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RESEARCH ARTICLE

EROSION SENSITIVITY MAPPING IN THE TONKPI REGION (WESTERN CÔTE D'IVOIRE)

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ABSTRACT

Soil erosion is at the root of serious economic, social, and environmental problems in many countries around the world. It is therefore essential to spatially evaluate its effects in order to face them and to be able to propose the best strategies of fight, conservation and planning of land. The objective of this study was to qualitatively evaluate the vulnerability of soils to water erosion through an approach based on the Mediterranean Desertification and Land Use (MEDALUS) model across the Tonkpi Region (Western Cote d'Ivoire). It enabled rational choices of sites where to implement anti-erosive works in priority. Coupling remote sensing and by considering relevant factors known to influence the processes of erosion, such climate, vegetation, soil, and demography, map of the sensitivity to erosion was designed. The erosion risk map obtained showed that 43% of the study area was exposed to a high vulnerability to erosion. On top, the results showed a strong influence of the vegetation quality index (65%) in the risk of erosion. This map will be a tool for decision-makers in allocating crop areas and socio-economic infrastructure sites in the region.

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INTRODUCTION

Soil erosion is still the biggest environmental problem in the world; 65% of soils on earth are confronted with degradation phenomena including erosion and desertification. Erosion threatening not only developed countries, but even more developing countries. In Africa, 12500 million ha of soils are being threatened by water and wind erosion (Pushpam and Vuola, 2015). In the long term, it results in a loss of fertility and a decline in soil biodiversity while soil is an essential element of agricultural production which is in turn crucial for the development of the livelihoods of the majority of people who depend on this natural resource (Kali *et al*, 2016). In Côte d'Ivoire, the first work on land erosion was carried out by Rougerie (1958, 1960) in the forest region. These studies analyzed the various erosion processes, factors and anti-erosion methods. Roose (1967, 1977, 1985), spent several years measuring runoff and erosion; he helped characterize erosion in its quantitative aspect. More recent studies have attempted to model erosive risks (Boyossoro *et al*., 2007; N'dri, 2007; Georges, 2008; Aké *et al*., 2012).

Concerning the mountainous region of the Tonkpi Region, it presents features favorable to erosion due to its relief and high rainfall (greater than 1500 mm per year). These particular conditions contribute to floods, landslides, and especially soil erosion (Boyossoro *et al*, 2007). In addition, human activities such as deforestation and agriculture have helped strip most of the mountain slopes, which has aggravated erosion (N'guessan, 1989, Bakayoko *et al*., 2013) causing the erosion, and outcrop and boulders. This leads to material damage in crops and constitutes civil protection risks. In addition, erosion causes degradation of natural soil fertility and decrease in productivity (Raphiou, 2013). Many efforts are needed to address this issue. In the Tonkpi region, the Mountain Hills Reforestation Project (PRFM) was initiated in order to reforest about 400 ha of land in the vast region of the Tonkpi, covering 1,228,400 ha. Effective implementation of such soil conservation and restoration measures must first be preceded by an assessment of erosion risk spatial distribution. Erosion resulting from the combination of several factors, remote sensing and GIS are powerful tools that can be used to collect and combine data. Today, they are essential tools in interactive decision support systems.

In general, there are two approaches to water erosion risk assessment: the modeling approach and the expertise approach. The expertise-based approach has been designed for temperate zones whereas modeling approach has no territorial limitation and is therefore better suited for this study. Among the existing models, the most used are the USLE model and its variants: RUSLE and MUSLE which are applied to sheet erosion and not to linear and mass erosion. In this study, MEDALUS model coupled with a GIS was used for a qualitative assessment of erosion risks in the Tonkpi region of Côte d'Ivoire. MEDALUS (Mediterranean Desertification and Land Use) uses a qualitative approach based on a multi-criteria method allowing to draw up index maps. This model takes into account linear erosion, which is the type of erosion encountered in the Tonkpi region and is also applicable on a regional scale (Hussein, 2011).The result obtained by the model was a vulnerability map of the region that takes into account the physico-climatic factors responsible for water erosion. As such, this document is a decision support tool in terms of management and protection of natural resources.

Location of the study site

The study was conducted in the Tonkpi Region, located in the far west of the Mountain District in Côte d'Ivoire. This region belongs to the mountainous sector of the Guinean domain (Guillaumet and Adjanohoun, 1971) and covers an area of 12,284 km^2. It lies between longitudes 5°24' and 7°3' West and latitudes 8°4' and 6°34' North (Figure 1).

