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Diachronic Study Of Water Erosion By GIS/RUSLE Approach In The Upper Catchment Of The Sissili (Burkina Faso)

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Abstract – Soil erosion is one of the main sources of land degradation and is an important issue in Burkina Faso, including the upper Sissili watershed. Among the degradation processes, water erosion is the most important threat to soils. It results in a reduction of the thickness of the soil and a decrease in the level of organic matter, thus a degradation of their fertility. The objective of this study is to characterize the dynamics of water erosion in the upper Sissili watershed between 2002 and 2018. The methodology is based on modeling of the different factors of water erosion in a geographic information system. Factors such as rainfall erosivity, soil erosibility, slope and slope length, vegetation cover and anti-erosion practices are assessed from the RUSLE universal soil loss equation. The average rate of erosion in the watershed increased from 0.59 t/ha/year in 2002 to 1.22 t/ha/year in 2018, with a total loss of 189,640.05 t/year to 392,835.46 t/year. Five erosion classes were determined such as 0–1 t/ha/year, 1–5 t/ha/year, 5–10 t/ha/year, 10 to 20 t/ha/year. Class 0 to 1 t/ha/year is the most represented of the two dates with 83.50% of the total area in 2002, and 61.38% in 2018. Erosion maps are a decision-making tool and help to guide the various interventions for water and soil conservation.

Keywords – Water Erosion, RUSLE, Watershed, Sissili, Burkina Faso.

I. INTRODUCTION

Land degradation affects more than 41% of the world's land surface and affects over 80% of the population in developing countries (Sylla, 2012; EEM 2005; UNCED, 1992). Soil erosion is a global phenomenon and one of the main sources of land degradation (Da, 2007; Roose, 1975). Erosion is mainly influenced by human activities. It is a source of degradation of ecosystems

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(environment) due to anthropogenic factors, including agricultural activities (Gomgnimbou et *al.* , 2010). Payet (2015) argues that anthropogenic activities generate a landscape dynamic that rapidly transforms environments. This transformation of the environment contributes to the intensification of erosion processes. These erosion processes become a serious environmental problem, accelerated by human activities such as the intensification of agriculture and the extension of cultural and economic areas (Tahiri et *al.* , 2017 ; Meliho et*c., 2016)*. In the tropics, particularly in Africa, land degradation has become a critical issue as agro-pastoral activities occupy more than 3⁄4 of the total population (Da, 2007). In Burkina Faso, more than 80% of the population lives on agriculture and is therefore dependent on arable land. The ecological disaster of 1973 and 1974, the increase in population and the use of natural resources have led to a continuous degradation of land in the northern and central regions of Burkina Faso (Dipama, 2013, 2014; Kaboré and Dipama, 2014). This land degradation has caused a migration of these populations to areas with high agroecological potential such as the west and south of the country where the upper catchment area of the Sissili is located. The government's desire to make the agricultural sector professional and dynamic has encouraged new actors to settle in the watershed. The presence of these agribusiness men has led to a rapid increase in cultivated areas and an increase in land competition in the area (Zongo, 2010). These anthropogenic activities accelerate land degradation processes such as soil erosion in the upper Sissili watershed. The objective of this manuscript is to characterize the dynamics of water erosion in the upper Sissili watershed between 2002 and 2018.

II. MATERIALS AND METHODS

II.1 Presentation of the study area

The upper Sissili Basin is the site of this study. It belongs to the Sissili watershed and covers an area of about 3,232 km2. The study area is located between latitudes 11° and 12° north and longitudes 1°48′ and 2°24′ west and is in southern Burkina Faso (Figure 1). There are three classes of soils: crude mineral soils composed of lithosols on shells and various rocks (less than 1% of the total area), soils with sesquioxides of iron and manganese (94%) and shallow humid soils with surface pseudogley (5.50%).

