	
Min	0.013
Max	0.019
Average	0,016
Standard deviation	0,004

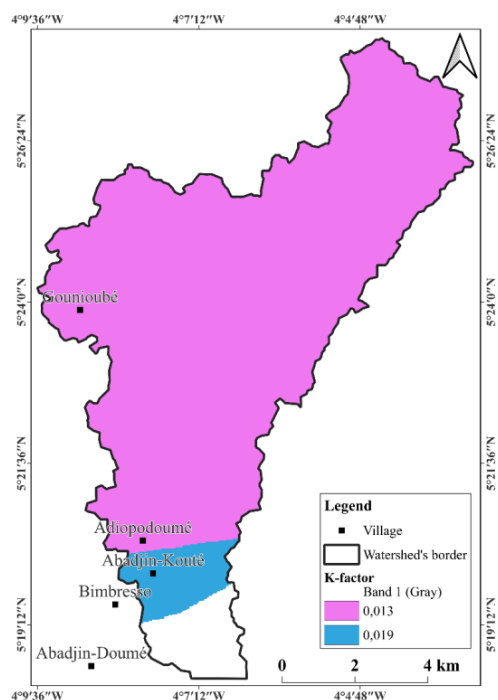


Figure 4. Map of the factor (K) for the Anguededou watershed.

3.1.3. Topographical Factor (Ls)

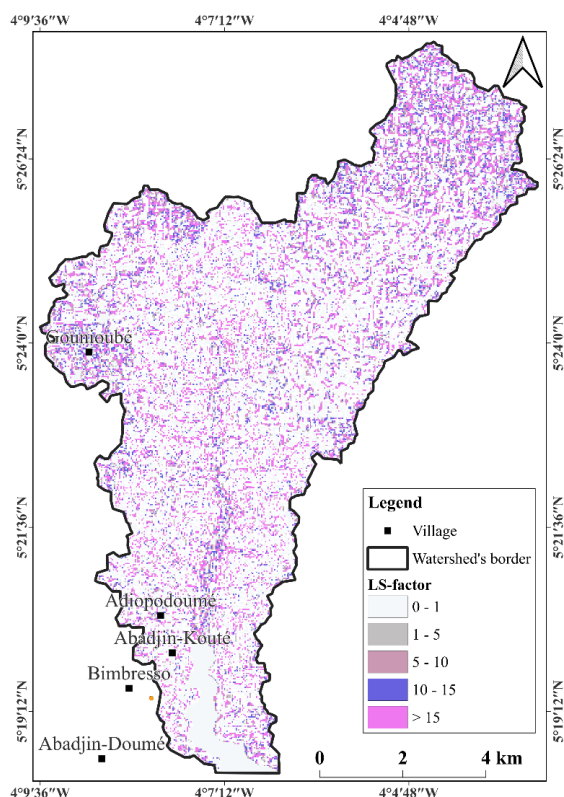


Figure 5. Map of the LS factor in the Anguededou catchment area.

The LS factor is synthesized from slope and basin length

maps (Figure 5). Slope is the main constraint on soils in the basin. This factor is represented by the degree of inclination of the terrain, as it is the slope that gives runoff the energy it needs to strip away soil and transport sediment. High LS values can promote all types of erosion, mainly gully erosion and rill erosion. The class corresponding to the highest LS values (5-10) covers a large part of the basin and is located on the steepest slopes, particularly in the northern part of the basin.

3.1.4. Map of the C Factor and Erosion Control P

Vegetation cover protects the soil and cushions raindrops, slowing runoff and infiltration. The map showing the distribution of factor C in the basin (Figure 6) shows the sensitivity of different types of land use to erosion processes. Across the entire catchment area, factor C varies between 0 and 1. Vegetated areas, such as dense forest, palm and rubber tree plantations, are characterized by very low factor (0.10), while the highest factors (1) correspond to bare soil, habitats and rocky areas. Anthropogenic activities such as deforestation and agricultural activities are factors that make soils vulnerable to erosion. The P factor represents soil protection and anti-erosion practices that reduce runoff velocity and thus decrease the risk of water erosion. It varies according to the developments carried out. In the case of the Anguededou watershed, the values of this factor generally vary between 0.5 in developed and protected areas and 1 where soil and slope protection and development are almost non-existent.

