Assessment of soil erosion in the Autonomous District of Abidjan, Côte d'Ivoire

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Abstract— *In a context of global changes and climatic uncertainties, this study poses the problem of the occurrence of water erosion induced by natural constraints and uncontrolled and speculative anthropisation of soils in the Autonomous District of Abidjan. The aim is to propose a decision-making tool that identifies the areas of the Autonomous District of Abidjan (ADA) most prone to soil loss and the risk of water erosion. More specifically, the aim is to evaluate, prioritise and map the levels of susceptibility to the occurrence of this hydroclimatic risk in the ADA. The mapping approach is based on the aggregation of factors such as climatic aggressiveness, soil erodibility, topography, soil cover and anti-erosion practices from the Revised Universal Soil Loss Equation (RUSLE). The exploitation of these data reveals that soil loss in the ADA oscillates between a minimum value of 0 t/ha/year largely observable in the south of the lagoon system to a maximum value of 107.53 t/ha/year which concerns the plateau areas in the north. The average of this series of 0.48 t/ha/year translates into an overall low level of water erosion in the ADA over nearly 95% of the ADA territory. This soil degradation, which impacts human settlements induced by the morphology of the site, is amplified by human activities. In a context of rapid urban expansion linked to a remarkable demographic growth coupled with climatic uncertainties, development policies must better integrate sustainable soil management.*

Keywords— Autonomous District of Abidjan, Water erosion, RUSLE model, Land use, Land cover, Vulnerabilities.

I. INTRODUCTION

In sub-Saharan Africa, water erosion is a major risk with more than 20% of land degraded, affecting more than 65% of the population (FAO, 2015). For Chafai and al., (2022), this phenomenon appears as a warning signal of the imbalance between the soil environment and its exploitation system. This risk can affect infrastructure such as roads, riverbanks, crop areas and urban land (Morgan, 2005; Sourlamtas, 2019). A direct product of complex interactions between natural and anthropogenic factors (Phinzi and Ngetar, 2019), it impacts on food production, drinking water quality, ecosystem services, landslides, eutrophication, biodiversity and declining carbon stocks (Boardman and Poesen, 2006; Panagos, 2015). This is a triptych due to firstly the extraction of particles from the soil surface, secondly the transport of these particles by water and thirdly the deposition of the soil when there is no more energy to move the particles (Renard and al., 1997; Morgan, 2005; Sourlamtas, 2019). The management of this major risk by restoring degraded soils is essential for the sustainability of territories. With this in mind, in May 2022, Abidjan, the economic capital of Côte d'Ivoire, hosted the fifteenth session of the Conference of the Parties (COP15) of the United Nations Convention to Combat Desertification (UNCCD). Adopted on 17 June 1994 and entered into force on 26 December 1996, this convention has 197 States and Parties. More generally, it aims to combat all forms of land degradation, understood as the reduction or disappearance of land resources as a result of land use, one or more phenomena caused by human activity and settlement patterns. Land degradation is defined as the reduction or loss of land resources as a result of land use, human activity and settlement patterns, such as soil erosion caused by wind and/or water, deterioration of the physical, chemical and biological or economic properties of soils, and the long-term loss of natural vegetation (United Nations, 1994).

This article is in line with this desire for sustainable soil management. It is intended as a decision-making tool for soil restoration and the anticipatory and preventive management of crises inherent in the risk of erosion in the Autonomous District of Abidjan (ADA). The choice of this area is justified not only by its morphology, which predisposes it to this hydroclimatic risk, but also by its pre-eminence in the urban framework of Côte d'Ivoire. Indeed, the ADA is home to around 42% of the urban population of Côte d'Ivoire (INS, 2021) and polarises almost 80% of the economic activities of Côte d'Ivoire (World Bank Group, 2019). This demographic and economic concentration is at the root of a rapid artificialisation of the land at a rate of almost 7% per year (Traoré, 2022). These mostly informal and spontaneous changes expose soils initially protected by plant cover to the kinetic energy of raindrops, to the ablation of particles from the upper horizons and increase the exposure and vulnerability of territorial issues to the risk of water erosion (Sourlamtas, 2019).

Through modelling based on the integration of the main soil loss factors of the Revised Universal Soil Loss Equation (RUSLE) model into a Geographic Information System, this study prioritises the susceptibility of occurrence of water erosion in the ADA. Specifically, it (i) maps the main erosive factors, (ii) maps soil loss susceptibility and (iii) identifies the soils most prone to erosion risk in the ADA.

II. MATERIAL AND METHODS

2.1 Study area

The Autonomous District of Abidjan is located on the coast of Côte d'Ivoire between 5°10′0″ and 5°40′0″ North Latitude and 4°30′0″ and 4°60′0″ West Longitude (Figure 1).