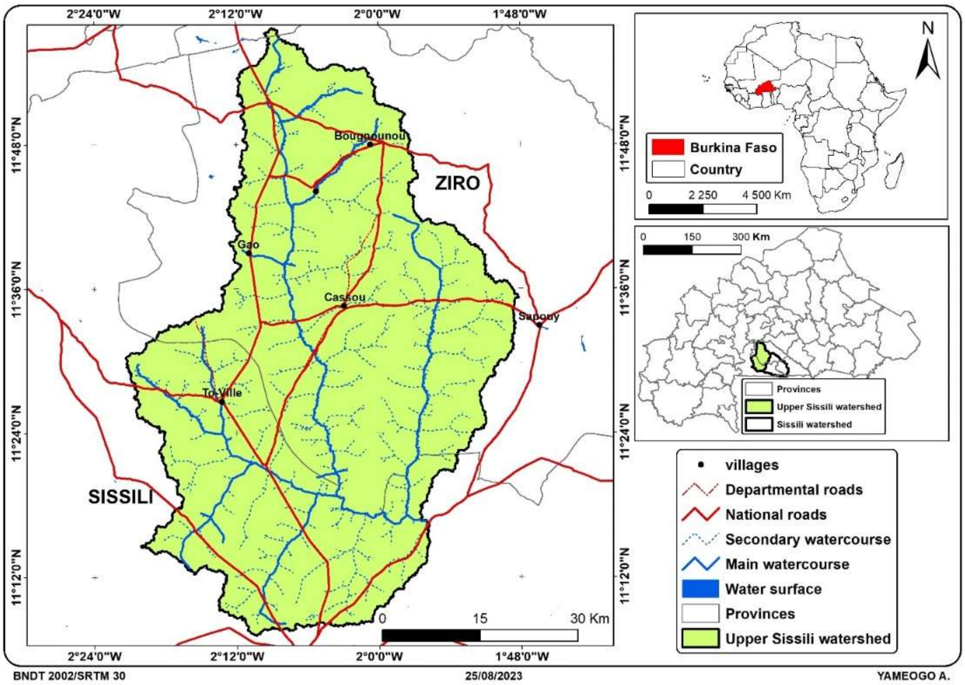

Figure 1: Geographical location of the upper Sissili watershed.

The climate of the watershed is characterized by two seasons, including a rainy season from May to October. The average annual rainfall varies from 1,020 mm in the south to 750 mm in the north of the basin.

The terrain is almost flat with low slopes and altitudes ranging from 285 m to 378 m. The overall average slope of the watershed is low (1.16%). More than 93% of the watershed area has a slope between 0 and 2%. The vegetation cover is shrub-to-tree savanna, savanna park at *Vitellaria paradoxa* and some relics of ripicole formation.

II.2 Materials

The hardware used for this study is composed of ancillary data, tools and software. The ancillary data are composed of a Landsat 8 OLI/TIRS image dated 10 January 2018, SRTM GOTOPO 30 m and Aster 30 m images, as well as data from the National Topographic Database (BNDT) of Burkina Faso, the soil mapping of the National Bureau des Soils (BUNASOLS) from Burkina Faso and finally climate data from the National Meteorological Agency (ANAM).

The ENVI 5 and ArcGIS10.8 software were used for Landsat image processing and the Geographic Information System, respectively. This image processing required the color composition of the 7-4-3 bands in view of their ability to discriminate between units of occupation which served as interpretative keys. The Garmin 62x GPS tool was used for field coordinates.

II.3 Determination of the various factors

The methodology used is centered on the differential analysis of land loss from the universal soil loss equation RUSLE. This equation was used in this study for the quantification of soil losses. It is an empirical model that brings together several factors affecting the speed of water erosion such as rainfall, soil properties, land characteristics, soil protection by vegetation cover and anthropogenic practices (Markhi *et al.*, 2015).

The RUSLE equation (1) is as follows:

$$A = R * K * LS * C * P \qquad \text{(equation 1)}$$

A is the annual rate of soil loss and is expressed in t/ha/year;

R (MJ/mm. ha. H. an), is the factor of erosivity of rainfall; it corresponds to the annual average of the sums of the products of the kinetic energy of rain by its intensity in 30 consecutive minutes;

K (t. H/MJ. mm), is the erodibility of soils; It is a function of the soil texture, humus content, surface layer structure and permeability;

LS is a dimensionless factor that represents the slope (S) and the length of the slope (L);

C is a dimensionless factor; it is the land use or the index of plant cover and crop practices;

P, factor without dimension, is a report which takes into account anti-erosion farming techniques such as tillage in level curves.

