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Modelling and Quantification of the Water Erosion of the Lake Itasy Watershed

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Abstract – Water erosion is recognized as a serious long-term threat to the sustainability of soil and water resources in Madagascar. Many factors, both physical and human, make the western slope of Madagascar in general and the Itasy Region in particular, a particularly eroded area. This study focuses on the assessment of soil water erosion in the Lake Itasy watershed by modelling and quantifying it. The empirical model RUSLE (Revised Universal SoilLoss Equation) was used to estimate soil losses, highlighting the contributions of multispectral remote sensing. This method is based on five parameters, including: rainfall erosivity R, soil erodibility K, topography LS, vegetation cover C and anti-erosion practices P. The map of areas at potential risk of soil loss thus obtained is supported by the analysis of multi-date satellite images, contributing to the understanding of the phenomenon of soil water erosion at the catchment scale.

Keywords – Modeling, Water erosion, RUSLE, Multi-criteria analysis.

I. Introduction

The problem of erosion is a phenomenon produced by nature but also by human activity. Erosion is a long-standing fact and concerns almost all tropical countries. It is classified as a recurrent phenomenon of environmental degradation and evokes a serious threat to the management of natural resources, particularly soil and water resources. According to ONE, 1999 the loss of land is estimated at 200 t/ha/year in the Malagasy Highlands. This statistic is very high compared to the world average of up to 11 t/ha/year. For several decades, several researchers have been studying this scourge and have tried to develop ways to evaluate and quantify the phenomenon.

Erosion in the Itasy Lake and Alaotra Lake watersheds is very active. These areas indeed deserve a specific concentration of this scourge. It is due to several factors, namely: the geological context, the nature of the soil, the climate, the change in the plant cover due to anthropic activities. Of these factors, climate is the most tragic. Rain and wind cause a rapid degradation of the superficial horizons which are not sufficiently protected by vegetation and which have aggressive characteristics. Erosion management is thus complex. Thus, the spatialization of this phenomenon is essential to ensure sustainable management of soil and water resources.

Indeed, this research is conducted in the Lake Itasy watershed and focuses on modelling water erosion and monitoring the evolution of Lake Itasy based on remote sensing combined with the empirical and spatialized RUSLE model. The objective of this work is to assess the impacts of erosion on soil and water resources by modelling the main factors involved in this phenomenon and by using the empirical RUSLE model.

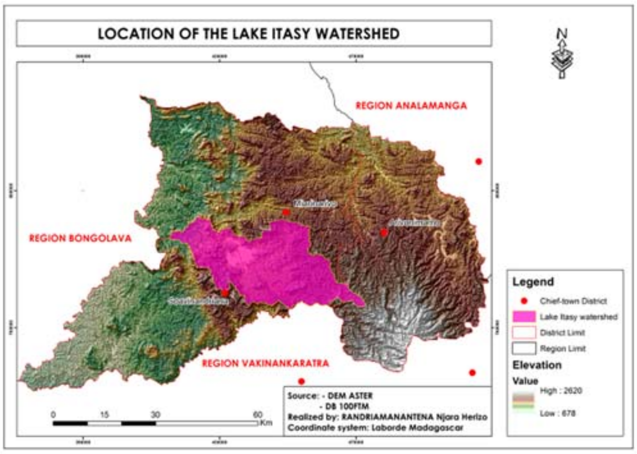
The research interest is twofold. On the one hand, erosion mapping makes it possible to monitor and assess the current situation in the most affected sectors. On the other hand, knowledge of the different factors is necessary for the development of environmental action plans or management plans for rural areas in order to reduce the impact of erosion.

II. STUDY AREA

2.1. Geographical location

Our study area is the Itasy Lake watershed. It is delimited from the digital terrain model ASTER with a spatial accuracy of 30 m. It is thus delimited, has an area of 830 km2, divided between the districts of Miarinarivo and Soavinandriana.

The Lake Itasy watershed is bordered by the Communes of Miarinarivo II and Analavory in the North, the Communes of Soamahamanina and Mandiavato in the East, the Commune of Ampefy in the West and the Communes of Soavinandriana, Ambohidanerana and Faratsiho in the South. The Communes of Manazary, Antanetibe and TalataDondona are included in this watershed area. Its outlet is in the Lily River towards the west of Lake Itasy, flowing into the Sakay River (*See* ***Map1***).



Map 1 : Location map of Itasy Lake watershed

2.2. Climate

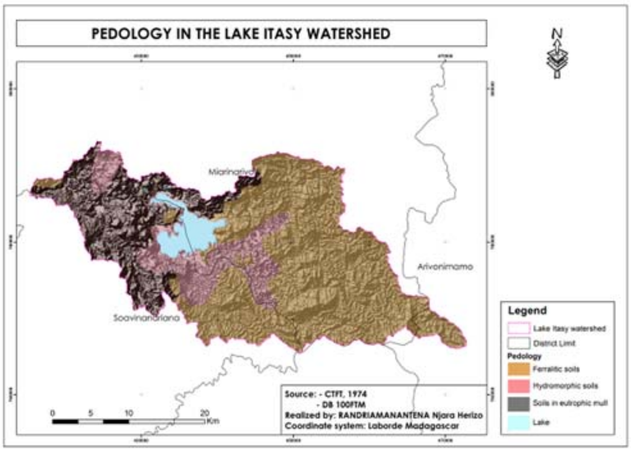
The Itasy Region has a humid tropical climate with spatial variability. This zone is divided into two climatic zones: the East-Central part and the Western part.