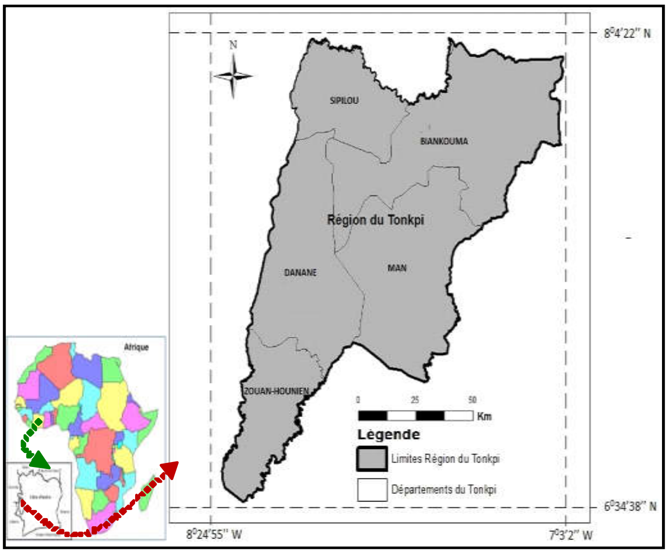

Figure 1. Localization of the region of Tonkpi

Population was estimated at 435,196 (RGPH, 2014) with an average density of 85 inhabitants/km^2 with a maximum of 150 for the department of Man which is the regional capital. The region is one of the most watered in the country; rainfall amount oscillates between 1300 and 2400 mm per year. Temperatures remain high with an average of 24 °C and hygrometry oscillates between 80 and 85%. The Sassandra and Cavally with many tributaries, are the major rivers that water this region (CNRA, 2009). Vegetation consists of 80% of humid forest. However, this forest has been converted to fallows or is exploited for perennial crops such as coffee, cocoa or rubber plantations. Topography is marked by a series of lowlands (Bakayoko *et al*., 2013). These elementary forms are linked in places with very rugged lands with contours varying between medium and concave slopes with altitudes sometimes exceeding 1000 m. The highest peaks were Mount Tonkpi (1189 m), Mount Mia (1077 m), and Mount Glas (1175 m). Most of the mountain slopes, steep and fractured, and valleys are at high risk of erosion. Ferralitic soils with medium chemical fertility are dominant. There are also soils developed on basic rocks, ferralitic soils on granite rock, mountain-type ferrisols, hydromorphic soils in lowlands and mineral soils in mountainous areas (CNRA, 2009). This region also presents a great diversity of production systems related to three main factors namely: (1) agro-climatic conditions that favor a wide range of agricultural speculations, (2) ecosystems specific to the mountainous morphology distributed on slopes or granitic mountain slopes, low slopes, and shallows, and (3) a high level of land saturation, forcing farmers to optimize the area, especially by growing the associated food crops. This land pressure factors the advent of soil vulnerability to erosion.

MATERIALS AND METHODS

Inventory and data processing

Three types of data were used in this study; these were satellite images, cartographic and demographic data. The satellite imagery consisted of EVI (Enhance Vegetation Index) vegetation images from the MODIS satellite from December 1 to 15 of year 2001 to 2017, four Landsat 8 images from February 11 results from the 198-55 scene in 2016, ASTER SRTM images and rainfall simulation images from Tropical Rainfall Measuring Mission (TRMM). MODIS images with medium spatial resolution (250 m) were used to define the index of vegetation quality through land use and the coefficient of variation of vegetation. They are of particular interest through their EVI vegetation index resulting from a synthesis of 15 days observation. These images were taken in the last two weeks of December (dry season), when clouds are the most dissipated. They have the advantage of a very high temporal resolution which facilitates regular follow-up of the state of the vegetation. Landsat 8 imagery, with a spatial resolution of 30 m, obtained from its sensor 10 monitors soil surface temperature data which is an important bioclimatic parameters of the phenological state of the vegetation. ASTER SRTM images are Digital Terrain Models (DTMs) that allow the representation of terrain and thus topography. Slope classes were generated from this DTM. Cartographic data are composed of soil map from Dabin *et al* (1960) and georeferenced map layers of the boundaries of the Tonkpi region, road network, administrative division, and human settlements (villages). Alphanumeric data consist of demographic data of the Tonkpi region, derived from the 2014 General Population and Housing Census (RGPH), obtained from the National Institute of Statistics (INS).

Evaluation of MEDALUS model parameters

The methodology used in this study was based on the MEDALUS model, which identifies the sensitivity to erosion from the geometric mean of quality indices derived from the environment and human activities (soil, climate, vegetation and land use planning) (Tra Bi, 2013). These parameters are likely to act on soil degradation (Floret et Le Floc'h, 1975; Le Houérou, 1992; Aidoud and Touffet, 1996; Khelil, 1997; Jauffret, 2001; Escadafal, 2002; Salamani and Hirche, 2006; Chakroun *et al*., 2006; Hirche *et al*., 2007).

Table 1. Vulnerability of fields to erosion as a function of slope

Slope	Classe
< 5 %	Extremely low
5 à 15 %	Low
15 à 25 %	Medium
>25 %	steep

Table 2. Classification of land vulnerability factors to water erosion in the Tonkpi Mountain region

Index	Erosion factors	Classes	Description	Code
Index of soil quality	Soil texture	1	balanced	1
		2	Fine	1,33
		3	coarse	1,66
		4	coarse	2
	Slope	1	<5	1
		2	15-May	1,33
		3	15-25	1,66
		4	>25	2
Anthropic quality index	Population density	1	<40	1
		2	40-100	1,33
		3	100-200	1,66
		4	>200	2
	Density of settlements	1	<8	1
		2	16-Aug	1,5
		3	>16	2
	Road density	1	<8	1
		2	20-Aug	1,5
		3	>20	2
Index of the quality of vegetation	Variation coefficient	1	4,5	1
		2	20-Oct	1,5
		3	20-75	2
	Land cover	1	Forest and water eau	1
		2	Degraded forests	1,5
		3	Savannah, cultivation, and soil	2
Climate quality index	Rainfall	1	<200	1
		2	1200-1500	1,5
		3	>1500	2
	Temperature	1	<24	1
		2	24-30	1,5
		3	>30	2

The evaluation of soil vulnerability was based on the analysis of four main factors: soil quality, human quality, vegetation quality, and climatic quality.

Soil quality Index: The influence of soil quality on soil erosion sensitivity is governed by soil texture (T) and soil slope (Sl) as described by equation 1. It was derived from the digitization of soil map of Perraud and Souchère (1968) relying on field assessment to obtain classified units (Table 1). The slope map generated from the Digital Terrain Model (DTM) was reclassified based on the classification of Mayer L (1990), and converted into land erosion vulnerability map (Table 1).

$$IQS = (T \times P_e)^{1/2} \qquad \text{……………………(1)}$$

Classification criterion was, in the absence of an adequate test, soil cultivation suitability. Thus, four classes of soils were determined: very good cultivation suitability (index 2), average to good cultivation suitability (index 1.66), poor cultivation suitability (index 1.33) and poor cultivation suitability (index 1). The combination of the two maps generated soil quality index map.

Anthropic Quality Index (AQI): Anthropogenic quality index was a combination of three factors: population density (P_d), road density (R_d), of localities density (L_d) (equation 2).

$$AQI= (P_d \times R_d \times L_d)^{1/3} \qquad \text{………………….(2)}$$

Population density index, as measured by the average density per sub-prefecture, was extracted from 2014 General Population and Housing Census (RGPH) that was further coded (Table 2). Settlement density map was made by applying a regular grid of 20 km² on the map of the region and by approximate counting of localities. For the map of road densities, it was done by applying a regular grid of 20 km² on the map of the region and by approximate counting of the intersections of roads in each grid.

