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Modelling and quantification of soil water erosion using remote sensing in the Antanetibe Anativolo watershed

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Abstract

An erosion risk map is an essential tool against erosion. It makes it possible to have an overview of the problems and therefore to locate the sectors requiring priority intervention. The Antanetibe Anativolo watershed is a vast plain for rice cultivation, vast fields of food crops, and that even on the slopes of the hills surround it. Then, a region that supplies the capital with various agricultural products. For the sustainability of these activities given this potential and the presence of many lavakas that cut into the hills, the watershed was subject to a quantification of soil losses. The RUSLE model (Revised Universal Soil Loss Equation) was chosen in order to quantify and spatialize the water erosion processes at the catchment scale. A model widely implemented in the world, established at different scales and taking into account five determining parameters in the erosion process: the aggressiveness of precipitation, the erodibility of soils, the inclination and the length of the slope, the plant cover as well as the means put in place to fight against soil erosion. Three years are considered: 1990, 2006, 2022 to discern the evolution of erosion. The results show the average quantities of soil losses which are respectively 21,30 t/ha/year, 28,83 t/ha/year, and 43,08 t/ha/year.

Keywords: Antanetibe Anativolo, Remote sensing, RUSLE, Soil loss, Water erosion, Watershed.

1. Introduction

Erosion is a natural phenomenon as old as the earth itself, and few civilizations have not experienced it as a part of their development **[1]**. All regions of the globe are affected by soil erosion, a so-called "natural" phenomenon in the balance of the different elements of a given ecosystem. It is one of the main sources of soil degradation and a major global issue. Water erosion is the main cause of soil degradation. As a result of socio-economic changes and rainfall contrasts, the erosion hazard has become a major environmental problem threatening the sustainability of economic activities. Despite this, no estimate has been made of annual soil losses in Antanetibe, a highly productive agricultural commune in the Anjozorobe District, which supplies the capital Antananarivo with its produce, but which shows alarming indicators of soil erosion: bare hills and steep slopes.

This study evaluates soil losses using the derived version of the Universal Soil Loss Equation (USLE/RUSLE) by Wischmeier and Smith **[2]**. This equation remains the world's most widely used water erosion prediction model **[3]**. RUSLE is the combination of six specific factors that describe the characteristics of the Antanetibe watershed. Multi-temporal remote sensing data and GIS are used to assess and map each factor individually. Integration of the RUSLE model's thematic factor maps into the GIS enables the impact of each factor on soil losses to be identified, erosion zones to be ranked by relative importance, and soil losses in the basin to be quantified. Its integration into the Geographic Information System (ArcGIS) facilitates the combination of layers bearing the six factors, the estimation of the impact of each factor and the classification of soil losses per unit area.

2. Methodology

2. 1 Presentation of the study area

Administratively, the Antanetibe Anativolo watershed is located on the borders of five Districts: Antananarivo Avaradrano, Manjakandriana, Anjozorobe, Ankazobe and Ambohidratrimo of the Analamanga Region. The basin is drained by two rivers, Amparihibe and Jabo, which join at their outlets to form the Betsiboka River. The basin covers an area of 1482.66 Km^2, with an altitude distribution ranging from 923 to 1,688 m.

Climatically, the basin enjoys a high-altitude tropical climate, characterized mainly by cool winters. The average temperature is 19°C, with an average maximum of 24.8°C and a maximum of 28.3°C in December, and an average minimum of 14.2°C and a minimum of 10.7°C in July. Precipitation ranges from 900 to 1,500 mm.

Pedologically, the study area is dominated, especially at higher altitudes, by moderately desaturated ferralitic soils rejuvenated or penetrated, eroded and reworked red on gneiss-migmatite and typical weakly desaturated ferralitic soils yellow or red on granite. Low-lying areas are characterized by clay alluvium **[4]**, **[5]**, **[6]**.

A digital terrain model or elevation distribution map of the entire area is shown in Figure 1, which also presents the study area. From the south to the center of the region, in the east and west, there are high-altitude zones overlooking the highly fertile Antanetibe plain, which extends across the entire northern part.

2. 2 Model description

The water erosion model by RUSLE used several natural and anthropogenic elements and parameters, which control runoff in the Antanetibe basin, to determine the soil loss rate (A in t/ha/yr) by multiplying the five factors as follows:

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

A = soil loss rate (t/ha/an),

R = rainfall erosivity (MJ.mm/ ha.h.an),

K = soil erodibility (t.h/ha. MJ.mm),

LS = topographical factor (L in m, S in %),

C = plant cover,

P = agricultural activities and practices and anti-erosion projects.

To this end, satellite data (vegetation cover, land use and occupancy), lithology data, terrain morphology and climatic data will be cross-referenced in a Geographic Information System using ArcGIS software. Figure 2 shows the flow chart for this method.