According to the monograph of the Itasy region produced by CREAM in 2013, the average annual rainfall varies according to the above zoning. They are between 800 and 1000 mm in the Eastern and Central zone, and between 900 and 1100 mm in the Western zone. The dry season is well marked from April to October with a monthly average of 40 mm. In the East and Central zone, the temperature varies from 26.7°C to 7.1°C. In the Western zone, however, this average temperature is much higher, respectively 28°C and 10°C in August.

This area is one of the low-risk areas for natural disasters. However, some of them have already caused considerable damage to the environment and socio-economic life of the Region, namely cyclones GAFILO and ELITA in February and March 2004.

2.3. Pedology

According to the study of soil types in Madagascar carried out by soil scientists J Riquier, Bourgeat and Graffin in 1954, the Lake Itasy watershed is characterized by three main soil types (See ***Map 2***):



Map 2 : Pedology of Itasy lake watershed

- Ferralitic soils: This type of soil covers almost the eastern part of the Itasy region. They have different minerals such as alumina silicates, hydroxides and iron oxide.
- Hydromorphic soils: These are soils with genesis dominated by excess water, permanent or temporary, in all or part of the profile. They are generally located on low topographic points or on the edges of watercourses.
- Soils with mull eutrophes: These soil types develop on volcanic ash or waste. These soils are biochemically altered, with organic matter playing an important role in pedogenesis through the organomineral complexes to which it gives rise.

The pedological nature of soils determines their vulnerability to water erosion.

III. DATA AND METHODS

3.1. Data used

To conduct this research, several satellite images were used. These images are of the following type:
- LandSat 1 TM acquired on 31 July 1973, LandSat5 MMS acquired on 08 March 1986, LandSat 5 TM acquired on 13 April 1998, LandSat 7 TM acquired on 13 April 2009, LandSat8 OLI & TIRS acquired on July 12, 2019 with spatial resolution of 80m, 30m and 15m respectively;

- Sentinel-2A MSI acquired on July 18, 2019 with 10m spatial resolution
- Digital terrain model of the ASTER terrain acquired in 2009 with a spatial resolution of 30mWorldclim/ MODIS climate data from 1970 to 2000 with an accuracy of 1km.

All these Landsat, Sentinel and MNT ASTER images were downloaded free of charge from the US Geological Survey (USGS) website and georeferenced in Laborde Madagascar projection before use. The computer hardware used to process the data in this study consisted of a number of software packages. These included ENVI 5.2 software, which was used for satellite image processing, and ArcGIS.10.2.2, which was used for thematic analysis and cartographic restitution, for extraction, digitization, combination, and integration of the various vector layers.

3.2. Methods

3.2.1. Choice of criteria from the empirical model : RUSLE

The RUSLE model is applied for erosion modelling. The RUSLE model is used to estimate the average annual loss of soil in an area. This model is a revised version of the universal soil loss equation USLE by Wischmeier& Smith (1978). The universal soil loss equation is therefore of the form:

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

With:

A*:* The average annual soil loss in [t/ha/year].

A: Rainfall Erosivity Index [MJ mm/ha/h]

K: Soil erodibility index [t h /MJ/ mm].

LS: Topographic factor which intervenes by the length and inclination of the slope (dimensionless)

C: Vegetation factor (dimensionless)

P: Supportive Practice Factor (Dimensionless)

3.2.1.1. Factor R

It is the rainfall erosivity index which includes 2 variables:

- the amount of rainwater;

- the maximum intensity sustained over an extended period of time.

The R-factor is a measure of the total annual amount of erosive rain at a given location and the distribution of this rain over the year. The factor R varies according to the energy and intensity of the showers and the amount of rain and runoff during the various seasons of the year.

According to Wall et al, 1997, it is expressed in [MJ.mm/ha/h]. This factor is calculated using rainfall data or recorded climate data. Due to the unavailability of data, two formulas were used to calculate the R factor in order to optimize the result:

formula of de Renard and Freimund (1997) whose expression is:

$$Si\ P_i < 850\ \ R = 0{,}0483\ \times P_i^{1{,}61} \times 0{,}1$$

$$Si\ P_i > 850\ \ R = (587{,}8\ -\ 1{,}219P_i + 0{,}004105P_i^2)0{,}1$$

- formula of Lo et al in 1985

$$R = [38{,}46 + (3{,}48P)].\,0{,}1$$

The value of the R factor that we used is the average of the values obtained by the two formulas above.

3.2.1.2. K factor

Soil erodibility is the quantitative measure of the inherent sensitivity or resistance of soil to erosion and the impact of soil on runoff production (volume and runoff rate). The K factor varies according to the texture and structure of the soil, the organic matter content and the season. In the absence of data, the method of Wischmeier and Smith proposed in 1978 could not be applied in the context of this study. Indeed, the determination of the value of the factor K is done analogically from the comparison of existing previous data.