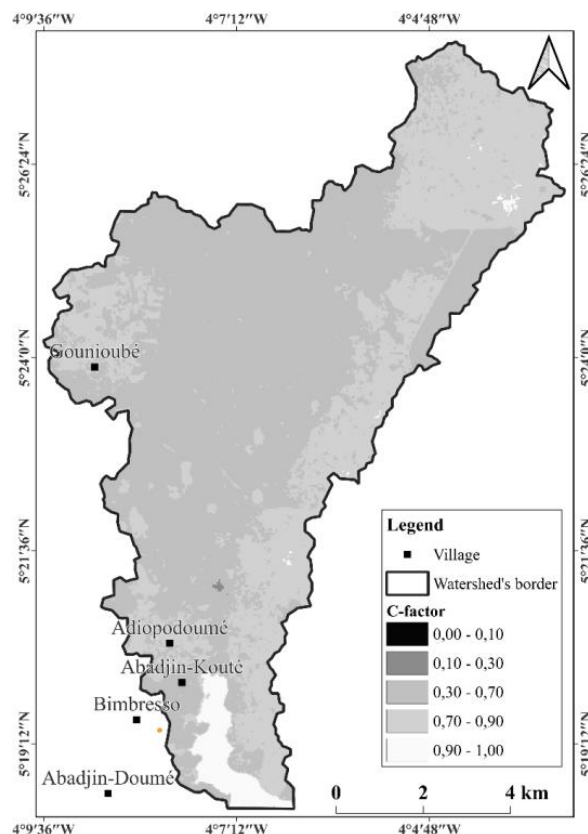


Figure 6. Map of factor C for the Anguededou watershed.

3.1.5. Assessment of Soil Loss

The soil loss map shows that soil loss in the basin varies from 0 to 250 t/ha/year, with an average of 41.27 t/ha year (Figure 7). The erosion rate calculated using the USLE Wischmeier et Smith (1978) model provides information on the distribution of erosion risk. It varies from one area of the catchment to another depending on the influence of various explanatory factors that control erosion, such as slope, climate aggressiveness, type and rate of vegetation cover, and anthropogenic action. Analysis of the annual soil loss result shows that areas at high risk of erosion are located on hills and slopes characterized by steep gradients and favourable substrates. The resulting map is subdivided into five soil loss classes: 0-1 t/ha/year, 1-10 t/ha/year, 10-50 t/ha/year, 50-100 t/ha/year and > 100 t/ha/year. The threshold considered in this study is 7 t/ha/year, a value used in other erosion studies [28, 31].

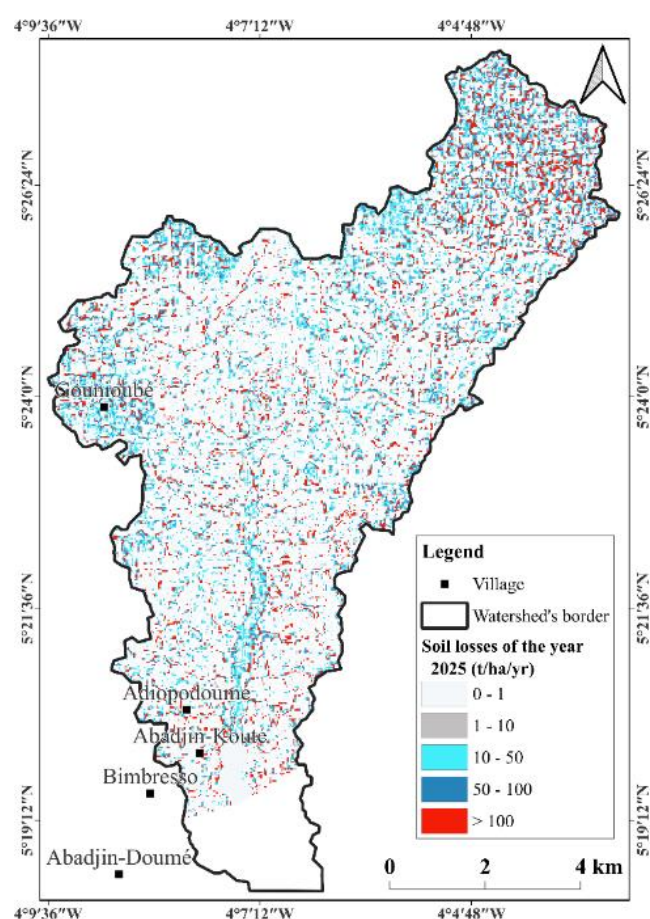


Figure 7. Soil loss map of the Anguededou watershed.

From Table 4, we can see that soil loss classes between 0-1 t/ha/year represent an area of 6.02 km. The 1-10 t/ha/year class represents 15.5 km. 25.2 km for the 10-50 t/ha/year class, and 16.78 km for the 50-100 t/ha/year class. And finally, 23.5 km for the area of soil loss greater than 100 t/ha/year. Based on a comparative analysis of the maps of the factors in the soil loss equation, we observe that the spatial distribution of the high

erosion classes corresponds to that of the steep slope classes with a high density of waterways. This shows that erosion is significant in the rugged parts of the catchment area that have very steep slopes. It is accentuated by watercourses. Areas subject to severe erosion generally correspond to rugged terrain with little or no vegetation cover. In general, these are the areas most at risk from erosion.