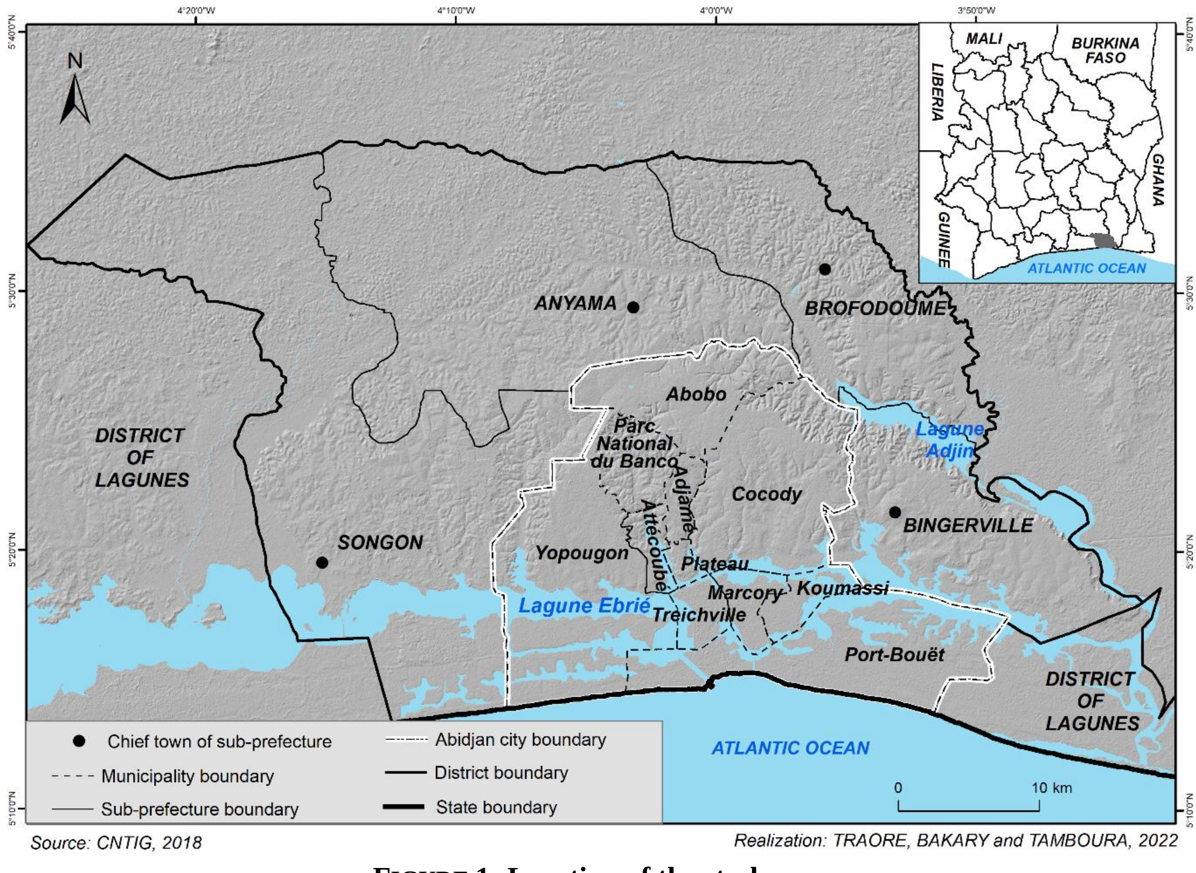


FIGURE 1: Location of the study area

In addition to the city of Abidjan, the ADA has four Sub-Prefectures (Anyama, Bingerville, Brofoudoumé and Songon). It covers about 2,034 km² with an estimated population of 4,707,404 in 2014 (SDUGA, 2015). The ADA is located on the sedimentary basin which covers a substratum of Birrimian formations made up of rocks (flysch, schists, micaschists, quartzites, etc.). Geological evolution has given the site a morphology divided between coastal plains and inland plateaus separated by the Ebrié lagoon system (Figure 1). Altitudes vary from 0 to 5 m on the coastal plains and 173 m on the inland plateaus. The southern part corresponds to an area of coastal sediment cover belonging to the Cretaceous. The northern part corresponds to an area of fairly thick cover of sediments belonging to the Tertiary. The dominant forms are plateaus made up of more or less ferruginised sandstones, clayey sediments, and shales and grauwackes in the north (BNEDT, 2008).

This area is dominated by four types of soil cover. These are ferrallitic soils, hydromorphic soils, podzolic soils and soils that are not very advanced on marine sands. Ferrallitic soils with a sandy-clay texture cover more than three quarters (77.6%) of the area (E. Roose et al, 1966).

This territory is located in the intertropical zone characterised by average temperatures that remain above 20°C. The ADA region has a humid equatorial climate with four seasons. The average annual rainfall is well over 1200 mm. The entire area was once covered by dense evergreen rainforest, which now exists only as a relic, such as the Banco National Park.

2.2 Input data

In this study soil loss and erosion risk were assessed and mapped according to the Revised Universal Soil Loss Equation (RUSLE). The RUSLE model, based on the empirical equation of Wischmeier and Smith proposed at the Seventh Congress of Soil Science in Madison (1960), is based on the statistical analysis of more than 10,000 annual results from various stations in the American Great Plain (Roose, 1975). The revised version RUSLE (Revised Universal Soil Loss Equation) was produced by Renard et al (2011). It estimates the long-term average annual loss of soil through sheet erosion and gully erosion (Wischmeier and Smith, 1978: Panagos et al, 2015). This equation (equation 1) integrates five erosive factors of water erosion which are: climatic aggressiveness, soil erodibility, the topographic factor integrating slope inclination and length, land use and anti-erosion practices. It is written :

$$A = R * K * LS * C * P \quad (1)$$

- A (t/ha/yr): Soil loss per unit area per year;
- R: Rainfall index characterising the climatic aggressiveness;
- K: Erodibility index in relation to soil resistance to sheet and channel erosion;
- LS: Topographic index combining both the effect of length L and slope steepness S;
- C: Land cover index and
- P: Erosion control index.

Although designed in the United States, this equation is one of the most suitable models for the annual estimation of water erosion (Payet et al, 2011). These erosive factors were determined from input data (Table 1).

TABLE 1
DATA USED

N°	Data	Factor	Format	Sources	Dates	Resolution
1	Climatological	R	NC	crudata.uea.ac.uk/cru/data/hrg	2011-2020	0,5° x 0,5°
2	Pedological	K	Shapefile	FAO (DSMW)	Jan. 2003	0,5° x 0,5°
3	Topographic	LS	GEOTIFF	ALOS PALSAR –R.T.C. (https://search.asf.alaska.edu/#/)	18/07/2007 04/08/2007	12,5 m
4	Soil cover	C	TIFF	Sentinel 2	01/01/21-31/12/21	10 m
5	Supporting or protective practice	P	GEOTIFF	ALOS PALSAR –Radiometric Land Correction	18/07/2007 04/08/2007	12,5 m

2.3 Modelling processes for soil loss and erosion risk

While in the literature there are several empirical, semi-empirical and physical approaches to assess soil loss, Nacishali Nteranya, (2021) notes that the direct measurement approach remains practically the most reliable. However, due to prohibitive difficulties linked to the enormous cost in terms of time and money for data collection, especially in southern countries, the modelling approach using a GIS makes it possible to give a first approximation of the risk of erosion at the scale of a territory (Ganasri and Ramesh, 2015; Nacishali Nteranya, 2021; Adamou and al., 2022).

In this study, using GIS and remote sensing tools, the five parameters (R, K, LS, C and P) of the RUSLE model were determined and a hierarchy of soil loss and erosion risk was established. However, these five parameters relate to different realities. Indeed, while the R, K, L and S factors relate to the physical characteristics of the site, i.e. precipitation, pedology and topography, the C and P factors emanate from anthropogenic soil use and protection practices. In this study, soil loss is therefore a combination of both physical processes, the so-called "potential" erosion factor, and anthropogenic processes, the so-called "induced" erosion factor. Soil loss and consequently the risk of erosion is the product of these two processes which are in fact complementary and interact in a holistic manner. These parameters are not independent but for the convenience of the analysis they have been treated separately before being aggregated (Roose, 1977).

2.3.1 Potential Erosion Risk in the ADA

Potential Erosion (PE) is modelled on the basis of the universal soil loss equation, taking into account only the factors R, K and LS (De Figueiredo and Fonseca, 1997; Pradhan et al., 2012; Le Van et al., 2014; Karamage et al., 2016, 2017; Nacishali Nteranya, 2021).

2.3.1.1 R-factor of climatic aggressiveness

Rainfall data between 2011 and 2020 with a resolution of 0.5° x 0.5° (Table 1) was used to determine the average rainfall amounts. From these average rainfall amounts, the climatic aggressiveness index R was determined. It should be recalled, however, that the original design of the USLE model requires rainfall intensity data to calculate the R-index (Wischmeier and Smith, 1978; Nacishali Nteranya, 2021). This condition is generally met in the absence of rainfall data. Authors then proposed mathematical models that make it possible to correlate R and average annual rainfall (P) (Nacishali Nteranya, 2021). Thus, in his work on soil losses in Adiopodoumé (Côte d'Ivoire), E. Roose came to the conclusion that rainfall alone does not explain erosion phenomena and that the relationship between rainfall and erosion only becomes highly significant when the maximum intensities are measured over more than 20 minutes for erosion and 10 minutes for runoff (Roose, 1973, 1975, 1977). For the West African zone, the author's observations established a theoretical relationship (R / P = 0.50) between the mean annual climatic aggressiveness index (R) and the mean annual rainfall (P). From this simple relationship, the climatic aggressiveness parameter R was derived through equation 2:

$$\mathbf{R = P * 0.5} \qquad \mathbf{(2)}$$

From this equation developed for Côte d'Ivoire and Burkina Faso (Roose, 1977), the R index expressed in MJ.mm/ha.h.year was determined.

2.3.1.2 Soil erodibility factor K

The erodibility index K is expressed in t/ha/h and varies from 0 for less sensitive soils to 1 for soils highly prone to water erosion (Ganasri and Ramesh, 2015; Nacishali Nteranya, 2021). Soil erodibility is defined as its susceptibility to erosion (chuma and Rosseau, 1978) or its resistance to erosion (Khemiri and Jebari, 2021). It expresses the vulnerability of the soil to be eroded by rain and is inherent to the texture, structure, organic matter content of the upper horizons and permeability of the soil (Wischmeier and Smith, 1978; Nacishali Nteranya, 2021).