Vegetation Quality Index (VQI): VQI was derived as the geometric mean of the Coefficient of Variation of Plant Coverage (CV) with the current land use data of the study area (CLU) (Equation 3).

$$VQI = (CV \times CLU)^{1/2} \qquad \text{…………………….(3)}$$

The map of the Coefficient of variation of vegetation cover was obtained using MODIS satellite images acquired from 2000 to 2016 and having a spatial resolution of 30 meters (15 m for the panchromatic band) in UTM projection and ortho rectified. These images were compiled to obtain a single image that was used to calculate the coefficient of variation of vegetation cover. Land cover map was derived from LANDSAT TM (2016) image classification of the Tonkpi region. This georeferenced image was combined with other vector layers (terrain maps, raster map), into a GIS allowed the production of land cover map. The procedure used is a classification by visual analysis of the various calculated remote sensing indices (NDVI) and color compositions (TM 5-4-3 ETM + 5-4-3 and OLI 6-5-4). Then, manual extraction of cartographic themes (hydrographic network, roads, habitat, etc.) and delimitation of classes. Subsequently, terrain visits were done in order to validate this classification.

Climate Quality Index: The climate quality index (CQI) was obtained by crossing total precipitation layer (PP) and surface temperature layer (T) using equation 4:

$$CQI = (PP \times T)^{1/2} \qquad \text{.............................(4)}$$

Climate which is one of the main factors influencing soil degradation, is evaluated by considering the parameters that influence the availability of water: quantity of precipitation, and soil temperature (Mostephaoui, 2013). The map of soil surface temperature (T) was derived from the thermal bands (bands 10 and 11) of LANDSAT 8 images and three classes were set: (1) Below 24 °C, (2) From 24 - 30 °C, Greater than 30 °C. Rainfall is actively involved in the degradation of bare soils and soil erosion from sheet runoff. It detaches soil particles from runoff but also by the effect "splash" or the strength of water droplets erosivity. Rainfall data used was the annual average for the period 2000 to 2014 of the Region. Three classes were set: rainfall less than 1200 mm (low), between 1200 and 1500 mm (average), and higher than 1500 mm (strong).

Elaboration of the sensitivity map to water erosion: Figure 2 summarizes the general procedure applied for mapping the multifactorial vulnerability to water erosion of soils in the Tonkpi region.

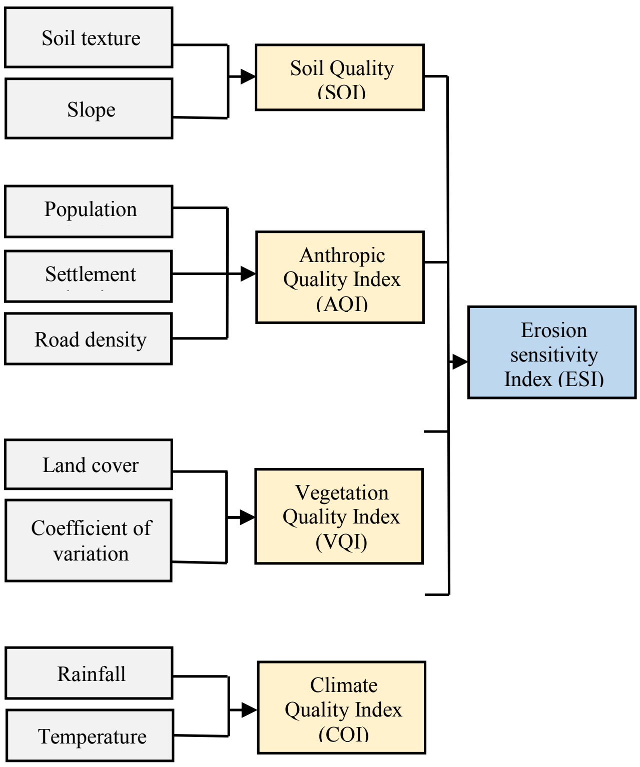

Figure 2. Methodology framework for erosion sensitivity index (ISE) determination

The MEDALUS model used identifies ecologically sensitive areas (Kosmas *et al*., 1999) taking into account soil, vegetation, climatic and management factors (Benabderrahmane and Chenchouni, 2010). Each factor was represented by an index that was calculated by the logical combination of sub-index in a GIS. The output map represented the sensitivity to erosion zones. Based on current knowledge of the different types of erosive processes, the factors selected were: soil quality, human quality, vegetation quality, and climatic quality accord (Equation 5). The validation of the final map was obtained by comparing the obtained results with field observations using GPS.

RESULTS

The computation of each index was done using algebraic combination of maps in matrix format (raster mode) and by a multitude of spatial analysis function.

Climate Quality Index (CQI)

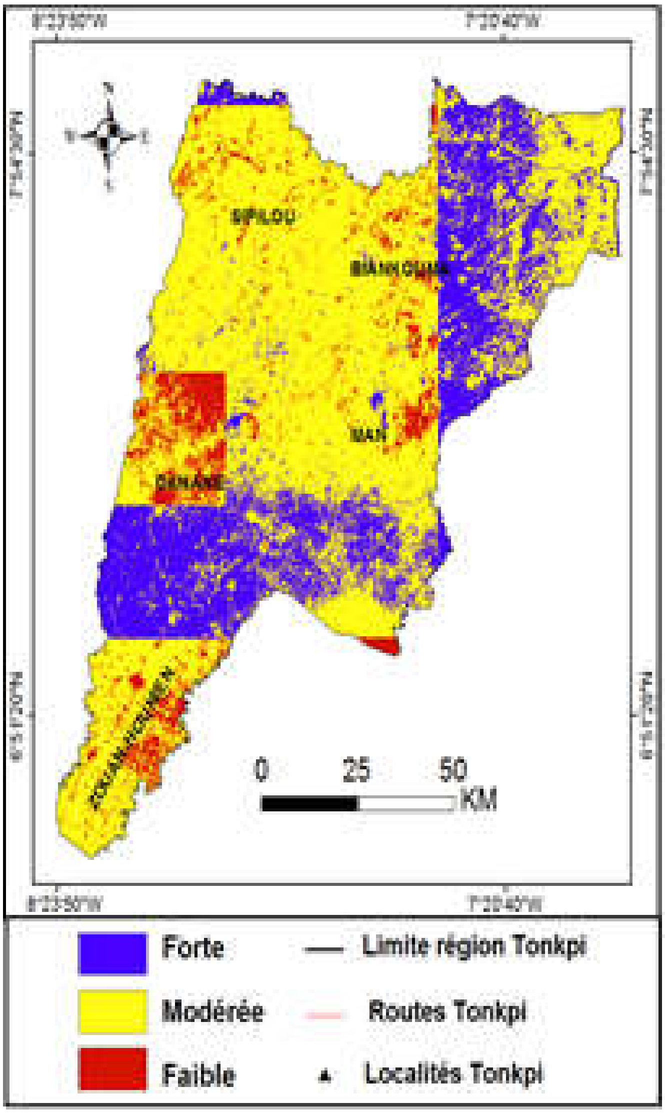

Figure 3. Map of climate quality index in the Tonkpi Region

Figure 3 indicated a medium vulnerability to erosion due to climatic factors (rainfall, temperature). The effect of climatic factors is strong in only 8% of the territory, in a band below Danané and east of Biankouma. Most of the region (66%) was weakly sensitive to erosion due to climatic factors.