II.3.1 Rainfall erosivity (R)

For the study of rainfall erosivity (R), Wischmeïer & Smith (1978) established a relationship between kinetic energy and rainfall intensity (equation 2)

$$R = EI_{30} \qquad \text{(equation 2)}$$

With R the rainfall erosivity in MJ.mm/ha.hr.an, E the kinetic energy of the rain in MJ/ha.mm and I_{30}, the maximum intensity of the duration of 30 minutes and is expressed in mm/h.

Intensity is the main parameter that represents a link between rain and erosion. Its intervention is on two levels, namely the momentary saturation of soil porosity and the kinetic energy that rain dissipates by destroying the structure of the soil surface (battance) (Roose, 1977). The unavailability of the various parameters of Wischmeïer & Smith (1978) in the watershed presents a major difficulty for the calculation of the rainfall erosivity index. The stations in the study area do not have a 30-minute maximum precipitation recorder. Several authors have encountered this type of difficulty. Therefore, researchers around the world have developed, after many years of research, alternative equations and other empirical indices to estimate the R factor (Maamar-Kouadri et *al.*, 2016).

Roose (1977) in this research work in West Africa found that there is a relationship between the average annual index (R am) and the average annual rainfall height (H am) during a given period. The relationship (equation 3) between the average annual index and the average annual rainfall is as follows:

$$\frac{\text{R am}}{\text{H am}} = 0.50 \pm 0.05 \quad \text{(equation 3)}$$

This relationship is particularly consistent. This is particularly the case for some 20 sites located in Côte d'Ivoire, Burkina Faso, Senegal, Niger, Chad, Cameroon and Madagascar. However, the consistency of this report is not observed in mountain areas.

Rainfall erosivity was calculated from the measurements of 5 ANAM pluviometric stations near the watershed. The calculation of rainfall erosivity in the study area was performed using the formula of Nguyen (1996). Indeed, Nguyen (1996) suggested a method for measuring the R factor (equation 4) based on annual rainfall by analyzing 54-year rainfall data from 253 meteorological stations around the world.

$$R = 0{,}548257 * P - 59{,}9 \quad \text{(equation 4)}$$

R is the rainfall erosivity and P, the annual rainfall

II.3.2 Soil erodibility (K)

Soil erodibility is a function of soil organic matter, permeability, texture and structure. Wischmeier et *al., (*1971) have studied more than twenty-three parameters and proposed a nomogram for the determination of soil erodibility. Roose (1994) defines soil erodibility as its resistance to rain drop battance and runoff. It is a measure of soil particle vulnerability to detachment and transport by rain and runoff (Tahiri et *al.* , 2017). The K index is measured by the following formula (equation 5):

$$K = ((2{,}1 * 10^{-4} * M^{1{,}14}) * (12 - A) + 3{,}25 * (B - 2) + 2{,}5 * (C - 3))/100 \quad \text{(equation 5)}$$

K, is the factor of erosibility;

M, the particle size factor, = % (2 to 100 microns) * % (100 to 2000 microns);

A= % of organic matter;

B, the soil structure code (very fine granular: 1; fine granular: 2; average and coarse granular: 3; in block or massive: 4);

C, the code of the permeability class (fast: 1; moderate to rapid: 2; moderate: 3; slow to moderate: 4; slow: 5; very slow: 6).

II.3.3 The topographic factor LS

Slope has a significant impact on the water erosion process; Runoff is generally strong and rapid on steep slopes, causing severe water erosion (Fils et *al.,* 2014). The determination of the topographic factor (LS) is a function of the length of the slopes (L in m) and their inclination (S in %). LS is determined from the Aster image 30 m of the study area.

In this study, the topographic index is calculated on the basis of the multidirectional flow algorithm proposed by Freemann (1991) using the GIS matrix calculation tool. LS was determined by the following formulae (equations 6 and 7):

$$\text{L} = \left(\frac{\varepsilon}{22.1}\right)^{\text{m}} \quad \text{(equation 6)}$$

ε is the product between Flow accumulation and pixel size.

The pixel size or resolution in our study is 30 m x 30 m, or 900 m^2. The constant in equation (6) 22.1 represents a uniform length (in meters) to avoid uncertainties about the influence of slope on erosion.

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Table 1: Variations in m as a function of the slope.