In practice, there are several methods and equations for determining the K-factor. These different approaches depend on the availability of soil data (Benavidez, 2018). In this study, the K-factor was calculated from FAO data (Table 1) and the rates of sand, silt, clay and organic matter in the upper horizons of the soils that are most exposed to the effects of rainfall. This calculation was made through the equation (equation 3) of J. R. Williams: (Williams, 1995; Eitsch, 2000; Waver et al, 2005). It is written.

$$\mathbf{K = fcsand * fcl\text{-}si * forgc * fhisand} \qquad \mathbf{(3)}$$

With:

$$fcsand = 0.2 + 0.3 * \exp\left[-0.256 * ms * (1 - \frac{msilt}{100})\right]$$

$$fcl - si = (\frac{msilt}{mc + msilt})^{0.3}$$

$$forgc = 1 - \frac{0.036 * orgC}{orgC + \exp\left[3.72 - (2.95 * orgC)\right.}$$

$$fhisamd = 1 - \frac{0.7 * (1 - \frac{ms}{100})}{\left(1 - \frac{ms}{100}\right) + \exp\left[-5.51 + 22.9 * (1 - \frac{ms}{100}\right)}$$

2.3.1.3 Topographical factor LS

In the process of soil erosion the parameter LS is a topographical factor which takes into account the length (L) and angle (S) of the slope. In fact, the slope typology influences the surface runoff velocity and plays an important role in erosion (Biswas and Pani, 2015; J. Nacishali Nteranya, 2021; Adamou et al, 2022). Roose (1975) points out that many authors have shown that soil loss increases exponentially with slope steepness. The LS factor was calculated according to the equation (equation 4) developed by (Stone and Hilborn, 2012):

LS = [0.065 + 0.0456 (Slope) + 0.006541 (Slope)2] * (Length of slope ÷ Constant)NN **(4)**

Where:

Slope = slope inclination in %.

Slope length = length of slope in m (Flow accumulation)

Constant = 22.1 metric units

NN = see Table 2

TABLE 2
VALUES OF NN

S	< 1	1 ≤ Slope < 3	3 ≤ Slope < 5	≥ 5
NN	0.2	0.3	0.4	0.5

Source : http://www.omafra.gov.on.ca/english/engineer/facts/12-051.htm

The different calculations were carried out using the Arc Hydro extension tools that work in the ArcGIS environment. The slope raster (in percent) obtained was reclassified according to the values in Table 2 in order to deduce the NN value according to the dominant slope class. After these operations, it appears that more than 60% of the ADA territory has a slope value higher than 5%. Thus, the NN value retained is 0.5. Finally, using the Map Algebra Raster calculator, the LS factor was calculated by numerically applying the equation of STONE and HILBORN, (2012) as follows:

LS = (0.065 + 0.0456 * "Slope" + 0.006541 * ("Slope") ²) * (("FlowAcc" * 30 / 22.1) ^0.5)

From these factors the Potential Erosion (PE) was determined. PE refers to the power of a soil to produce sediment as a result of the degradation of rainfall droplets in its morphological environment (Tahiri and al, 2017). It results from the factors R of climatic aggressiveness, K of soil erodibility and LS of length and slope angle and is written as follows (equation 5):

EP= R * K *LS **(5)**

2.3.2 Induced Erosion Risk in the ADA

Potential erosion due to climatic, pedological and topographical factors can be mitigated or exacerbated by human development choices and practices. Indeed, man, through his actions, causes the destruction, total or partial, of the surface structure of the soil and, consequently, accentuates the erosive phenomenon (El Hage Hassan, 2018). This erosion process due to soil artificialisation is referred to in this study as ″Induced Erosion″. It is determined by equation 6.

IE= C *P **(6)**

2.3.2.1 Cover factor C

Vegetative soil cover plays a vital role in erosion prevention (Sourlamtas, 2019). It appears to be the most active factor in controlling the risk of water erosion as it provides the soil with mechanical protection against climatic aggressiveness and ablation by reducing the energy released by raindrops (El Hage Hassan, 2018). The C-factor is therefore intrinsically linked to land use and land cover patterns. As the definition of land use classes varies from one area to another, from one country to another and from one zone to another depending on the landscape units (Nacishali Nteranya, 2021), in this study, the NDVI (Normalized Difference Vegetation Index) approach was preferred.

Calculated from the red and near infrared channels **($NDVI = \frac{NIR-RED}{NIR+RED}$)** (equation 7), this index is sensitive to vegetation variation and quantity. The NDVI values and map were determined from 2021 Sentinel 2 images on the Google Earth Engine platform and exported to One Drive and ArcGIS. From the NDVI raster, the C-factor was calculated using the CrA method of Colman (2018) adapted from Durigon et al (2014). This method is applied according to equation 8:

$$CrA = 0.1\left(\frac{-NDVI+1}{2}\right) \quad \textbf{(8)}$$

The CrA is based on the NDVI for areas under tropical climate with intense rainfall.

2.3.2.2 Support practice factor P

The support practice factor (P), or protection factor, is considered to be one of the most uncertain parameters in the RUSLE model and thus in the assessment of water erosion risk (Haan and al, 1994; Alloi and al, 2022). This uncertainty arises from the multitude of approaches and methods used to determine the values of the P-factor. Many of them have a universality problem as their predictive capacity is limited only to the regions for which they have been developed (De Vente and Poesen, 2005; Phinzi and. Ngetar, 2019); Alloi and al., 2022). In fact, like the C-factor, the most common approach to estimating P-factor values uses in situ observation data and/or visually interpreted images (Phinzi and Ngetar, 2019). From this approach P-factor values are derived either from remote sensing image classification, land use and land cover maps, previous studies or expert knowledge (Panagos and al, 2015); Alloi and al, 2022).

However, following the literature, this classification approach using remote sensing methods requires very high resolution images and feedbacks that are not always freely available (Panagos et al, 2015b; Phinzi and Ngetar, 2019). This issue of availability and free availability of satellite imagery with adequate spatial resolution to detect soil conservation practices with certainty is more pronounced in southern territories like the ADA. From the above, in this study, we opted for equation 9 developed by Wener (1981) in Kenya.

$$\mathbf{P = 0.2 + 0.03 \times S} \quad (9)$$

with **S** expressing the value of the slope in percentage.

This empirical equation has been used by various researchers in different areas, notably in the Lake Victoria catchment (Lufafa et al, 2003), in Italy (Terranova, 2009; Napoli, 2017) and in China (Fu et al., 2005).

From these C and P factors, the Induced Soil Loss (IL) from land use and land cover patterns was determined. Finally, the susceptibility of occurrence of water erosion risk in the ADA was determined by crossing the Potential Erosion raster related to physical factors and the Induced Erosion raster related to land use and development choices. All these calculations were performed with the Map Algebra Raster Calculator tool, from the Spatial Analyst Tools group in Arctoolbox. For the sake of accuracy of the statistical results, the lagoon water body was removed from the DEM.