3.2.1.3. LS factor

The length, the shape and above all the slope inclination are parameters which influence much soil erosion. The length of the slope determines the speed of runoff and the transport of particles increases as a function of the length of the plot. Likewise, solid transport increases exponentially with the percentage of slope. The factors L (slope length) and S (slope angle in%) are most often combined into a single dimensionless factor.

Many methods have been developed to calculate the LS factor but the USPED method invented by Jim Pelton et al, in 2012, was used thanks to its ease of calculations. This method proposes to calculate the factors L and S from the following formulas:

$$L = (m + 1)(\frac{\lambda_A}{22{,}1})^m$$

With L: Slope length
λ_A: Upper drainage area [m2]
m: Variable depending on the susceptibility of the soil to erosion
22.1: Elementary plot length

$$S = (\frac{\sin\,(0{,}01745.\,\theta_{deg}}{0{,}09})^n$$

With S: Stiffness of the slope
θ_{deg}: Slope in degrees

n = Variable depending on the susceptibility of the soil to erosion

The values considered for m and n are 0.4 and 1.4 respectively. These values are typical of areas susceptible to gully and channel formation.

3.2.1.4. Factor C

The vegetation protects the soil and ensures the attenuation of raindrops, the slowdown of runoff and infiltration. For low type vegetation, soil losses reduce with increasing plant cover. The value of factor C for a given land use on a surface varies between 0 to 1 depending on the categories of land use.

Many researchers and experts have invented new simplified approaches, namely: the use of the land cover map, the use of vegetation indices (De Jong 1994) and the class assignment for each entity (Borrelli et al. 2014).

The experiment of De Jong (1994) is adopted to conduct this research. The latter is based on the use of the vegetation index from the following equation:

$$C_i = 0 \qquad \text{si NDVI} \leq 0$$
$$C_i = -\left(\frac{1}{\text{NDVI}_{max}}\right).\text{NDVI}_i + 1 \quad \text{si NDVI} \leq 0$$

3.2.1.5. P factor

The P factor takes into account soil conservation practices. Anti-erosion practices concern all the cultivation techniques used to reduce runoff and erosion. According to Lufafaet al, 2003; Fu et al, 2005, the values of P are between 0 and 1, with 0 represents a very good medium for resistance to erosion and 1 shows the absence or failure of anti-erosion practice.

The value invented by Wischmeier and Smith (1978) is used for this research. These values were established by classification according to slope and land use. All values are shown in the following table:

Table 1:P factor values according to Wischmeier and Smith

Land use	**Slope**	**P factor**
Cultivated area	0 - 5	0.1
	5 - 10	0.12
	10 - 20	0.14
	20 - 30	0.19
	30 - 50	0.25
	50 - 100	0.33
Other areas	All	1

3.2.2. Method for monitoring Lake Itasy

Since erosion has negative impacts on soils and water resources. It is therefore important to monitor Lake Itasy in terms of area since 1973.

For easier access to information on the presence of open water, the use of the standardized NDWI water difference index was the most credible. This method is adopted in order to extract surface water from open water in Lake Itasy.

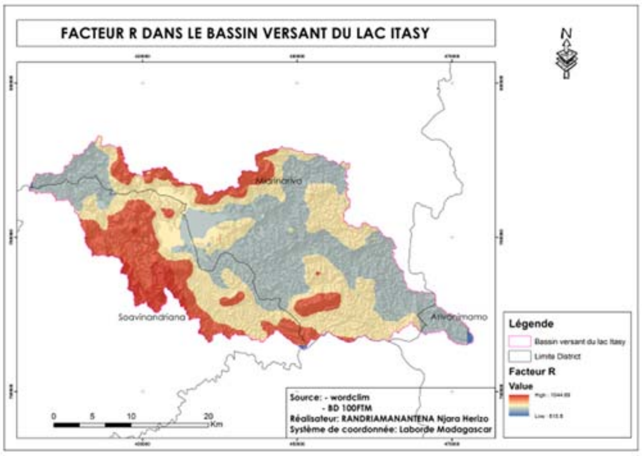
IV. Results And Interpretations

4.1. Modeling of erosion factors

4.1.1. R factor

The R factor values are obtained by processing the precipitation data, themselves obtained from wordclim.org/version2 integrated by the formulas of Renard and Freimund (1997) and Lo et al (1985). The values obtained from these two equations are different. Thus, the average of the two results was used in this study in order to avoid overestimating and underestimating the result.

After treatment, the R factor values in the watershed vary from 615.8 to 1044.69 MJ.mm/ha/h. The average value is 719.88 MJ.mm/ha/h.