Slope in %	P <1	1 ≤P <3.5	3.5 ≤P <5	P≥5
m	0.2	0.3	0.4	0.5

For the determination of the value in m of the watershed, a classification of the slopes as a percentage was generated. The classes of slopes P <1 and 1 ≤P <3,5 occupy most of the study space. They cover 40.08% and 59.4% of the total area of study respectively. For the calculation of slope length, an average value of m = 0.25 was defined. The slope is determined by the following formula:

$$S = \left(\frac{\sin(\theta * 0{,}01745)}{0{,}09}\right)^{1{,}4} \quad \text{(Equation 7)}$$

With (θ) the slope expressed in degree and 0.01745 is a constant to change from degree to radiant.

The topographic index was calculated by combining L and S into a single LS. The topographic factor (LS) is a function of slope length (L in m) and slope.

II.3.4 The C-factor

Factor C in the WISCHMEIER equation is the relationship between erosion measured under a specific crop and that observed on the standard bare plot and expresses the interaction between the plant and the cropping techniques (Roose, 1975). Factor C was determined based on land use patterns in the watershed. A land-use dynamic map was produced using Landsat images (30 m resolution) for this purpose. Seven classes were identified: crop areas, habitat, water bodies, bare areas, riparian formation, arboreal and shrub savannas. These occupation units were determined on the basis of the 1996 National Land use Classification by the National Environmental Information Management Program (NMMI). C varies from 1 on bare soil, that is its maximum value in terms of efficiency of erosive processes, to 1/1000 th under forest, 1/100 th under grassland and cover plants, 1 to 9/10 th under crops (Payet et al., *2011).* The determination of C values in the upper Sissili watershed is based on studies by Roose (1977) in West Africa, including Burkina Faso.

The most cultivated speculations in the basin are:

- maize, millet and sorghum which occupy about 60% of the cultivated area;
- cotton uses approximately 25% of the seeded area;
- the sesame and other speculations occupy 10% and 5% respectively.

All these speculations represent the crop areas of the study space. Given the difficulty of allocating these crops in the watershed, a mean C was thus established for all these products. The value of C is 0.5. The estimated recovery rates for vegetation are as follows: 95% recovery is estimated for riparian formation, 70% for the treed savannah and shrub savanna with 50%. Based on the reading of authors who conducted studies in West Africa, an average value of C was attributed to the different plant formations. The index of vegetation cover C is 0.006, 0.03 and 0.05 for the ripicole formation, the arboreal savanna and the shrub savanna respectively. Habitat and bare areas have a value of C equal to 1. Water bodies have a degradation index C equal to 0.

II.3.5 The P factor

The P factor takes into account soil conservation techniques such as anti-erosion practices. Level tillage, butchering, leveling, stone-cutting, grass strips, hedges and mulching are crop techniques used to reduce runoff and erosion. The value of the P factor is between 0 and 1 (Table 2), where 1 represents the areas for which anti-erosion practices are absent. There is no modeling study of the P factor. Only field observations allow for its calculation by comparing soil loss with or without anti-erosion practices (Mostephaoui *et al.*, 2013).

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Table 2: Overall value of P based on conservation practices

Conservation practice	**Value of P**
No conservation practices	1,00
Cross-slope crop	0,75
Crop along contour lines (slopes 3–8%)	0,50
Alternating belt cultivation, cross slope (slopes 3–8%)	0,38
Alternating band, level curve (3–8% slope)	0,25

Source: (Wall *Etal.* , 2002).

Almost the entire upper Sissili watershed (99.97%) has a slope between 0 and 7%. By superimposing land-use layers on the slopes of the watershed, all growing areas are located on slopes between 0 and 7%.

Observations made in the study area reveal that billon crops are the anti-erosion practices in the watershed. The lack of a database on anti-erosion practices and the difficulty of its implementation in the watershed led us to assign a value of 1 P for undeveloped areas and 0.55 for cultivated areas.

II.4 Erosion class dynamics analysis

The transition matrix approach was used for the analysis of the 2002 and 2018 erosion class conversions of the watershed. According to Oloukoi and *al.,* (2006), the transition matrix is a double-entry table that allows for condensed description of changes in the status of land occupation cells between two given dates. The crossing between two themes consists of combining in an arithmetic way the values of the cell-to-cell themes (Souley Yero, 2012). The matrix produced in this study results from the crossing of the two erosion maps (2002 and 2018). The transition matrix (table 3) allows for the various conversions of units of occupation in a given period. The values in the cells of the matrix represent the change in area from an initial class i to a final class j between two dates with t_0 the initial date and t1the final date. "The values in the columns represent the proportions of the areas occupied in the landscape by each land use class at time j and those of the lines at time i" (Ouoba, 2013).