Table 3. Climate quality index in the Tonkpi Region

IQC Classes	Area (Ha)	Percentage (%)
Low	291 403	26,02
Moderate	737 370	65,85
High	90 979	8,12

Soil Quality Index (IQS): Figure 4 indicated that soils which are moderately susceptible to erosion, consisting mainly of moderately leached ferralitic soils and ferralitic to granitic soils are dominant in the region. They represented 74.25% of the surface of the Tonkpi region and occupied 836 664.56 ha (Table 4). These soils are found in the departments of Zouan-hounien and Man. In the extreme north of the territory, in the departments of Biankouma and Sipilou, soils were most vulnerable to erosion due to the presence of very steep slopes. These soils represented 3.17% of the region and were mainly composed of mountain type ferrisols. Soils with low sensitivity to erosion, about 22.6% of the territory, were ferralitic soils on granites. These soils are found scarcely in the departments of Sipilou, Biankouma and Danané.

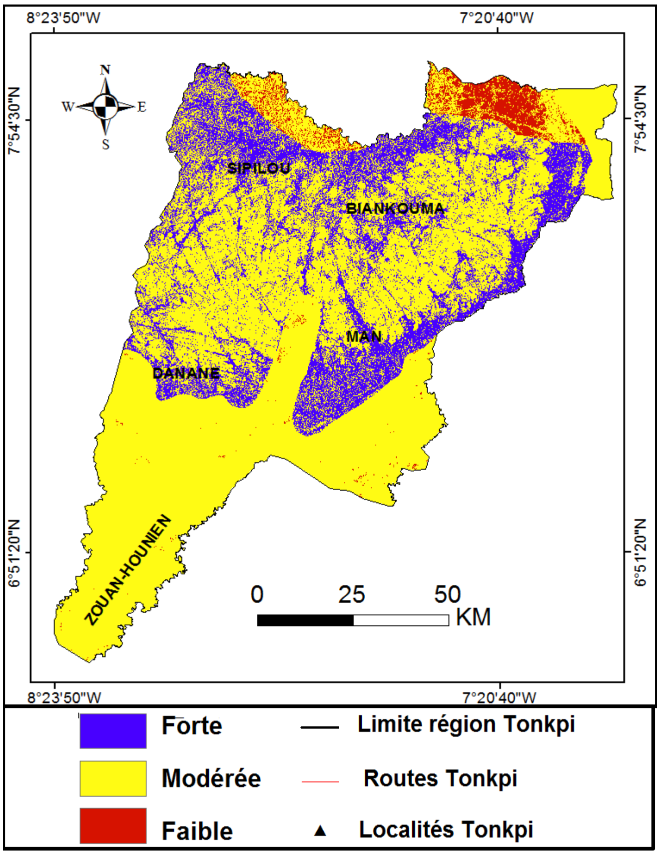

Figure 4. Map of soil quality index in the Tonkpi Region

Table 4. Soil quality index in the Tonkpi Region

IQS Class	Area (Ha)	Percentage (%)
Low	254 331.25	22,57
Moderate	836 664,56	74,25
High	35 740,19	3,17

Anthropogenic Quality Index (AQI): Demographic pressure and the density of the roads in a given area are anthropic factors that favor the erosion of the ground. Figure 6 shows that the far north-west (Mid North of Biankouma Department) and the North-East (Sipilou Department) of the region appear less vulnerable to erosion compared to the center.

Figure 5. Image of eroded soil due to steepy slopes

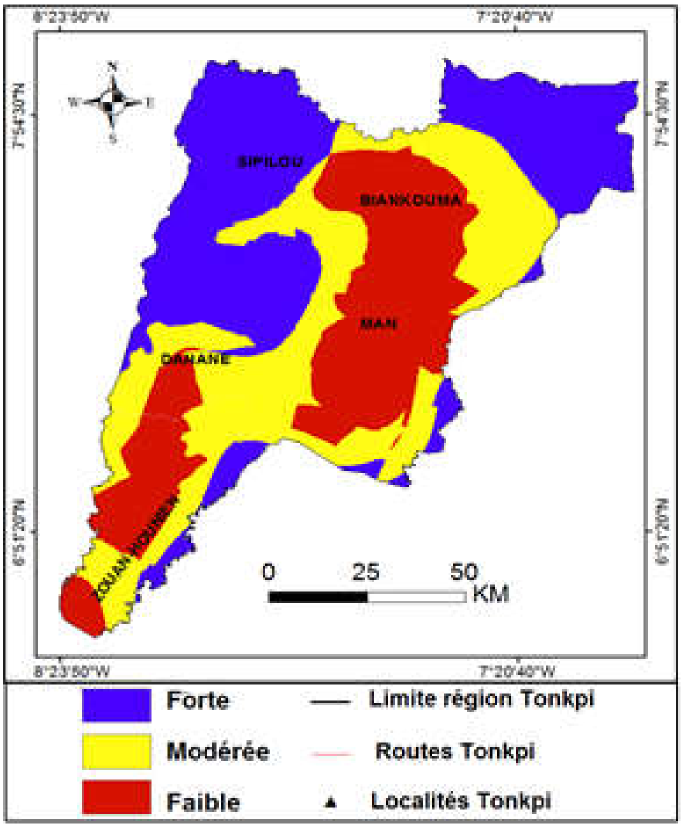

Figure 6. Map of the Human Quality Index (AQI)

Table 5. Geographical Distribution of the Human Quality Index

IQA Classes	Area (Ha)	Proportion (%)
Low	190 411,09	17,1
Moderate	461 243,12	41,2
High	467 222,59	41,7

Table 5 indicated that there are as many moderately erodible zones (41.2%) as highly erodible zones (41.73%). Only 17.1% of the region has a low vulnerability due to anthropogenic factors. Anthropogenic activities that influence soil erosion are the crushing of granite boulders around cities such as Man and Biankouma. Once the granite boulders are crushed, the soil is stripped by the rains, leaving the reddish parental rock (Figure 7).