Table 4. Area of soil loss classes in t/ha/year.

Soil loss class A (t/ha/year)	Area (km ²)	Degrees of erosion
0-1	6.02	Low
1-10	15.2	Moderately low
10-50	25.2	Medium
50-100	16.78	High
>100	23.5	Very high
Total	87	

3.2. Discussion

The model presented in this study combines the elements of the USLE equation (R, K, LS, C, P). However, integrating the model into a GIS offered many advantages, particularly those related to the factors involved in erosion. This integration made it possible to rationally manage a multitude of qualitative and quantitative data relating to the various factors of soil degradation. According to the summary map, the rate of soil loss varies from one area to another depending on the impact of the factors determining erosion. The impact of the rainfall aggressiveness factor (R) is manifested in the processes of sediment detachment and transport. Given the variable but high values, it can be concluded that the R factor could cause significant variability in erosion. The soils of the Anguededou watershed consist largely of ferrallitic and ferruginous soils. According to [29], ferrallitic soils are generally permeable and fairly resistant when K varies from 0.015 to 0.20. The K factor for the watershed varies between 0.013 and 0.019 MJ.mm/ha.h.year. This indicates that the soils in the watershed studied are permeable and therefore less resistant to erosion. Thus, [30], noted that soil erodibility is not homogeneous across space and changes over time: it increases during the rainy season and varies according to soil characteristics, age of clearing and cultivation techniques. The calculated LS factor shows that the erosive power is relatively strong. Indeed, the average LS value is 11.72. The erosion rate between 0t/ha/year and 250 t/ha/year, spread across the entire study area, with an average of 41.27 t/ha/year. This average value is higher than 7.41 t/ha/year, because according to the classification accepted by RUSLE, soils can tolerate losses of up to 7.41 t/ha/year while still allowing a high of agricultural production [31]. The average value of soil loss is 41.27 t/ha/year in the basin, which is considered very high.

These high values of soil loss may be due to the topographical factor, which includes the length of slopes along the hydrographic network [32]. Overall, the increased risk of erosion in the watershed could be explained by rapid urbanisation and overgrazing leading to the destruction of existing vegetation. In addition, this degradation exposes the watershed to very high runoff and very low infiltration [33]. Soil displaced by erosion carried nutrients, pesticides and other chemicals [34]. Most of these harmful products can be carried by the Anguedou river to lagoon. The deposition of soil losses and substances in the lagoon could contribute to its pollution and siltation in the long term, causing a drastic reduction in surface water [35, 36].

4. Conclusions

Soil sensitivity to erosion depends on soil type, season and farming techniques. The study conducted in the Anguedou watershed highlights the combined impact of natural factors and human activities on erosion dynamics. The summary map shows the high amount of soil loss. The empirical soil loss estimation model (USLE) developed by Wischmeier & Smith (1978) was used to map the areas affected by sheet erosion. The study showed that the average soil loss in the basin is estimated at 41.27 t/ha/year, which is higher than 7t/ha/year (the tolerance threshold). Topography and hydrographic network are the main factors explaining these values, especially as they are limiting factors in the Wischmeier model. The high values could also be explained by rapid urbanization and overgrazing, leading to the destruction of existing vegetation.

It is important to note that the USLE model enables decision-makers to consider intervention strategies within the framework of sustainable development. Efforts should focus on restoring slopes and introducing soil-protective agricultural techniques. Finally, the implementation of the USLE model requires monitoring over several years. Station studies must be designed to compare estimated loss values with values measured in the field.

Abbreviations

GIS	Geographic Information Systems
RGPH	General Population and Housing Census
USLE	Universal Soil Loss Equation
RUSLE	Revised Universal Soil Loss Equation

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improvement of this work.

Author Contributions

Anzoumanan Kamagate: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing– review & editing

Seydou Diallo: Formal Analysis, Methodology, Resources, Software, Validation, Visualization

Kouadio Euclide N’Goran: Formal Analysis, Investigation, Methodology, Software, Visualization

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Anzoumanan Kamagate is a doctor. I obtained my PhD in hydrology, specializing in water resources and the environment. I am a senior lecturer at the University of San Pedro in Côte d'Ivoire. I work on issues related to water resource management and land use modelling. My work also focuses on climate change and coastal erosion issues.



Seydou Diallo is a doctor of hydrology-GIS, an expert in hydrology/hydrogeology and the environment.



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Research Field

Anzoumanan Kamagate: hydrology, hydrogeology, climate change, erosion, water resources.

Seydou Diallo: hydrology, geographic information system, water resources.

Kouadio Euclide N'Goran: hydrogeomatics, remote sensing, water resources.