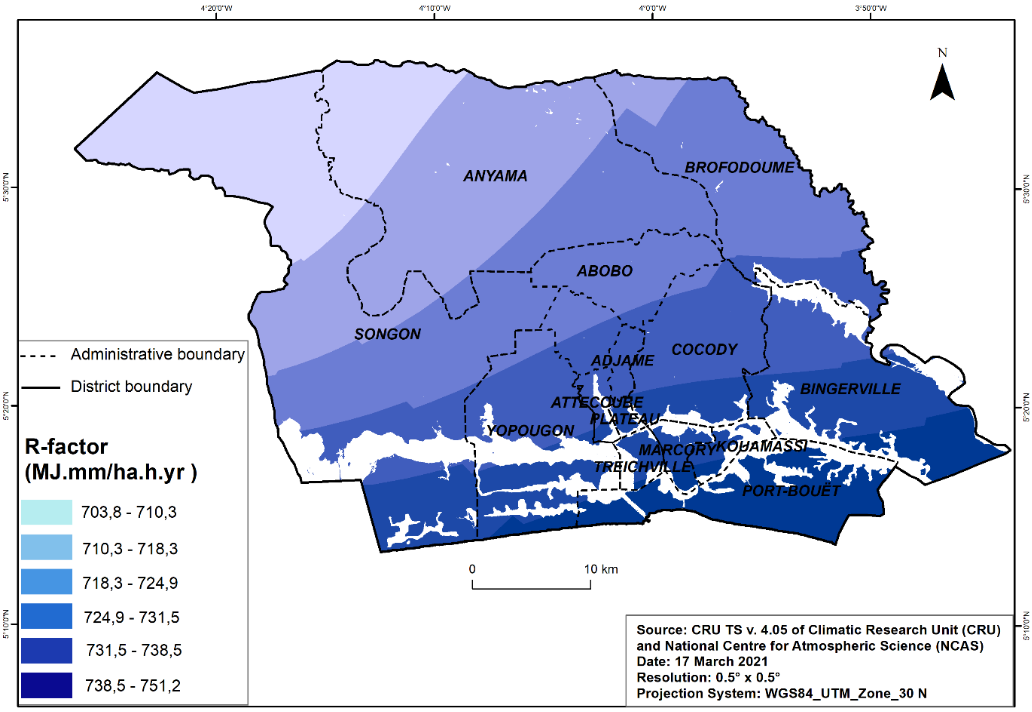
III. RESULTS AND DISCUSSION

3.1 Potential Erosion Risk: Favorable physical conditions

3.1.1 R-factor

The R-factor values determined vary between 704 and 751 MJ.mm/ha.h.yr (Figure 2).

These values belong to the interval [500 - 1400] determined by Roose (1973, 1975) in Côte d'Ivoire. The mean of this statistical distribution is 723 MJ.mm/ha.h.yr. The standard deviation of 10.767 shows a relatively large dispersion of values around the mean. The R-index evolves crescendo along a south-east and north-west axis.



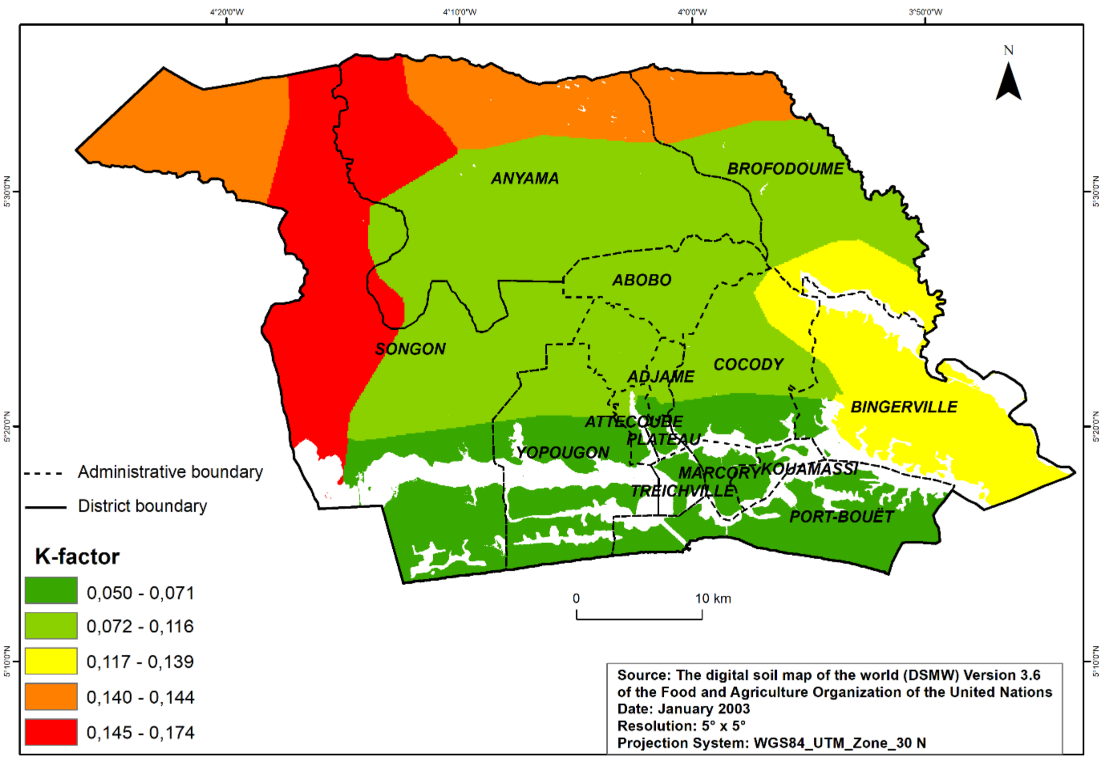
Realization: TRAORE, BAKARY and TAMBOURA, 2022

FIGURE 2: R-factor of climatic aggressiveness in the ADA

The low values of the R factor cover more than 60% of the District. The high levels mainly concern the southern districts of the city of Abidjan and almost a third of the communes of Bingerville, Cocody, Plateau and Yopougon.

3.1.2 Soil erodibility factor K

The values of the K index vary between 0.07 and 0.17 t/ha/h (Figure 3).



Realization: TRAORE, BAKARY and TAMBOURA, 2022

FIGURE 3: Distribution of soil erodibility K-factor values

Despite the difference in approaches, these values remain within the limits of 0.05 and 0.18 t/ha/h defined by E. J. Roose in his work on erosion and runoff in West Africa (Roose, 1972; 1975; 1977). The standard deviation of a value of 0.04 reflects a small dispersion of thevalues of the distribution around the mean of 0.10.

The spatial distribution of soil erodibility in the ADA according to the K-factor indicates that the high levels of erodibility related to soil texture and structure are mainly found in the extreme north and northwest of the sub-prefectures of Brofodoumé, Anyama and Songon. With K-factor values above 0.140, these are ferralitic soils that are most often reworked or evolved. In contrast, low levels of erosivity are found in the south and centre of the ADA on typical ferralitic soils, podzolic soils or soils that are not very developed, with K-factor values between 0.071 t/ha/h and 0.116 t/ha/h. Statistically, more than three-fifths of the ADA area has a low erodibility level of 41.27%.

3.1.3 Topographical factor LS

The values of the LS index vary between 0 and 32.3984 (Figure 4). The mean of this statistical distribution is 0.3137 with a standard deviation of 0.8125. This higher standard deviation value reflects a certain dispersion of the LS factor values around the mean. The mapping results show a strong dominance of the classes [0 - 0.381] and [0.382 - 1.271]. These two classes with small slope gradients cover 79.83% and 13.59% of the area respectively.