Figure 7. Crushing and excavation of granite blocks contributing to erosion

Vegetation Quality Index (VQI): Figure 8 showed that 65.31% of the Tonkpi region has a low vegetation quality, therefore it has a high sensitivity to water erosion. Much of the North of the region and in the southern tip are the most concerned. This can be explained by the strong deforestation observed in these areas (Tiesse et al., 2017). In contrast, Central West (Danané) (30.69% of the region) and North-East (Man and Biankouma) (3.38%) zones presented moderate erosion capacity due to the quality of the vegetation.

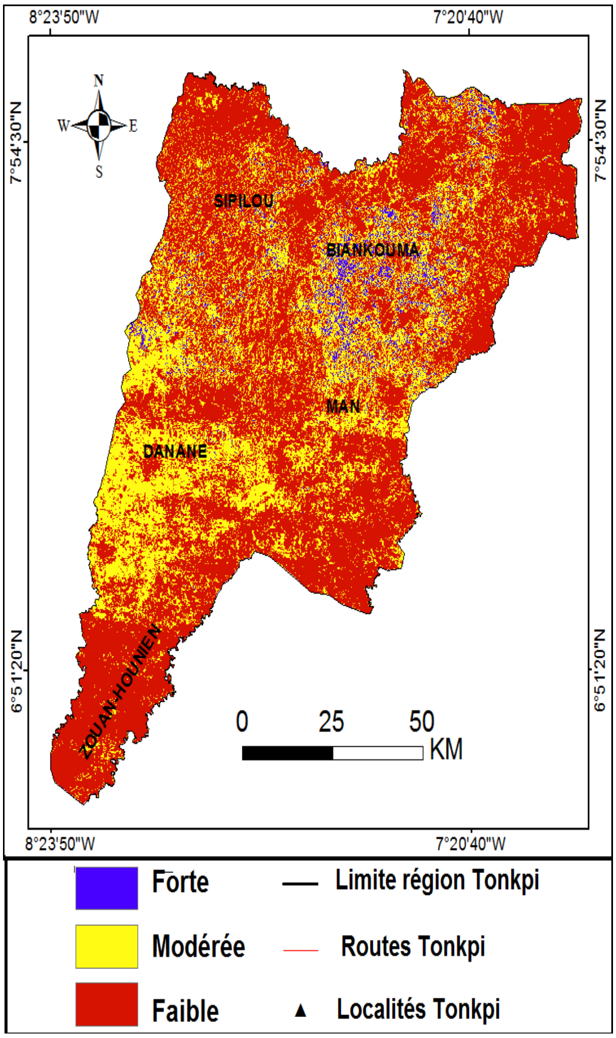

Figure 8. Map of the vegetation quality index

Table 6. Vegetation quality index

IQV Classes	Area (Ha)	Percentage (%)
Low	37 958,76	3,38
Moderate	343 704,75	30,69
High	738 085,70	65,31

Figure 9. Erosion under reforested Teak trees on the steep of mountains

Map of Erosion Sensitivity Index (ISE): Figure 10 represented the map determining the susceptibility to erosion for any area of the Tonkpi region. Table 7 showed that almost half (43.45%) of the Tonkpi region was highly susceptible to erosion. Only one fifth of the territory has a low sensitivity to erosion; the remaining 34.82% was moderately susceptible to erosion.

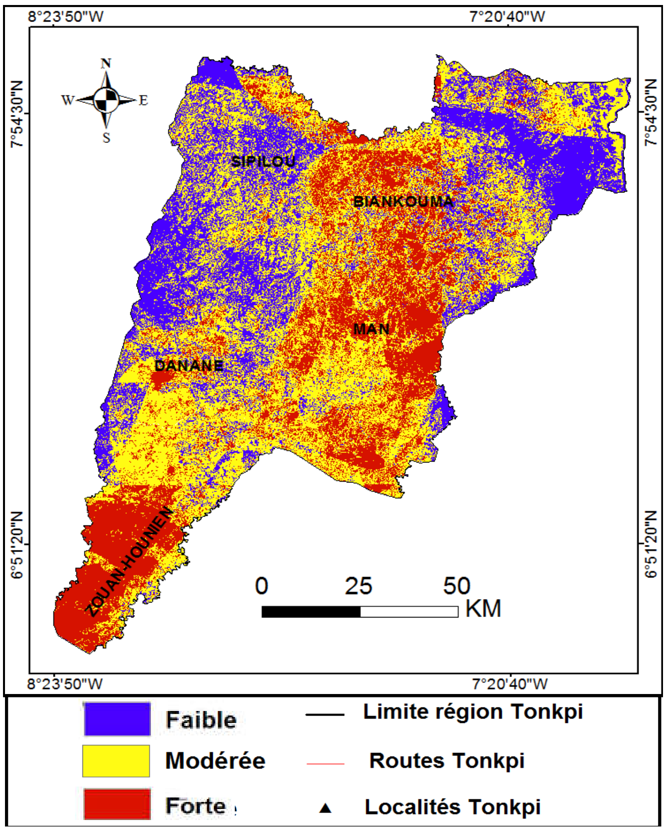

Figure 10. Map of erosion sensitivity in Tonkpi Region

Table 7. Erosion sensitivity index (ISE)

ISE Classes	Area (Ha)	Proportion (%)
Low	242 855,39	21,71
Moderate	389 470,63	34,82
High	486 004,84	43,45