Map 1 : R factor

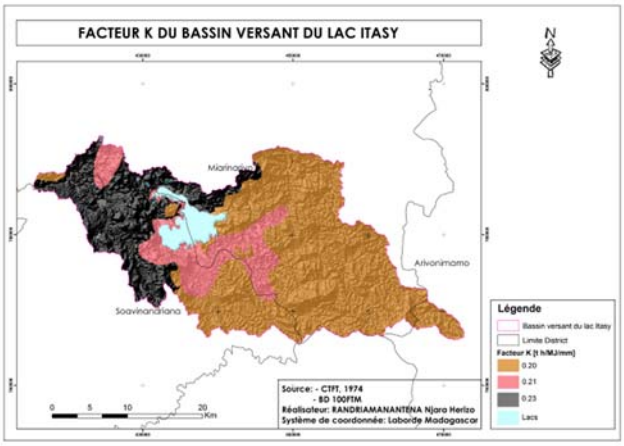
4.1.2. K factor

In the absence of data, the K factor was determined by analogy, based on previous work (CTFT, 1974; Rambeloson, 2006; Ranivoson, 2007; Roose, 1978). The values are precalculated for each type of soil. Table 2 presents these values.

This data is combined with the soil data from our study area and reclassified to obtain the final result. The map below shows the K factor values obtained in the Itasy Lake watershed.

Table 2: K Factor Classification

Type of soil	**K [th / MJ / mm]**			**Erodibility**
	Min	Max	Retained	
Ferraliticsoils	0.02	0.20	0.20	Way
Hydromorphicsoils	0.10	0.27	0.21	Way
Soils in eutrophe mull	0.08	0.25	0.23	Way

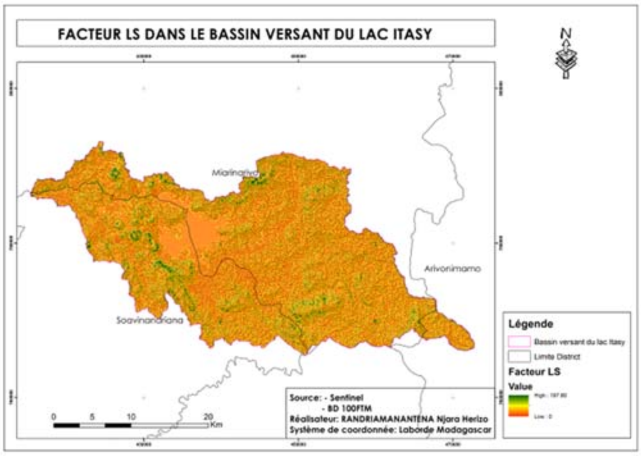


Map 2 :K factor

4.1.3. LS factor

Before applying the equation USPED by Jim Pelton et al, in 2012, the development of a sloping map of the Lake Itasy basin was performed using the ASTER digital model.

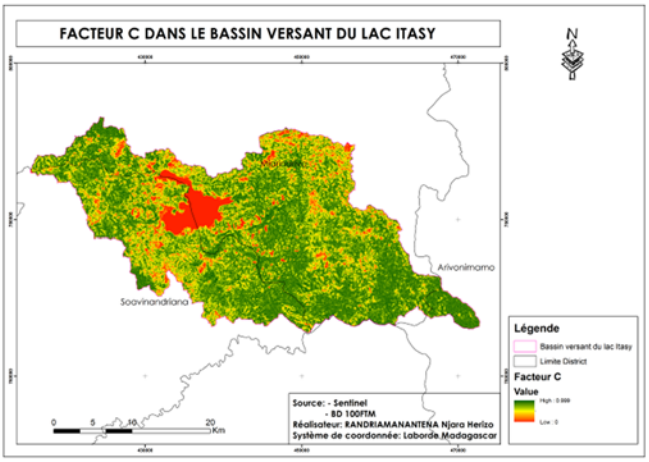
After treatment, the value of the LS factor varies between 0 to 197. However, the average value reaches 4.3. The result is represented by the map opposite.



Map 3 : LS factor

4.1.4. Factor C

Factor C is estimated from the NDVI vegetation index obtained by processing sentinel-2A MSI images with spatial precision of 10m. The procedure for calculating the values of factor C applies the relationship of De Jong (1997). The values of factor C obtained vary from 0 to 0.99, the maximum values of which are found in cultivated areas and the zero value is found on water bodies. The mapbelow shows the result of factor C.

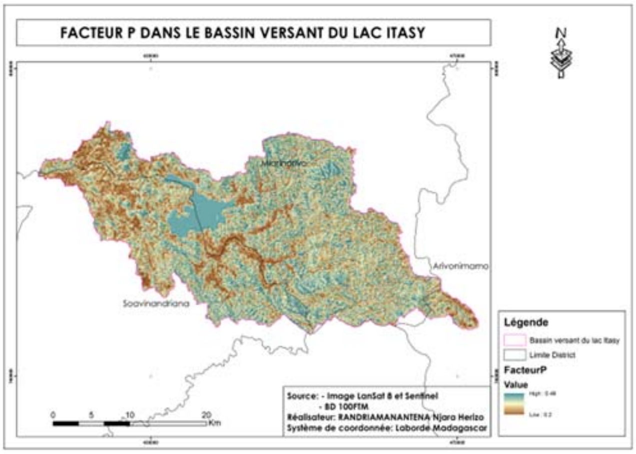


Map 4 : C factor

4.1.5. P factor

The support factor P is the ratio between the cultivation techniques and the slope. Indeed, the determination of the P factor requires knowledge of the land occupations in the watershed and the slope. The land use map was obtained by the object-oriented mosaic classification of the three sentinel images. The land use map proceeds to reclassification into 2 categories: cultivated area and other areas.