Table 3: an example of a transition matrix between the t0 and t1 dates

	Land Tenure Unit	j at time t1			
		Unit 1 (j=1)	**Unit 2 (j=2)**	**Unit 3 (J=3)**	**Sum of lines**
i at time t0	**Unit 1 (i=1)**	a (1,1)	a (1,2)	a (1,3)	$E1t_0 = \Sigma$ a (1, j)
	Unit 2 (i=2)	a (2,1)	a (2,2)	a (2,3)	$E2t_0 = \Sigma$ a (2, j)
	Unit 3 (i=3)	a (3.1)	a (3,2)	a (3,3)	$E3t_0 = \Sigma$ a (3, j)
	Sum Ej t1 of columns	$E1t_1 = \Sigma$ a (i, 1)	$E2t_1 = \Sigma$ a (i, 2)	$E3t_1 = \Sigma$ a (i, 3)	ΣΣ a (i, j)

Source: Oloukoi et al., (2006)

III. Results and Discussion

III.1 Soil erosion in the watershed between 2002 and 2018

The superposition of the different indices allowed the establishment of water erosion maps for the upper Sissili watershed between 2002 and 2018 (Figure 2).

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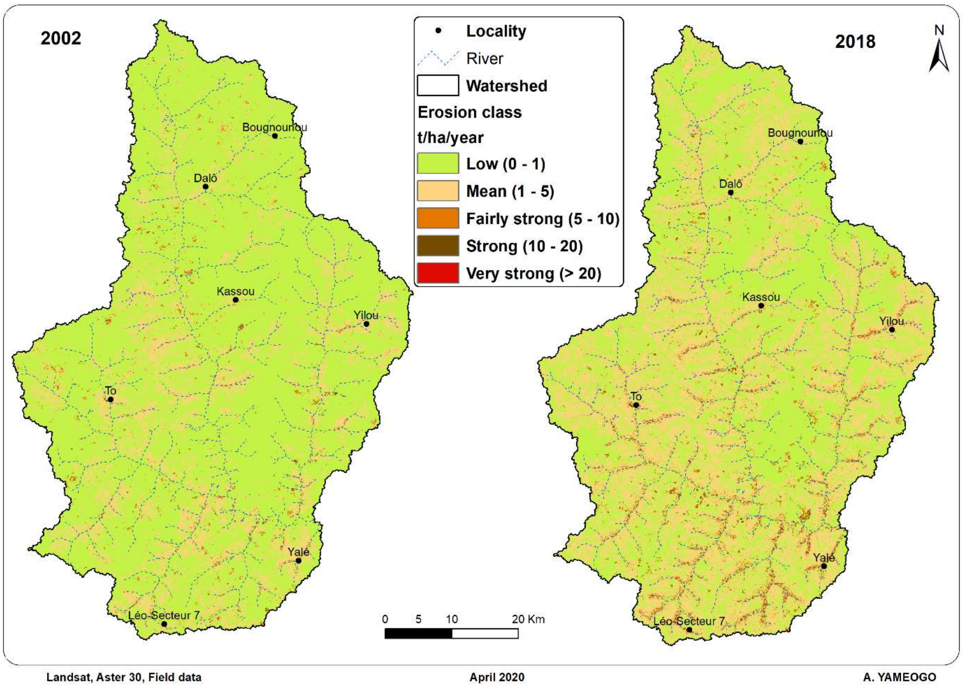