Figure 11. Pictures of eroded land in the city of Danané

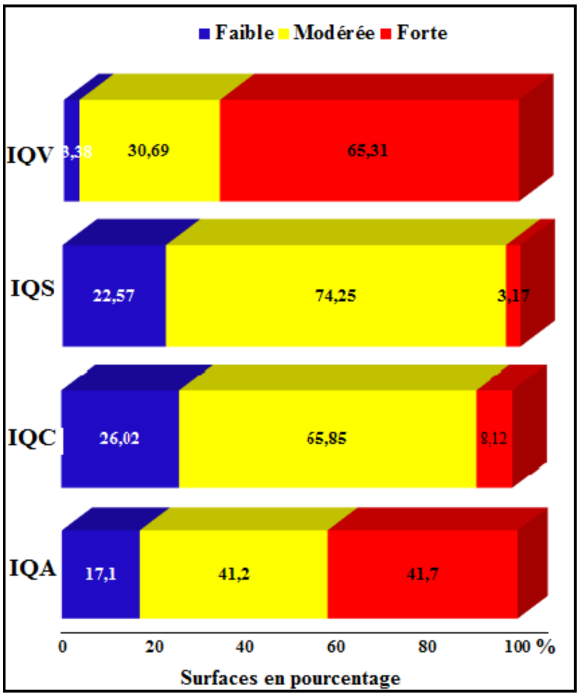

Figure 12. Contribution of each quality index to the erosion sensitivity

Areas highly erodible are located in the Departments of Biankouma, Man and Zouan-Hounien. The result indicated that urbanization was one of the main factors of erosion; this is depicted by figure 11 showing the highly eroded surrounding of the city of Danané. Moderately erodible soils are scattered throughout the region, especially south of Danané and Man. The less erodible soils were found mainly in the Northeast (Sipilou) and Northwest (Biankouma) of the Region. Overall results indicated that more than 65% of the region has a moderate to high sensitivity to soil erosion therefore it can be stated that the Tonkpi Region presented a high sensitivity to erosion. Figure 12 summarized the impact of the different indices contributing to soil susceptibility to erosion in the Tonkpi region. It allowed an explicit comparison of the erosion sensitivity levels for each index. Thus, it appears that the vegetation quality index (65.31%) and the anthropogenic quality index (41.7%) were the most important contributor to the soil erosion sensitivity in the region.

DISCUSSION

The results indicated that 66% of the Tonkpi region is moderately sensitive to erosion due to climatic factors. Like all regions of Côte d'Ivoire, the Tonkpi Region has experienced a drought but since 1991, rain has becomes regular with rainfall between 1200 and 2100 mm/year with a southwest gradient. This occurrence of rainfall these years may explain the moderate influence of climatic factors on erosion sensitivity in the region. The Soil Quality Index (SQI), which expresses the influence of soil texture and slope on soil erosion sensitivity, was moderate in 74% of the territory. The topography of the Tonkpi region is represented by high altitudes and a rugged landscape. The sharp slopes affect the rate of soil erosion through its morphological characteristics such as gradient and slope length (Wischmeier and Smith, 1978). Slope maps derived from the DEM showed that sharp slopes observed in 32% of the territory and located in the center of the region, were very vulnerable to erosion. The remaining of the territory, whose slopes are very low (<5%) to weak (5-15%) occupying 69% of the territory, is slightly or less vulnerable to erosion. Soils of the region are ferralitic partly coarse (61%) and fine (25%) which affect soil degradation differently. Ferralitic soils on granitic rocks have a poor cultural aptitude; when they are cultivated, they are vulnerable to erosion because of their shallow depth.

Human quality index was moderate for 41% of the territory and strong for 42% of the territory. Therefore, anthropogenic factors were important in the sensitivity to soil erosion in the Tonkpi region. The area devoted to settlements and road network are considered highly favorable to erosion vulnerability because human activities increase soil erodability. Indeed, the anthropogenic impact increases with the increase of population density and human pressure. It was shown by Thomas (1991) that of all the factors influencing erosion in the Left Basin in Kenya, 81% were caused by human factors including deforestation, agricultural practices such as overgrazing and overexploitation of land. As people do not have enough resources and because of the scarcity of land, farmers no longer practice soil protection techniques. Fallows has traditionally been used for soil fertility management, but because of the high pressure on land, fallow has been reduced or no more exist, leading to continuous cultivation of land. In the Tonkpi, where rains are often heavy, during the long rainy season, fallows established on the mountainsides cannot stop erosion. In addition, although livestock breeding is not a tradition in the region, the few existing animals graze along the mountainsides where grass is available and fresh. Which is a complementary contribution for erosion. Tiesse *et al* (2017) showed that in the Tonkpi region, forests were severely destroyed whereas they were the least vulnerable to erosion (Pimentel *et al*., 1998). Forest cover was reduced from 145,565.40 ha in 1990 to only 93,745.95 ha in 2015, a reduction of 36% over 25 years. In the same period, lands extremely vulnerable to erosion, degraded forests and settlements increased by 15% and 11%, respectively. Land devoted to crops and fallows, located on arable land around cities, although sensitive to erosion were replaced by housing, which are very vulnerable to erosion. This change in land cover/use lead to the increased to erosion due to vegetation loss, overgrazing and plowing. In fact, the foliage above the ground slows down the speed of water flowing over the ground, which reduces the amount of water and soil lost through runoff. Similarly, plant roots physically bind the particles and also improve water retention by creating pores in the soil, which stabilizes soil and increases its resistance to erosion. In addition, cutting trees for firewood or coal without replacement is a serious problem that contributes to the loss of vegetation and thus to increased soil erosion. The increase in the human population has reduced land availability and created pressure on land in this semi-mountainous area where farmland is limited. The erosion risk map showed that areas with high risk of erosion occupy about 43% of the Tonkpi region, on sharp mountain slopes and in deep valleys. These results were consistent with those of Boyossoro *et al* (2007) who showed that 40% of the territory of the Department of Man presented high risks to erosion. This map showed that the slopes undergo erosion stronger than the upstream parts of the mountains whereas on the plateaus, erosion was less. The results also indicated that there is a scattered spatial distribution of erosion sensitivity in the territory of the region, which clearly shows the cumulative impact of the various factors determining erosion (Chandoul, 2014). In fact, the areas highly exposed to erosion (33% of the territory) were those where Soil Quality Index (SQI) represented 32% and the vegetation quality index was 25%. Similarly, these results showed a strong influence of the vegetation quality index (VQI = 65%) in the risk of erosion.