After the superimposition of the map obtained and the slope, the factor calculation is carried out. The value of factor P on cultivated areas is between 0.2 to 0.49 with an average of 0.17. The result obtained is indicated by the map below.

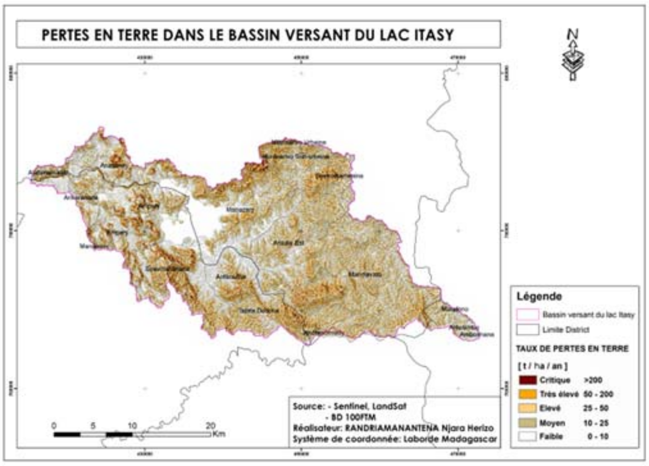


Map 5 :P factor

4.2. Quantification of erosion

4.2.1. Estimated land loss

The RUSLE model can know an estimate of the average value of soil loss in tonnes per hectare per year in the area studied. This estimate depends on the precision of the factors previously. According to the calculation applying this model, the estimated value of soil losses in the Lake Itasy watershed varies from 0 to 2029 t / ha / year with an average of 28 t / ha / year. To better understand the fact, this result is reclassified into 5 classes and the result is mapped on the map below.



Map6 :Land loss from erosion

Table 3: Classification of soil loss rates

Values	Classes	Area (ha)	Percentage (%)
0 - 10	Low	47,540.02	61.37
10 - 25	Way	9,880.47	12.76
25 - 50	Student	7,764.75	10.02
50 - 200	Very high	11,037.74	14.25
> 200	Critical	1,235.45	1.59

4.2.2. Distribution of soil losses according to the soil type

Ferralitic soils are more affected by soil water erosion with a rate of 58.62% than the two other types of soils listed in our study site. This statistic is normal because this type of soil occupies the majority of the watershed (Cf Map 2). Soils with eutrophic mulls show a rate of 29% of soil loss while Hydromorphic soils represent 12.26% (Cf Figure 2). Determining the most vulnerable soil type is difficult because these statistics are proportional to the area of the soil type.

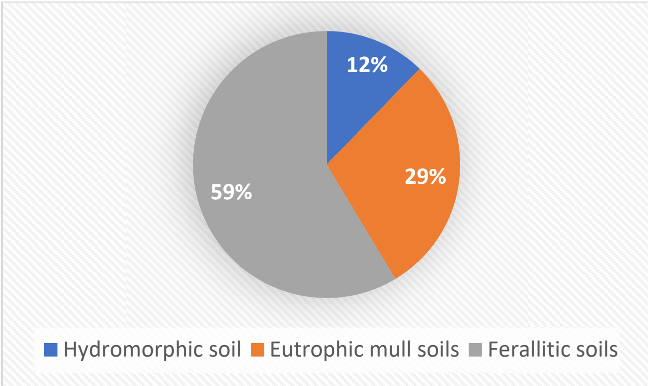
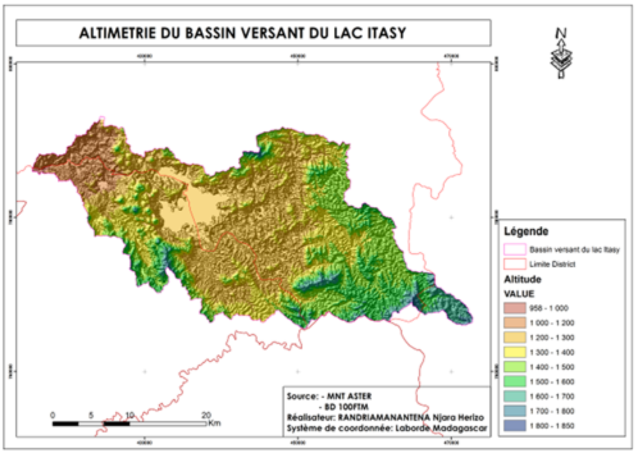