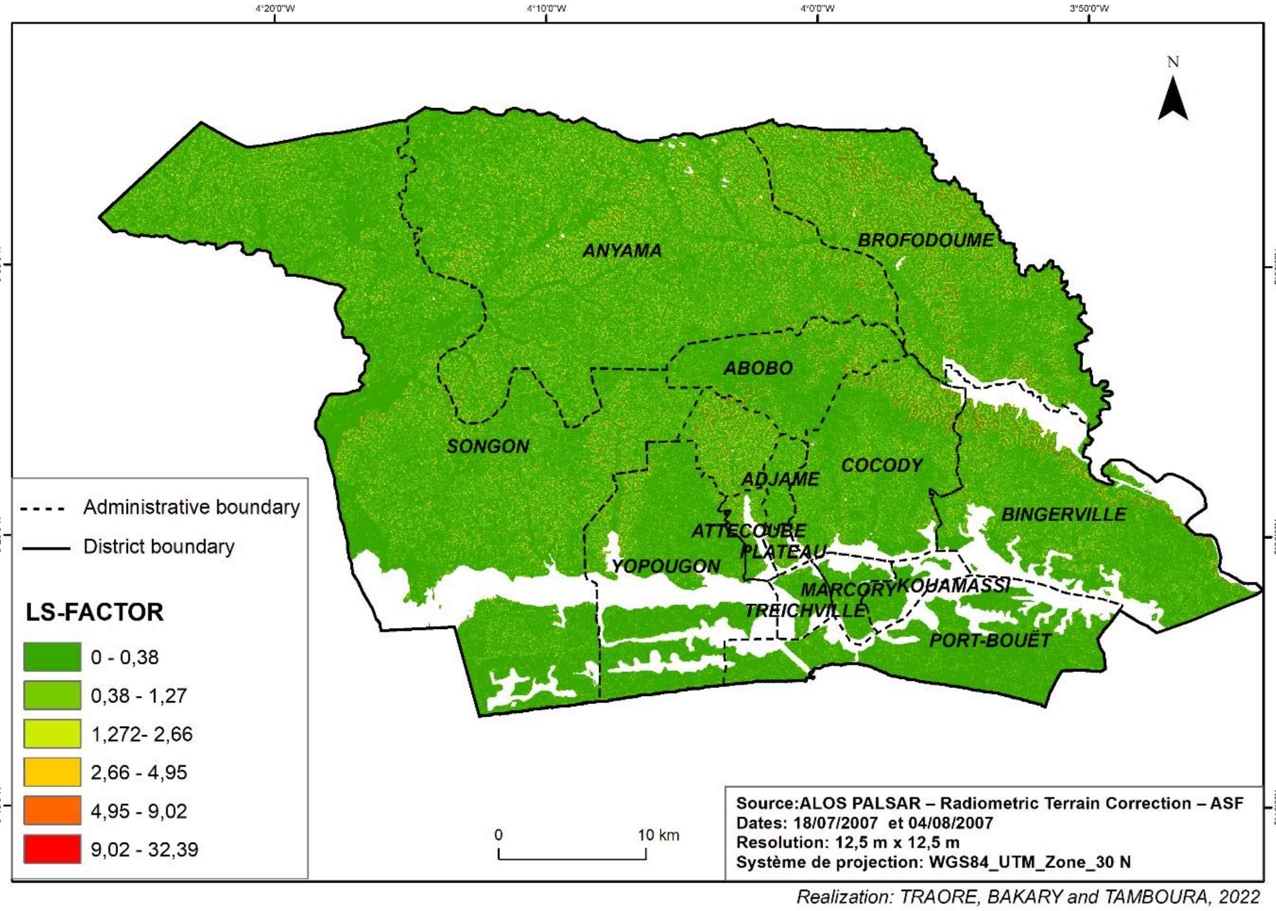


FIGURE 4: LS factor

The values resulting from the intersection of climatic (R), edaphic (K) and topographic (LS) factors have made it possible to map the risk of Potential Erosion (figure 5).

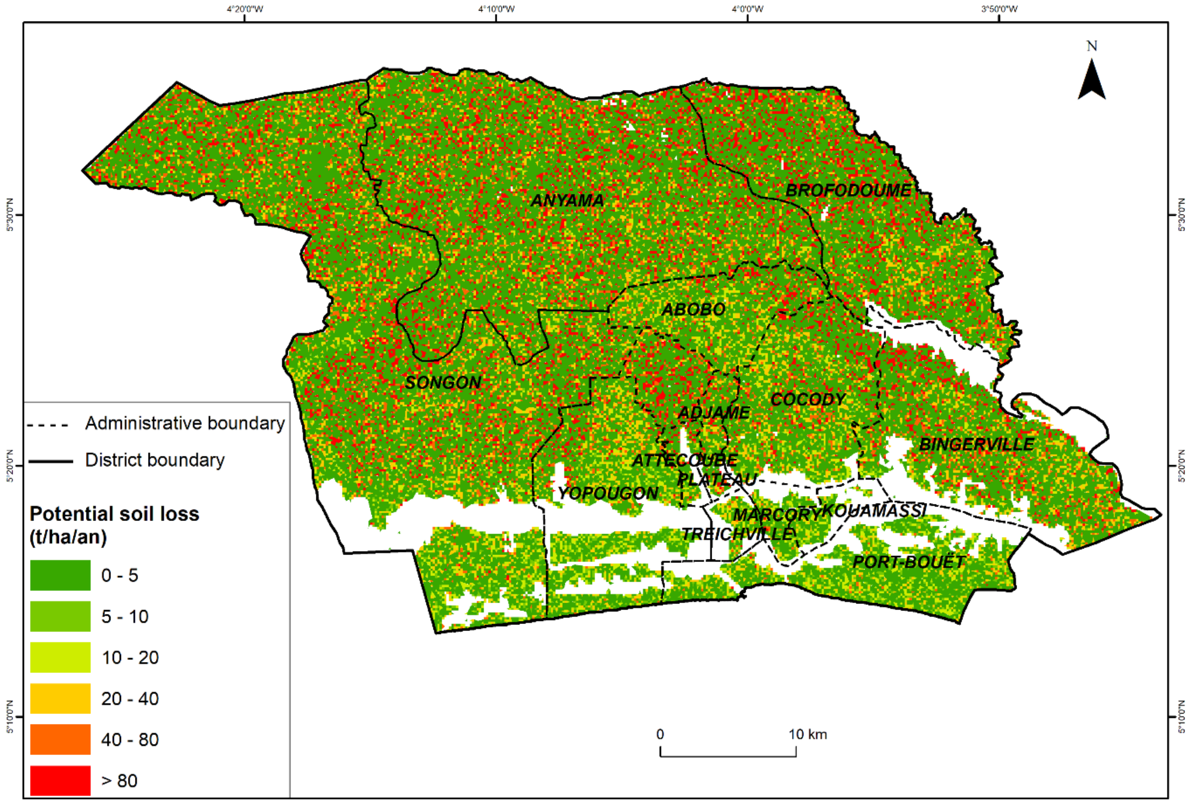


FIGURE 5: Potential soil loss and erosion risk in the ADA

These three factors: climatic aggressiveness, soil erodibility and topography were crossed and a potential erosion risk map was generated

The values are between 0 (Xmin) and 1943.35 (Xmax). The average of this statistical series is 29.51 for a standard deviation of 78.15 which reflects a strong dispersion of values.

These values are significantly influenced by the climatic aggressiveness index, which is higher than 700. Thus, as Roose (1977) observed, the serious erosion damage observed locally in Africa is due above all to the aggressiveness of tropical rains (whose energy is two to six times higher than in temperate zones) rather than to a hypothetical fragility of tropical soils.

The spatial analysis shows a rather heterogeneous distribution of Potential Erosion levels. On the whole, these levels are low over more than two thirds of the territory (68.30%). Thus, due to the relatively low slopes of our study area and the better resistance of ferralitic soils, potential water erosion is largely influenced by the R factor of the aggressiveness of the climate marked by the height, intensity and duration of rainfall (Roose, 1977).