The results indicated that, apart from the intrinsic properties of soils, parameters such as vegetation and slope contributed to a greater extent, to the modification of the sensibility to soil erosion. Vegetation protects soils against erosive agents, soil fixation and sediment trapping. It also helps to improve rainwater infiltration and promotes a less contrasting microclimate under trees due to shading. These conditions then favor more active fauna and flora and modify soil properties (Rey and Berger, 2002). Similarly, because soils in some parts of the territory are stony, the sensitivity to erosion was lower than that of a soil composed of fine or sandy materials (Roose and Sarrailh, 1990). The slope also conditions the property and the structure of the soil. So on flat land, soils are often thicker than on slop terrain around large cities such as Man, Duekoué and Biankouma where soils are generally thinner. This can be explained by product transportation from alteration of humification or mineralization (Duchaufour, 2001).

The comparison of our results with those obtained by Boyossoro *et al* (2007) showed a concordance. Indeed, with the USLE model, they found that 40% of the Tonkpi region was at risk of erosion. In general, no single index can explain the vulnerability of soils to erosion. However, vegetation quality index alone seems to capture to a larger extend, the sensitivity to soil erosion. Overall, the results indicated that the method used makes a very good integration of the different indices to produce the erosion sensitivity map.

Conclusion

Erosion is an irreversible process of soil degradation that is caused by both human and natural factors. It is manifested by the degradation of land suitability for agriculture and livestock and the stability of housing. It is therefore a phenomenon that threatens the sustainability of natural resources and the resilience of people to climate change. The methodology used in this study was based on the MEDALUS model. The rate of erosion sensitivity is generally considered high in the southern tip of the region, in the Department of Zouen Houein and in the central axis Man-Biankouma, and around large cities.

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REFERENCES

Aidoud, A. and Touffet, J. 1996. “La régression de l’Alfa (Stipa tenacissima) graminée pérenne, un indicateur de désertification des steppes algériennes ». *Sécheresse*, 7:187-193.

Ake G.E., Boyossoro, H.K, Miessan G.A., Ettien J.-B., Kokoh R. E. et Biemi, J., 2012. «Cartographie de la vulnérabilité multifactorielle à l'érosion hydrique des sols de la région de Bonoua (Sud-Est de la Côte d'Ivoire)», *Physio-Géo* [En ligne], Volume 6 | 2012, mis en ligne le 06 avril 2012, consulté le 09 mars 2018. URL : http://journals.openedition.org/physio-geo/2285; DOI: 10.4000/physio-geo.2285

Bakayoko S., Soro D., Kouadio K.K.H., Konan-W. A.B., Angui P. (2013), « Characteristics of Tonkpi Mountain soils and plateaus soils in West Côte d’Ivoire » [archive], sur www.heraldjournals.org, (consulté le 22 juin 2014)

Benabderrahmane, M.C.; Chenchouni, H. (2010). Assessing Environmental Sensitivity Areas to Desertification in Eastern Algeria using Mediterranean Desertification and Land Use “MEDALUS” Model. Int. J. Sustain. Water Environ. Syst. 2010, 1, 5–10.

Boyossoro H. K., Koffi F. K., Bachir M. S., Biemi J. et Traore I. (2007), "Insécurité climatique et géorisques en Côte d’Ivoire : étude du risque d’érosion hydrique des sols dans la région semi-montagneuse de Man (Ouest de la Côte d’Ivoire)", *Sécheresse*, 18 (1), 29-37

Chakroun H., Nouri M., Vacca A. et Rejeb M. N. (2006), "Modélisation de la Désertification par l’Adaptation de la Méthode MEDALUS à un Bassin Versant du Centre de la Tunisie", 14th International Soil Conservation Organization Conference, Water Management and Soil Conservation in Semi-Arid Environment, 4p.

Chandoul I.R., Bouaziz S., Dhia H.B., (2014). "Utilisation des SIG pour l'évaluation de la sensibilité à la désertification par l'approche MEDALUS Application à la région de Gabès" .*Geosp.net.* (https : www.researchgate.net/ publication/ 306401427), 13p.

CNRA (2009), La Direction Régionale CNRA de Man en quelques mots et chiffres, 12p

Domigo E. (1996). "Pression agricole et risques d'érosion dans le bassin versant du LOMON, affluent du Mono (Département du Mono-BENIN)", Université Nationale du Bénin, Cotonou, *Bulletin-Réseau Erosion, Vol 16,* 14p : p181-194.

Duchaufour, P. (2001). "Introduction à la science du sol: Sol, végétation, environnement". 6ème édition. Editions Dunod, Paris. 331 p.

Escadafal R. (2002). "CAMELEO: Changes in arid Mediterranean ecosystems on the long term and earth observation". Final report. INCO contract: ERBIC18CT970155, Ispra (Italie): Joint Research Center (JRC). Ispra, Italie, 116 p.

Floret C. et Le Floc'h E. (1975). "L'évaluation de la production des parcours et de la sensibilité de la végétation naturelle, éléments de l'aménagement rationnel des zones présahariennes de la Tunisie". *Options méditerranéennes*, 26: p.9-51.

Georges Y. (2008). "Evaluation de l'Erosion dans le bassin versant de la rivière Grise (Haiti)". En ligne, consulté le 16/03/2018 : URL : https://www.memoireonline.com/06/09/2109/m_Evaluation-de-lErosion-dans-le-bassin-versant-de-la-riviere-Grise-Haiti1.html

Guillaumet J. L. et Adjanohoun E. (1971). La végétation de Côte d'Ivoire. In : Avenard J.M., Eldin E., Girard G., Sircoul on J., Touchebeuf P., Guillaumet J. L., Adjanohoun E. and Perraud A. (eds). Le milieu naturel de la Côte d'Ivoire. 159-263. O.R.S.T.O.M., Paris.

Hirche A., Salamani M. Boughani M., Nedjraoui D. and Abdellaoui A. (2007). "Contribution à l'étude de la désertification dans le sud Oranais". *Revue Française de photogrammétrie et de Télédétection*, vol ¾ : pp187-188.

Hussein E. H. H. (2011). "Les apports d'un S.I.G. dans la connaissance des évolutions de l'occupation du sol et de la limitation du risque érosif dans la plaine de la Bekaa (LIBAN)". Thèse de Doctorat, Université d'Orléans, France, pp1-16

Jauffret, S. (2001). "Validation et comparaison de divers indicateurs de changements à long terme dans les écosystèmes méditerranéens arides. Application au suivi de la désertification dans le sud tunisien". Thèse de Doctorat, Université de Marseille III, France, 360 p.