Figure 1 : Distribution of soil loss according to soil condition

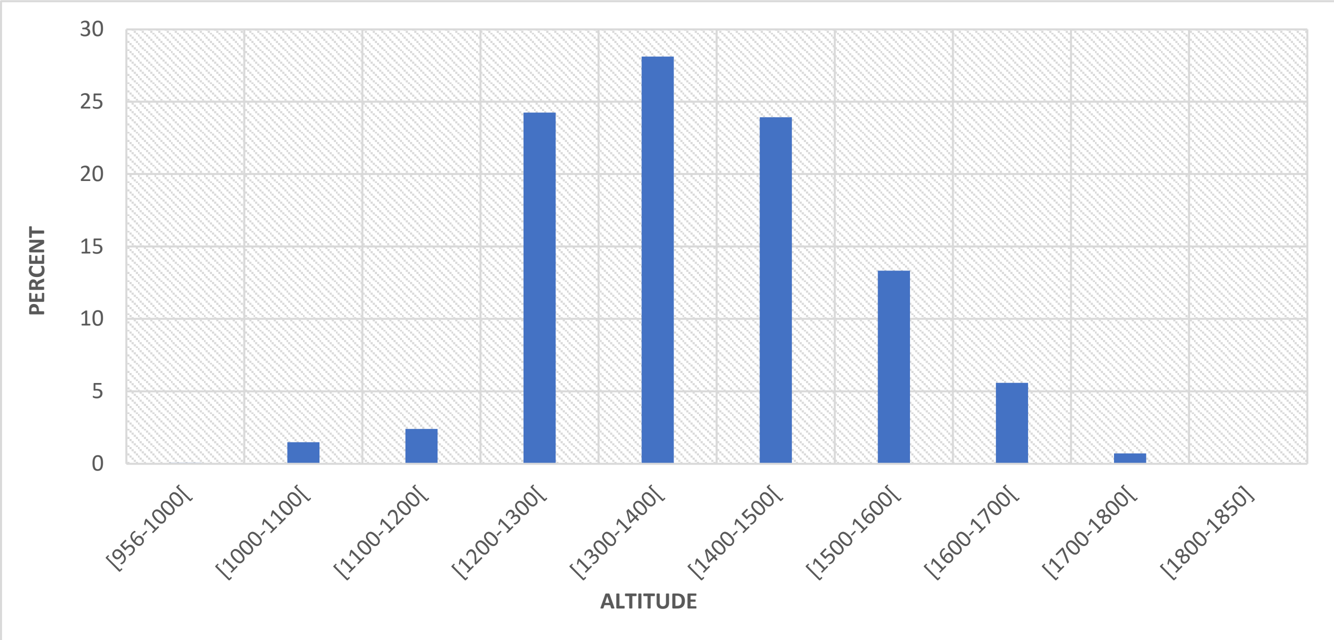
4.2.3. Distribution of land losses according to altitude

The altitudes in the Lake Itasy watershed varied from 950 m to 1850. In order to have a more efficient analysis, the altitudes were reclassified into 10 intervals (Cf Map 9). The analysis consists in determining which altitude interval is most subject to the high rates of soil losses due to water erosion.



Map7 : Altitude of Lake Itasy watershed

Since the trend in altitude in this watershed declines regularly from East to West, the graph shows that the areas with critical earth loss rates are mainly between altitude 1,200 meters and 1,600 meters, the peak of the general trend of which is in the range 1,300 - 1,400 meters with a statistic of 28.11%. This value is normal because this interval occupies the majority of the Lake Itasy watershed. These figures slowly decrease as you go up in altitude. These values are almost zero for altitudes above 1,750 meters. The proportions in altitudes below 1,200 meters are unimportant, since these zones are located almost near Lake Itasy and downstream from its watershed.



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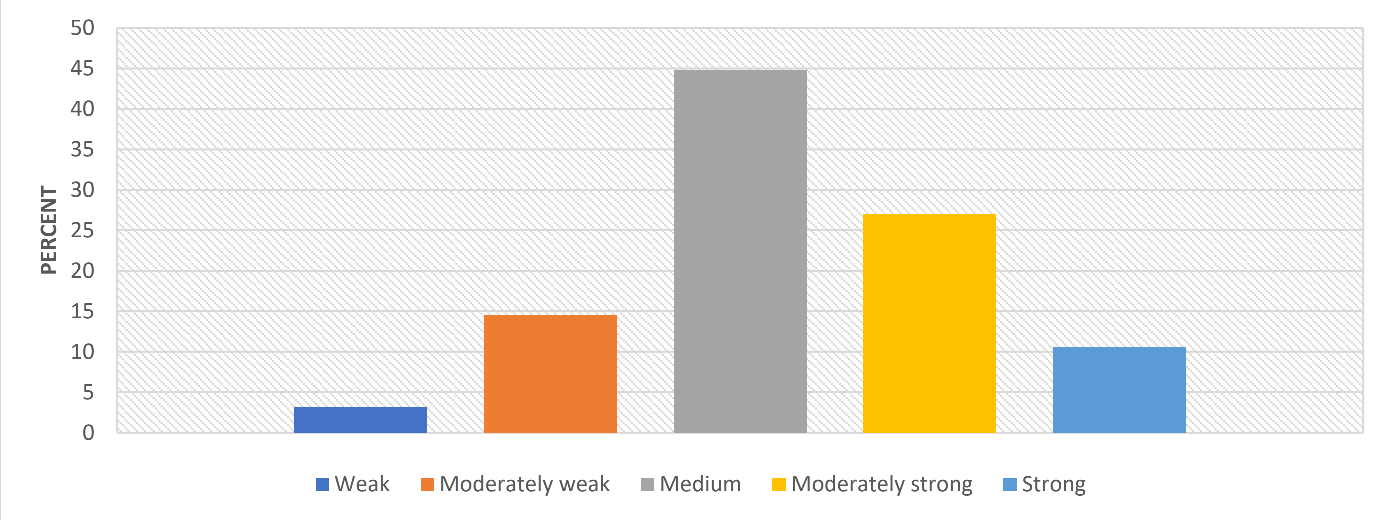
4.2.4. Distribution of land losses according to the slope

The slopes have been subdivided into five classes. The objective is to determine the slope class that most favors soil erosion.