As in Brazil, according to the findings of Panagos (2015), in tropical climates, it is the energy of raindrops that is the main factor in erosion in Africa and particularly in the ADA. Rainfall, through its intensity and energy, is considered the 'main causal agent' of land loss because its action amplifies the driving forces necessary to pull soil particles out of the ground (El Hage Hassan et al, 2018). As rain falls, the soil begins to become saturated and additional rainfall runs off its surface as runoff (Sourlamtas, 2019).

This potential vulnerability of soils to aggressive rainfall and water erosion will undoubtedly increase with climate change, which is now manifested by increasingly heavy rainfall with high intensity. In Petropolis, Brazil, for example, the rainfall that caused the massive flooding and landslides in February 2022 was equivalent to a month's worth of rain falling in just 6 hours. This is also the case in the Durban area of KwaZulu-Natal province in South Africa, where the weather system that triggered the floods in April 2022 resulted in more than 300 mm of rainfall over a 24-hour period, or about 75% of the country's average annual rainfall. These two hydroclimatic events, in addition to the extensive material damage, caused more than 110 and 440 deaths respectively. Thus, intensity is the main parameter that links rainfall to erosion through the momentary saturation of soil porosity, as runoff can only occur when the flow of rain exceeds the possibilities of absorption by the soil pores, the threshold of which is lowered as the rainfall is prolonged (Roose, 1977).

The risk of soil erosion will be affected by climate change (Nearing, 2004; Colman, 2019) as changes in temperature and precipitation impact plant biomass production, infiltration rates, soil moisture, land use and crop management (Li et al, 2016; Colman, 2019).

In addition to these climatic disturbances, this potential erosion remains influenced by human development choices and practices. Indeed, man, through the practices he carries out, causes the total or partial destruction of the soil structure and, consequently, accentuates the erosive phenomenon (Hage Hassan, 2018). An inevitable natural phenomenon, water erosion becomes a serious environmental and socio-economic problem when it is accelerated by human activities (Meliho, 2016; Lal, 1998; Del Mar López and 1998; Yameogo, 2020).

3.2 A steadily increasing risk of Induced Erosion

3.2.1 The coverage factor C

The values of C determined from the NDVI vary between 0.02 and 0.06 (Figure 6). The average of this series is 0.04. The standard deviation of 0.006 indicates a very low dispersion of these values. The values of parameter C are inversely proportional to those of NDVI. This evolution of the two variables in opposite directions implies that when the biomass is of good quality, it effectively protects the soil from erosion.

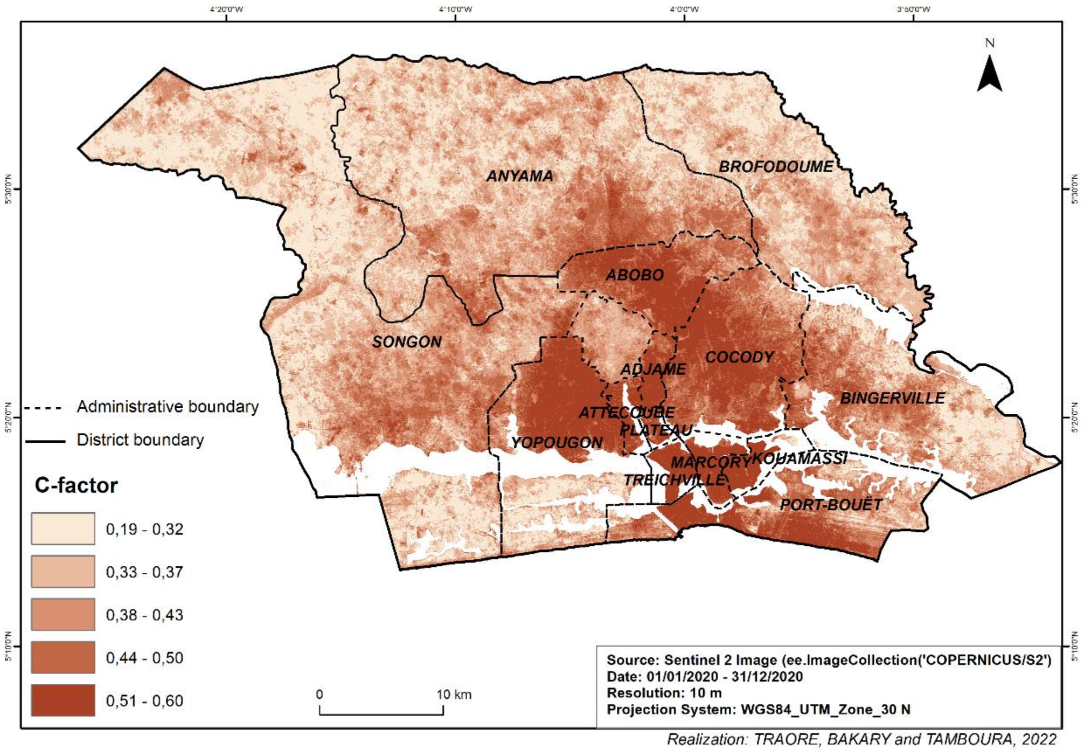


FIGURE 6: Spatial distribution of coverage C-factor

This high propensity for erosion is all the more worrying as these areas are home to most of the population (93%) and economic activity (80%). Also, the C factor is more important in areas where biomass is declining. These are naturally built-up areas, bare areas or, to a lesser extent, areas with severely degraded vegetation. They correspond globally to the ten communes of Abidjan (figure 6).

3.2.2 P-factor

The values of the soil erosion parameter P in the ADA range from 0.20 (Xmin) to 2.99 (Xmax) (Figure 7).

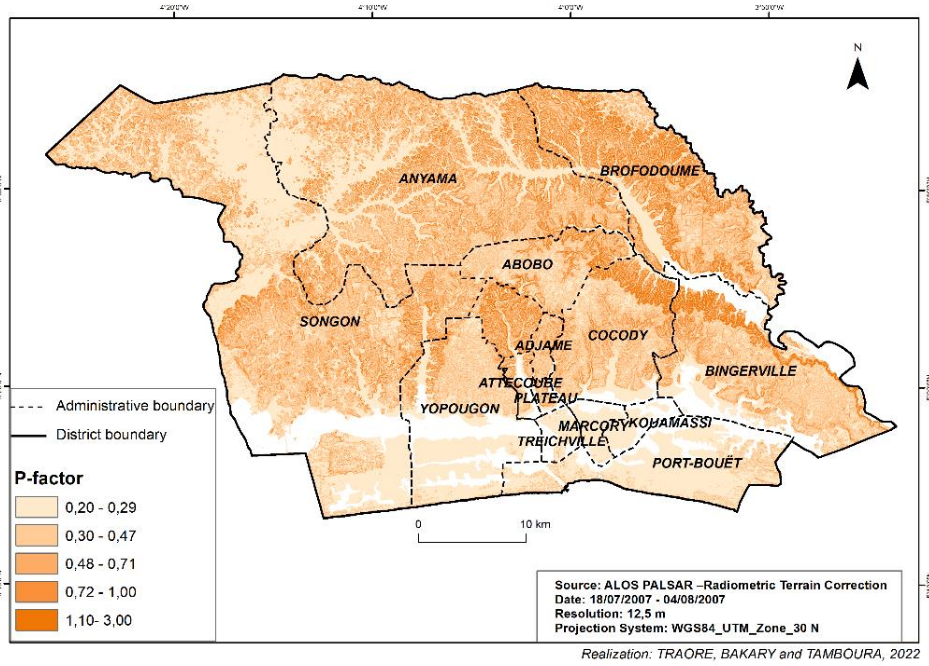


FIGURE 7: P-factor

Statistically, almost two thirds of the territory (65.22%) are of "Low" and "Very low" erodibility level while only 16.39% are of "Somewhat high", "High" and "Very high" level. The average erodibility level covers just under one fifth of the District.