Khali, I., Ben H. K.L-H., Raissouni, A. and El Arrim A. (2016), "Cartographie quantitative du risque d'érosion des sols par approche SIG/USLE au niveau du bassin versant Kalaya (Maroc Nord Occidental)". *J. Mater. Environ. Sci*., Vol 7 N°8: p2778–2795.

Khelil A., (1997), "L'écosystème steppique : Quel avenir?". Édition Dahleb, Alger. 228 p.

Kosmas, C., Ferrara, A., Briasouli, H., Imeson, A. (1999). "Methodology for Mapping Environmentally Sensitive Areas (ESAs) to Desertification". *In*: The Medalus Project Mediterranean Desertification and Land Use. Manual on Key Indicators of Desertification and Mapping Environmentaly Sensitive Areas to Desertification; Kosmas, C., Kirkby, M., Geeson, N., Eds.; EU: Brussels, Belgium, 1999; pp. 31–47.

Le Houerou. H.N. (1992). "Climatic change and desertification". In: Science and Society. UNESCO, Paris, pp.183-201.

Mayer L. (1990). "Introduction to quantitative geomorphology". Edition Prentice Hall, Englewood cliffs (New jersey), 380 p

Mostephaoui T. (2013). "Cartographie des risques d'érosion hydrique par l'application de l'équation universelle des pertes en sol à l'aide d'un Système d'Information Géographique dans le bassin Versant d'El Hamel (Boussaâda)". Journal Algerien des Régions Arides, N° Spécial 11

N'dri B.E. (2007). "Analyse des facteurs et quantification du ruissellement et de l'érosion hydrique par les outils de télédétection et SIG dans la commune d'Attécoubé (Abidjan, sud de la Côte d'Ivoire". Thèse de Doctorat, Université Félix Houphouët-Boigny, Côte d'Ivoire, 150p

N'guessan K.A. (1989). Commentaire du Code Forestier et de la législation forestière de la Côte d'Ivoire. Librairie Générale de Droit et de Jurisprudence, Paris, France, 333 p.

Organisation Météorologie Mondiale (OMM) (1997), Météorologie et hydrologie urbaine. Actes de la journée météorologie mondiale de l'année.

Pimentel D., Tort M., D'anna L., Krawic A., Berger J, Rossman J., Mugo F., Doon, N. Schriberg M., Howard E., Lee S., and Talbot T. (1998). "Ecology and increase disease, population growth and environnemtal degradation". *Bioscience* vol.48, n°10, p. 817-826.

Pushpam K. et Vuola A. (2015). "L'économie de la dégradation des terres en Afrique: les bénéfices de l'action l'emportent sur ses frais"; disponible sur www.eld-initiative.org. Rapport du Directeur : Pushpam Kumar, PNUE. Coordinateur et Editeur Technique: Aaron Vuola, PNUE. ELD Initiative & UNEP, 160 p.

Raphiou M., (2013). "Gestion de la fertilité des sols pour une meilleure productivité dans les systèmes de culture à base d'igname au Bénin (Benin)", Thèse de Doctorat, Université d'Abomey-Calavi, Cotonou, 253 p

Rey F. and Berger F, (2002). "Interactions végétation érosion et génie écologique pour la maitrise de l'érosion en montagne". Consulté en ligne le 16/03/18, 8p. URL : https://www.inbo-news.org/IMG/pdf/Rey-Berger-2.pdf

RGPH, (2014) : Recensement général de la population et de l'habitat, Résultats Globaux, Institut National de Statistiques, Côte d'ivoire. 12 p.

Roose E. (1967). "Dix années de mesure du ruissellement et de l'érosion à Sefa au Sénégal". *Agro Trop*, vol 22. Pp 123 – 152.

Roose E. (1977). "Érosion et ruissellement en Afrique de l'Ouest. Vingt années de mesures en parcelles expérimentales". Document Orstom 78. Paris : Orstom éditions. 107 p.

Roose E. and Sarrailh J.M., 1990, "Erodibilité de quelques sols tropicaux, vingt années de mesure en parcelles d'érosion sous pluies naturelles", *Cahiers de l'ORSTOM*, Série Pédologique, vol. 25, n° 12, 24 p.

Roose E., 1985. "Terrasses de diversions et microbarrages perméables ? Analyse de leur efficacité en milieu paysan ouest-africain pour la conservation de l'eau et des sols dans la zone soudano-sahélienne". IVe conférence Internationale de conservation des sols. ISCO. Maracay (Venezuela) 3-5 novembre 1985, 15 p

Rougerie G. (1960), "Le façonnement actuel des modelés en Côte d'Ivoire forestière". Mémoire IFAN 58. Dakar: Institut Fondamental d'Afrique Noire (IFAN). 542 p.

Rougerie, G. (1958). "Modalité du ruissellement sous forêt dense de Côte d'Ivoire". *CR Acad Sci Paris*, vol 246 : pp290- 292.

Salamani M. and Hirche A. (2006). "L'état de la désertification en Algérie. In : Actes des journées internationales sur la désertification et le développement durable". CRSTRA-Université, Biskra. Pp 165-171.

Thomas, T. (1991). "Aspects of soil degradation and conservation measures in Agucho catchment, West Hararghe". Soil Conservation Revercha Project Report 19. University of Bern, Switzerland. 125 pp.

Tiesse B.A., Wandan E. N., N'Da D. H.,., (2017), "Apport de la télédétection pour le suivi spatio-temporel de l'occupation du sol dans la région montagneuse du Tonkpi (Côte d'Ivoire)". *European Scientific Journal*.Vol.13, N° 15, pp 310-329.

Tra Bi Z. A. (2013). "Etude d'impact des activités anthropiques et de la variabilité climatique sur la végétation et les usages des sols, par l'utilisation de la télédétection et des statistiques agricoles, sur le bassin versant du Bouregreg (Maroc)". Thèse de doctorat unique, Université Félix Houphouet Boigny, Cote d'Ivoire, Université d'Artois, France 190p.

Wischmeier, W.H., and Smith, D.D. (1978). "Predicting rainfall erosion losses-A guide to conservation planning". US Department of Agriculture, Agriculture Handbook N° 537 The Universal soil Loss Equation. *Prepared By Sciences and Education Administration*. 69 p

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