Figure 2: Water erosion dynamics between 2002 and 2018

Total soil loss is estimated at 189 640.05 t/ha/year in 2002 compared to a loss of 392 835.46 t/year in 2018. Five erosion rate classes were determined in the upper Sissili watershed between 2002 and 2018. The average erosion rate has increased from 0.59 t/ha/year in 2002 to 1.22 t/ha/year in 2018, a trend of 0.63 t/ha/year. There is a concentration of erosion along watercourses. From the analysis of Figure 3, it appears that the low erosion class (0 to 1 t/ha/year) is the most represented in both 2002 and 2018. This class covers 270,875.01 ha and 197,868.55 ha, respectively, representing 83.81% and 61.22% of the total catchment area. It declined by 73,006.47 during this period. The erosion class 1 to 5 t/ha/year (medium) has seen its area changed between 2002 and 2018 from 65,874.37 ha, or 48,208.77 ha to 114,083.14 ha. The rate of erosion between 5 and 10 t/ha/year (quite strong) covers an area of 3,360.54 ha in 2002 and 8,914.34 ha in 2018. The area has increased by 5,553.81 ha. The largest portions of the study area are in the strong (10–20 t/ha/year) and very strong classes (20 t/ha/year). In 2002, the area of class 10 to 20 t/ha/year was 674.61 ha or 0.21% of the basin, compared with 2001.09 ha (0.62%) in 2018. The area studied was over 20 t/ha/year in 2002, representing 0.03% of the study area and 0.11% in 2018. This is a progressive evolution of 1326.48 ha for the strong class and 251.82 ha for the very strong one.

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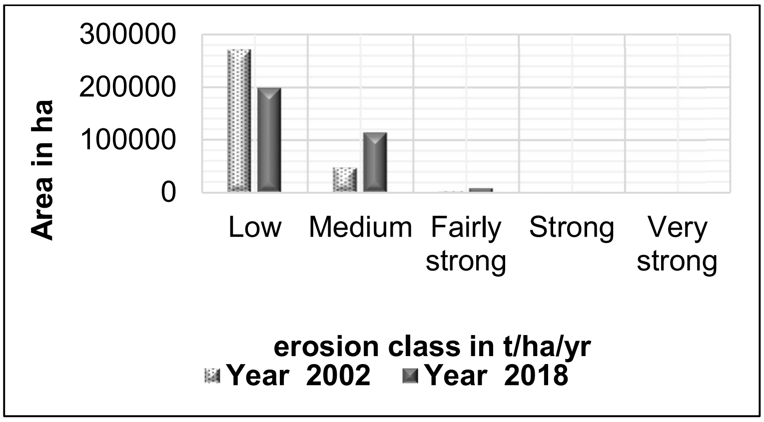

Figure 3: The erosion class evolution between 2002 and 2018

The erosion rates of these different classes have remained relatively stable between 2002 and 2018 (Figure 4).

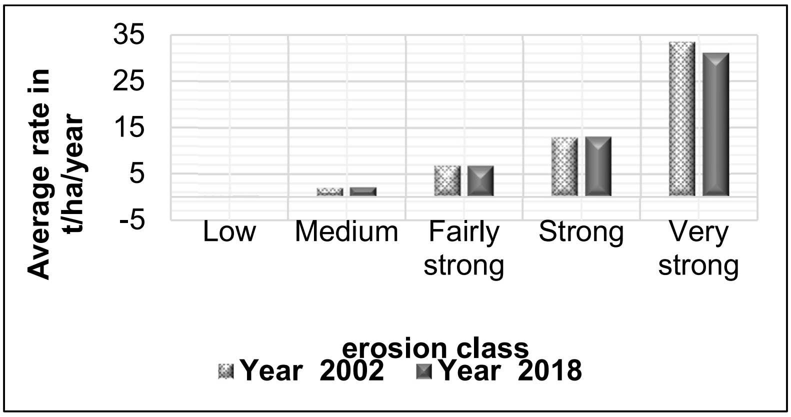

Figure 4: The evolution of erosion rates in different classes between 2002 and 2018

Erosion rates in the 0–1 t/ha/yr (low), 1–5 t/ha/yr (medium) and 10–20 t/ha/yr (high) classes increased slightly by 0.06 t/yr, 0.13 t/yr and 0.14 t/yr between 2002 and 2018. The rate for class 0 to 1 t/ha/year is 0.21 t/ha/year in 2002 compared with 0.27 t/ha/year in 2018 and for class 1 to 5 t/ha/year, 1.98 t/ha/year and 2.10 t/year. Class 10 to 20 t/ha/year has seen its rate change from 12.86 t/ha/year to 13 t/year during the same period. For the 5–10 t/ha/year (strong) and 20 t/ha/year (very strong), their erosion rate decreased between 2002 and 2018. For class 5 to 10 t/ha/year, the rate has increased from 6.73 t/ha/year to 6.72 t/ha/year with a decrease of 0.01 t/ha/year. The erosion rate for class 20 t/ha/year varies from 33.35 t/ha/year to 31.03 t/ha/year, with a change of -2.32 t/ha/year.