The results of the product of the C and P factors resulted in Induced Erosion values between 0.004 and 0.141 for a mean of 0.014 and a standard deviation of 0.008 which translates into a low dispersion of values and a certain homogeneity of the series. In contrast to Potential Erosivity, the spatial distribution of Induced Erosivity seems more homogeneous. The significant soil losses induced by development choices and human practices are globally concentrated between the lagoon system in the south and the marshy areas in the north-west of the ADA (Figure 8).

This high susceptibility to induced erosion particularly concerns the communes of Plateau, Adjamé and Attécoubé, the sub-prefectures of Brofodoumé, Bingerville and Anyama. The communes of Yopougon, Abobo and Cocody, which are home to nearly one in three (58%) of Abidjan's inhabitants, are also subject to this significant susceptibility to induced erosion. Statistically, more than two thirds (67.23%) of the territory have an overall low induced erosion risk.

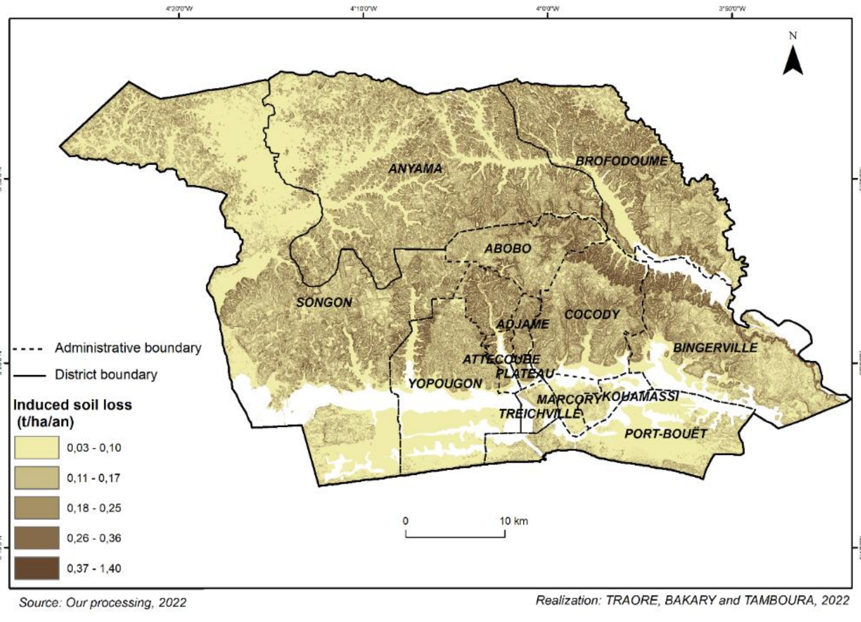


FIGURE 8: Induced soil loss and induced water erosion risk in the ADA

3.3 Susceptibility of occurrence of water erosion risk in the ADA

Crossing the Potential Erosion and Induced Erosion raster generated the raster of soil losses in the ACD. These values range from a minimum (Xmin) of 0 t/ha/yr to a maximum (Xmax) of 107.53 t/ha/yr. Using the RUSLE model in Burkina Faso, in the same West African spatial context, Ouédraogo et al (2019) found soil loss rate values between 0 - 36.35 t/ha/yr. Compared to the results obtained in our research, these soil losses can be considered low. The average distribution of 0.48 t/ha/year is lower but close to the average found by Yaméogo et al (2020) in Burkina Faso, which is 1.22 t/ha/year. However, these averages remain well below the 24 t/ha/yr and 76.59 t/ha/yr found respectively by Chuma et al (2022) and (Nacishali Nteranya, 2021) in the Democratic Republic of Congo. This difference is probably explained by the variation in edaphic, topographic and climatic conditions that can modify the values of the erosivity parameters.

It should be noted that with a Q1 equal to 0, 25% of the values are lower than 0, i.e. no soil loss. In addition, half of the soil losses are less than 0.42 t/ha/year, i.e. the median value (Q2). Three quarters of the annual soil losses are below 1.69 t/ha/year which is the Q3 value. Only 25% of the soil losses are above 1.69 t/ha/year. Based on the classification proposed by Yamego et al. (2020), a discretization of the values of the soil loss series A allowed the generation of the raster in Figure 9.

Visually, this figure corroborates the quartile analysis which showed a predominance of low values of annual soil loss in the ADA. These low losses occur throughout the ADA but particularly in the areas south of the lagoon system.

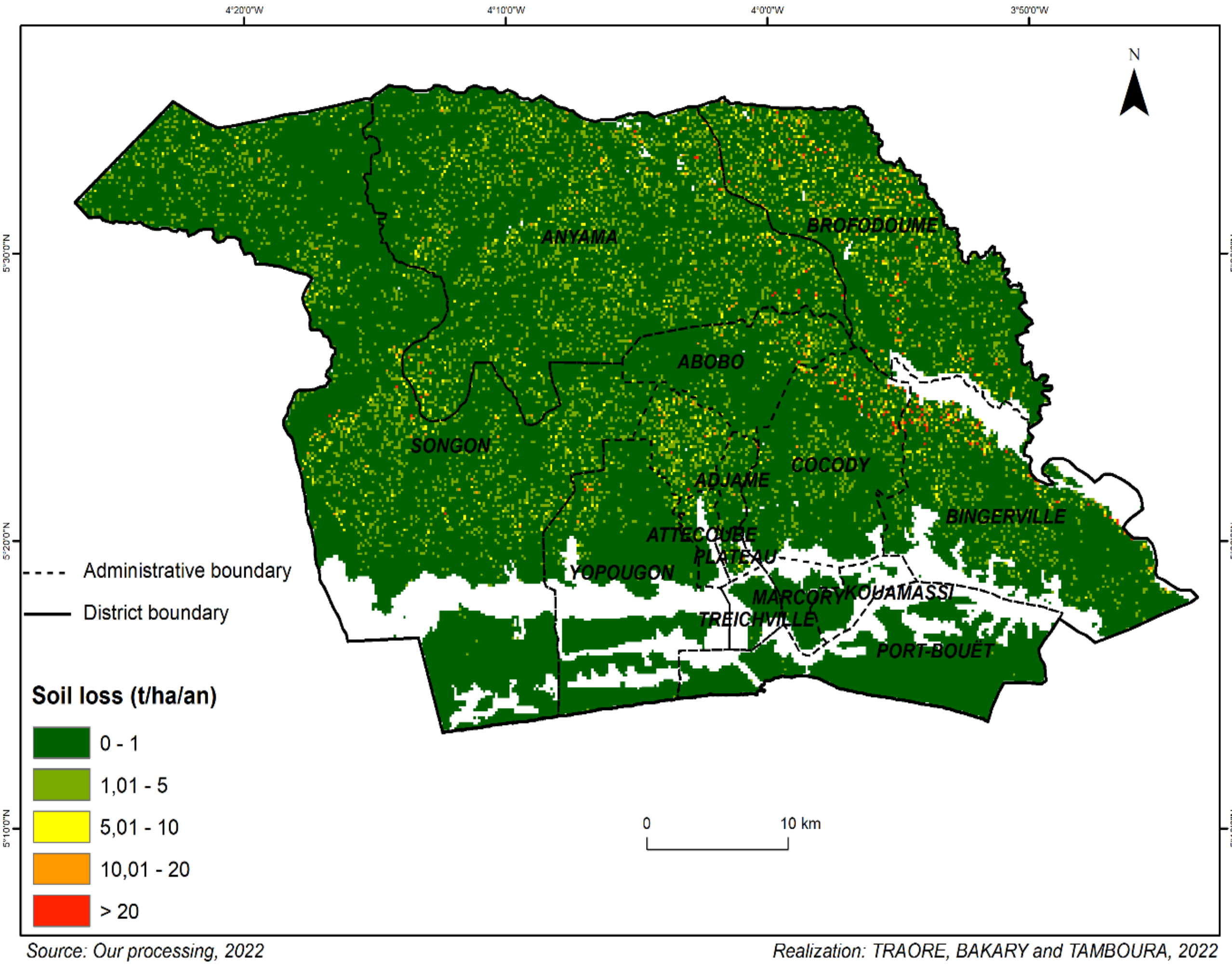


FIGURE 9: Erosion risk in the ADA

This situation could probably be explained by the very gentle relief (slopes of less than 2%) encountered in these areas. Even though the high values are not evenly distributed, they are mainly found on the Gbébouto plateau in the centre of Abidjan, somewhat in Songon, Anyama and along a south-east and north-west axis between Bingerville and Brofodoumé (Figure 9).