The general trend shows that land with medium slopes is the most affected by the high rates of soil loss, representing a value of 44.75%. However, the terrain with moderately steep slopes and the terrain with moderately slight slope have experienced a significant loss of soil, they show the values 26.96% and 14.57% respectively. This statistic is reduced by going to the steep slope. Low-slope terrain is less susceptible to water erosion than other classes of slopes.

Based on this analysis, slope is among the most essential factors in erosion. This proves that the slopes support the gravity and kinetics of the agents that can lead to soil erosion.



4.2.5. Temporal analysis of water erosion

This research focuses on an annual observation to identify the period during which erosion is most aggressive during a year. Since rainfall is a decisive factor in runoff, our calculation is based on the average monthly values of rain erosion in the watershed.

The adopted method is the relation used to calculate the factor R more precisely the formula of Lo et al.

The results obtained are therefore based on the average monthly precipitation values recorded during the year 1970 to 2000. These values are represented in the following graph.

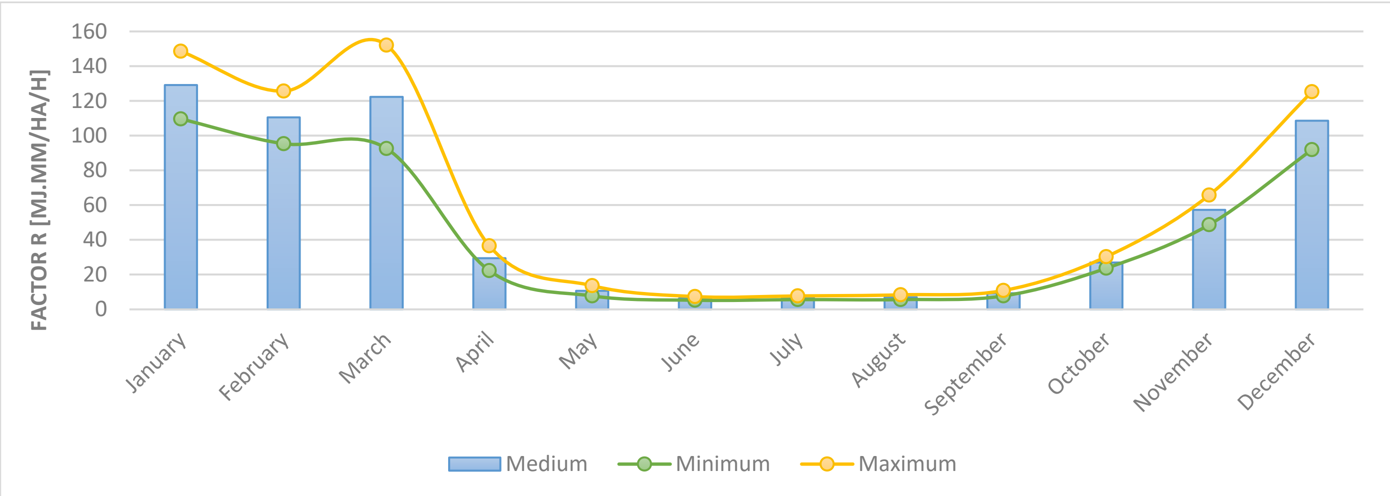


Figure 2 : Monthly erosiveness due to rain

This graph shows the monthly erosion result for the entire 1970-2000 period. This result is divided between two seasons including the rainy season from November to March and the wet season from May to September. The months of April and October showing almost equal values of 26.96 [MJ.mm/ha/h] and 26.92 [MJ.mm/ha/h] respectively in October. This is the interseason period.

The maximum value is determined in March (152.1 [MJ.mm/ha/h]), while the minimum value in July (5.23 [MJ.mm/ha/h]). However, it is important to note that the spatial distribution of rainfall in the watershed varies monthly.

4.3. Spatio-temporal assessment of the extent of Lake Itasy

Over a period of 46 years from 1973 to 2019, the results of the mapping of the area of Lake Itasy show a reduction of 268.10ha, or about 8.10% of its area in 1973. The northern, northwest and western areas of the lake are the most affected. (See Map 11). Table 4 summarizes this evolution of this lake.

Table 4 : Monitoring of the area of Lake Itasy from 1972 to 2019

Area [ha]	Difference [ha]	Regression%	Cumulative difference [ha]	Cumulative regression
3,396.50	0.00	0.00	0.00	0.00
3,265.60	130.90	3.85	130.90	3.85
3,210.70	54.90	1.68	185.80	5.54
3,207.20	3.50	0.11	189.30	5.64
3 128.40	78.80	2.46	268.10	8.10

The 1973 to 1986 period experienced the greatest upheaval with a 3.85% regression rate, while the 1998 - 2008 period experienced a more calm change. An increase in the regression of the lake is noted from 2008 to 2019. The curve below represents this situation.