III.2 The change in different erosion classes from 2002 to 2018

Over the 17 years, the upper Sissili erosion classes have undergone mutations summarized in Table 3. The transition matrix of the study area presents three situations such as the stable situation where the classes have not changed and the gain or loss of area.

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Table 3: the transition matrix of erosion classes in % between 2002 and 2018

Year		2002					
	Erosion class (t/ha/year)	0 to 1	1 to 5	5 to 10	10 to 20	≥ 20	Total
2018	0 à 1	**57 873**	2 926	0,340	0,075	0,005	61 220
	1 à 5	23 906	**10 970**	0,342	0,067	0,011	35 300
	5 à 10	1 621	0,868	**0,236**	0,026	0,006	2 760
	10 à 20	0,348	0,125	0,112	**0,030**	0,004	0,620
	> =20	0,059	0,026	0,009	0,010	**0,003**	0,110
	Total	83,807	14,915	1,040	0,209	0,029	100,000

Source: field data

The analysis of the table allows observing the major changes between the different erosion classes in the watershed. Areas that remained stable during the period 2002 to 2018 are shown diagonally. This is the case for the area of class 0 to 1 t/ha/year, where 57.87% of its total area did not change from 2002 to 2018. Only about 3.35% of the area of this erosion class mutated to the detriment of other classes such as 1–5 t/ha/year (2.93%), 5–10 t/ha/year (0.34%), 10–20 t/ha/year (0.08%) and 20 t/ha/year (0.005%). However, from 2002 to 2018, erosion class 0–1 t/ha/year lost area by approximately 23.91%, 1.62%, 0.35% and 0.06% for classes 1–5 t/ha/year, 5–10 t/ha/year, 10–20 t/ha/year and 20 t/ha/year respectively. It lost 22.59% of its area in 17 years.

IV. Discussion

Soil erosion is a process inherent in the evolution of the landscape and its intensity on the ground is governed by many natural and anthropogenic factors (Danilo and Stanchi, 2011). Soil loss or erosion rate differs from area to area depending on the influence of different factors controlling erosion in the upper Sissili watershed. Anthropogenic activities influence the dynamics of different erosion classes in the study area (Figure 5). Human occupation recorded the highest rates of erosion in 2018 with 6.75 t/ha/year in residential and bare areas and 1.66 t/ha/year in cultivated areas compared to an average rate of 1.22 t/ha/year (YAMEOGO *et al.*, 2020,2021). The fields cover approximately 79.13% (310,861.63 t/year) of total losses (392,835.46 t/year) over 57.90% of the total catchment area. According to the authors, forest formations have low rates of erosion with 0.28 t/ha/year in shrub savannah, 0.23 t/ha/year in arboreal savanna and 0.06 t/ha/year in ripicole formation. Soil erosion is a geomorphological process, but often accelerated by many factors such as human activities (Thomas, Joseph and Thrivikramji, 2018).

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Photo 1: Traces of Slab Erosion in a Field

This figure shows the influence of human action on land degradation through logging. These actions amplify the effects of erosion in the study space.

V. Conclusion

The diachronic study of erosion by surface runoff in the upper Sissili watershed shows an erosive dynamic between 2002 and 2018. Total erosion loss increased from 189,640.05 t/ha/year in 2002 to 392,835.46 t/ha/year in 2018. The average erosion rate has changed from 0.59 t/ha/year to 1.22 t/ha/year from 2002 to 2018. Five (05) erosion classes were defined at the end of this study. The most represented class is 0–1 t/ha/year with a watershed coverage of 83.81% in 2002 and 61.22% in 2018. There is a great change in the erosion classes between these two dates. This dynamic is mainly due to the anthropogenic action in the area through different cultural practices. Agricultural policies need to be adopted to effectively combat land degradation in the study area. This will prevent the land in the watershed from being degraded like that in the northern region of Burkina Faso. This will limit the migration of the watershed's farming population to other arable lands.

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