Statistically, this discretization results in five soil loss classes ranging from "Low" severity (0-1- t/ha/ha) to "Extremely high" severity (> 20 t/ha/ha) (Table 3).

TABLE 3
EROSION RISK IN THE ADA

Soil loss (t/ha/year)	Severity class	Area (ha)	Frequency (%)	Freq CC	Freq CD	Erosion risk
0 - 1	Low	161 808.7	90.47	90.47	100.00	Low
1 - 5	Fairly severe	13 794.7	7.71	98.18	9.53	Fairly high
5 - 10	severe	2 131.6	1.19	99.37	1.82	High
10 - 20	very severe	839.9	0.47	99.84	0.63	Very High
> 20	Extremely severe	283.1	0.16	100.00	0.16	Extremely high

Source: Our processing, 2021

These soil loss classes correspond to erosion risk levels ranging from "Low" to "Extremely high" (Table 3). Areas with a low level of erosion risk are the most prevalent. They cover more than 90% of the ADA territory, i.e. 161 808.7 ha. Soil losses greater than 5 t/ha/year, for an erosion risk ranging from "High" to "Extremely high" by our model, cover 17,049.3 ha, i.e. a little less than 10% of the District (table 3). This low spatial distribution of the significant risk of water erosion could be explained by the presence of a globally homogeneous relief with more than half of the territory (56.98%) on gentle slopes of less than 5%. To this must be added the use of land and the occupation of soils which are still mainly the preserve of nature reserves, orchards and plantations. These woody landscapes, which still occupy more than two thirds (68.17%) of the territory, contribute to the fixation and protection of the soil against the aggressiveness of the violent tropical rainfall. Runoff coefficients are obviously low on vegetated plots and high on bare soil and steep slopes (Sbai and Mouadili, 2021).

However, this soil stability conferred by the vegetation cover is gradually being eroded by the artificialization of the soil due to the agglomeration and urbanization phenomena that began when Abidjan was chosen as the capital in 1934 and the Port of Abidjan was created in 1950. Between 1932 and 2021, this agglomeration effect has seen land use indices such as built-up and bare land progress very significantly to the detriment of natural and planted forests, marshes, fields and formations dominated by grasses or fallow land. These indices increased by 97.95% from 1,178.57 ha to 52,494.0612 for an average annual growth rate over the period of 4.42%. The proportion of built-up area, which was only 6.19% in 1980, reached 10.89% in 2000, 25.81% in 2020 and 29.5% in 2021 (Traoré, 2022).

Today, the trend of water erosion is generally exacerbated by demographic growth, which increases the artificialisation of land. As in Burkina Faso (Yameogo et al, 2020), the extension of cultivation areas, farming techniques and above all urbanisation have profoundly modified the organisation of the ADA landscape. This is also the case in the Democratic Republic of Congo, where the change in land use due to population growth has favoured the extension of agricultural and urban areas to the detriment of forest areas (Nacishali Nteranya, 2021).

Dans les zones de plus en plus urbaines, l'érosion du sol est un problème important en raison de la perte de la végétation. En fait, comme l'indique Sourlamtas (2019) les surfaces urbaines plus résistantes à l'eau du fait du bâti et de l'asphalte ; recueillent les flux d'eau et les transportent vers les sols exposés.

In increasingly urban areas, soil erosion is a significant problem due to the loss of vegetation. In fact, as Sourlamtas (2019) points out, urban surfaces that are more resistant to water due to buildings and asphalt collect water flows and transport them to exposed soils.

In the District of Abidjan, as in the El Abed basin in Morocco, the significant occurrence of water erosion is therefore the result of natural predispositions but also and above all of anthropic actions reflected by changes in land use and land occupancy patterns (Sbai and Mouadili, 2021). In tropical climates such as that of the ADA, this erosion occurs mainly in the slick with selective removal of fine particles, which accelerates the physical, biological and chemical degradation of the surface soil horizons (Bwandamuka et al, 2021). This occurrence of hydroclimatic risks most often concerns the least affluent populations (Traoré, 2016; Traoré et al, 2018).

However, it should be noted that the rainfall, soil, topographic and land use data used from global and regional databases may contain biases (Payet et al, 2011). These may be related particularly to the high spatial resolutions and a certain imprecision of the information.

Rainfall data from the Climatic Researcher Unit database, for example, may have deviations from local data, which themselves are often biased by metrological and reading errors. The FAO soil data, on the other hand, remain globally general and may inevitably differ on a large scale. The same applies to the DEM and the Sentinel 2 image, which have a resolution of 12.5 and

10 m respectively. They probably minimise the differences in level and the values of certain slopes. The quality of the biomass could also be affected.

The probable biases and inaccuracies of the input data are likely to have influenced the output raster (Adamou et al., 2022). Also, more accurate input data could lead to quite different results. For example, LIDAR images with a finer resolution of 1 m would have led to possibly different results. The water erosion susceptibility layer generated from the RUSLE model applied in a GIS environment therefore deserves to be confronted with empirical results in situ.

Notwithstanding these limitations, this model remains a robust decision-making tool that assists in the use of spatial information, soil loss modelling and soil erosion risk management (Sourlamtas, 2019). This model has shown that water erosion despite its significant occurrence on only 2% of the territory remains a major risk in the ADA, as it affects more than one in four inhabitants. With an average annual growth rate of around 6.8%, this mostly informal land artificialisation combined with the effects of climate disturbances will inevitably increase these vulnerabilities. Political awareness of these threats and anticipatory and preventive management of immanent crises are a guarantee for preserving the environment, preserving human lives and promoting the social and economic development of the ADA.

IV. CONCLUSION

The objective of this study was to model water erosion in the Autonomous District of Abidjan. The approach integrates the parameters of the RUSLE model into a Geographic Information System. It allowed to discretize and map the levels of erosion risk occurrence susceptibility. On analysis, the ADA has an average erosive potential of 0.48 t/ha/year. The map of erosive potential has enabled the identification of the most vulnerable areas on which to concentrate efforts and direct investments aimed at restoring soils and protecting them against water erosion for preventive management of crisis situations.

In a research and development context, this tool is important for land use planning in order to achieve sustainable development objectives. In fact, in semi-urban areas where agriculture and urban areas are intermingled as in the ADA, soil erosion can be a significant problem due to exposed agricultural land and urban surfaces heavily waterproofed by developments. This significant vulnerability of human and material stakes to the risk of water erosion will thus crescendo in view of the development prospects of the ADA.

This model, in spite of some limitations linked in particular to the data, seems to be well adapted in the ADA in order to define the relative influence of the factors which condition water erosion.

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