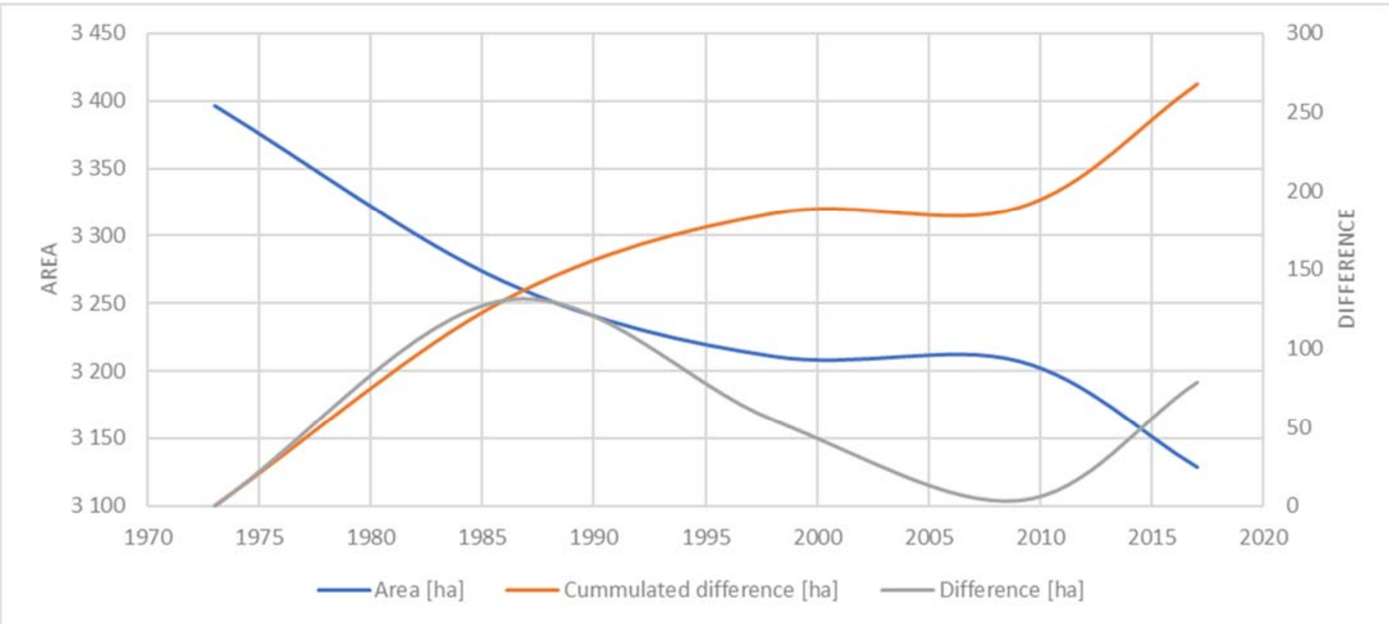


Figure 3 : Evolution of the area of Lake Itasy during the year 1973 to 2019

V. Discussions

5.1. Rate of soil loss A

This research is based on the analysis and quantification of water erosion in the watershed of Lake Itasy from the exploitation of the RUSLE model. The results are specialized in all areas of the Lake Itasy watershed. The limit of the results lies in the diversification of data used. Otherwise, the RUSLE model remains among the most efficient thanks to its universal adaptation and its simplicity.

Some data are no longer representative of current conditions. Once the soils are stripped, the modification of these soils is favored by the aggressiveness of the climate, the fragility of the soils and the rapid mineralization of organic matter; all these processes in action then lead to the acceleration of soil losses. Erosion phenomena increase once the soil is stripped and are accentuated in the case of discontinuous crops in the following years. It would therefore be interesting to have updated data on particle size according to the different types of land use. Regarding land use data, in view of the significant dynamics of deforestation.

However, this model only takes into account the geological formation of the terrain as well as the altitude. Despite this, these factors are used in the spatial analysis of the distribution of soil loss rates.

The results of the spatial factor analysis help us in decision making for soil management and the development of environmental action plans. A proposal for a development plan can be found in the Annex.

5.2. Multi date cartography of Lake Itasy

The evolution of the surface of the lake was obtained thanks to the vectorization of the satellite images of LandSat 1, LandSat 5 and LandSat 8. The extraction of the expanses of water body was carried out by two methods including SWIR and NDWI.

According to our research, that of Mcfeeters seems best suited for this study. The limit of this study is therefore mainly based on the methods adopted for the extraction of water surface areas and the spatial resolution of the available images. However, the results should only be slightly different.

VI. Conclusion

The objective of this study was to show the application of a widely distributed model, the RUSLE model integrating the technique provided by geomatics. Despite the heterogeneity of the data, it was possible to model soil erosion at the scale of the Lake Itasy watershed. The results obtained are rather aggressive because the average value of land loss is estimated at 28.5 tonnes per hectare per year over the entire basin. The effect of this scourge is significant, such as the decrease of approximately 8% in the area of Lake Itasy for only 46 years. The impact can be serious on the environment, especially on the Lake ecosystem.

The RUSLE model does not take into account other important factors. However, our results cross-checked with previous research results differ. It is therefore possible to establish from these management measures for the most fragile areas threatened by erosion.

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