2. 3 Factor (R): Aggressiveness of precipitation

The R factor expressed the capacity of rainfall to erode. Rainfall intensity and energy are among the factors that generate land loss **[7]**. To determine the R-factor, Nguyen **[8]** suggested a method of measuring the R-factor based on annual rainfall by analyzing 54 years of rainfall data from 253 weather stations around the world.

$$R = 0{,}548257 * P - 59{,}9 \quad (2)$$

- **R:** aggressive rainfall;
- **P**: annual precipitation in mm;

The calculation of the R factor is based on annual rainfall data from 13 stations in the study area, covering periods of 45 years (1950-1990), 15 years (1991-2006) and 15 years (2007-2022) respectively. These rainfall data are downloaded into Google Earth Engine, from ECMWF (European Centre for Medium-Range Weather Forecasts) of ERA5-LAND. ERA5 is the fifth generation of ECMWF's global atmospheric climate reanalysis, covering the period from January 1940 to the present day. ERA5 is produced by ECMWF's Copernicus Climate Change Service (C3S). ERA5 provides hourly estimates of a large number of atmospheric, terrestrial and oceanic climate variables. The data covers the Earth on a 30 km grid and resolves the atmosphere using 137 levels, from the surface to a height of 80 km. ERA5 includes uncertainty information for all variables at reduced spatial and temporal resolutions **[9]**, **[10]**. Similarly, the spatial interpolation of R was performed by the IDW method using ArcGIS software.

2. 4 Factor (K): Soil erodibility

Erodibility is the soil's resistance to erosion. It is a function of soil constituents and structure. Texture is the main component of K, but structure, organic matter and permeability also play a part. To estimate the K factor, we used data from FAO's Harmonized World Soil Database (HWSD) **[11]**. This is a database that includes all the granulometric parameters of soils namely, organic carbon percentage, pH, water storage capacity, salinity percentage, texture class ... The FAO data were calculated with the Williams (1995) equation as follows **[12]**.

$$K = f_{csand} * f_{cl-si} * f_{orgC} * f_{hisand} \tag{3}$$

avec

$$f_{csand} = \left(0.2 + 0.3 * e^{\left(-0.256 * m_s * \left(1 - \frac{m_{silt}}{100}\right)\right)}\right) \tag{4}$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_{silt} + m_C}\right)^{0.3} \tag{5}$$

$$f_{orgC} = \left(1 - \frac{0.0256 * orgC}{orgC + e^{(3.72 - 2.95 * orgC)}}\right) \tag{6}$$

$$f_{hisand} = \left[1 - \frac{0.7 * \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + e^{\left[-5.51 + 22.9 * \left(1 - \frac{m_s}{100}\right)\right]}}\right] \tag{7}$$

m_s: sand content (%), m_{silt}:silt content (%), m_C:clay content (%), $orgC$:carbon content (%)

2. 5 Factor (LS): Topographical factor

The topographical factor (LS) is the length and inclination of slopes that affect sediment production and transport in space. If the slope is steeper, the more runoff water will degrade the soil **[13]**. To determine the LS factor, this work prefers the ALOS PALSAR digital terrain model, characterized by a spatial resolution of 12,5 m. The following formulas were deployed to determine this factor:

$$L_{(i,j)} = \frac{\left(A_{(i,j)} + D^2\right)^{(m+1)} - A_{(i,j)}^{(m+1)}}{x_{(i,j)}^{m} * D^{(m+2)} * 22.13^m} \tag{8}$$

$$avec \quad m = \frac{\beta}{1 + \beta} \tag{9}$$

$$et \quad \beta = \frac{\frac{Sin\theta}{0.0896}}{3 * (Sin\theta)^{0.8} + 0.56} \tag{10}$$

$$S = \begin{cases} 10.8 * Sin\theta_{(i,j)} + 0.03\,, & tan\theta_{(i,j)} < 9\% \\ 16.8 * Sin\theta_{(i,j)} - 0.5\,, & tan\theta_{(i,j)} \geq 9\% \end{cases} \tag{11}$$

$L_{(i,j)}$: slope length, $A_{(i,j)}$: flow accumulation

D : cell size, x : coefficient equal to 1

S : slope inclination (%), $\theta_{(i,j)}$: slope angle in degrees

2. 6 Factor (C): Vegetation cover index

Several research studied have focused on the effects of vegetation cover on soil erosion mitigation, showing that it is a factor of prime importance in reducing this risk **[14]**, more specifically, natural vegetation which plays an anti-erosion role **[15]**. Raindrops can loosen soil particles on surfaces not protected by vegetation cover and initiate their transport to large watercourse. To determine the C factor, satellite images, Landsat Thematic Mapper "Image courtesy of the U.S. Geological Survey" dated May 25, 1990 for the 1990 image, May 21, 2006 for the 2006 image and Landsat OLI image dated on June 02, 2022 for the 2022 image, are used to calculate the normalized difference vegetation index (NDVI). The formula is as follows:

$$C = \frac{1 - NDVI}{2} \quad (12)$$

2. 7 Factor (P): Anti-erosion factor

This factor concerns the anti-erosion farming projects and practices that exist in the Antanetibe Anativolo basin, such as contour ploughing, alternating strip or terrace cultivation, ridging or contour ridging **[16]**. These are all effective practices for soil conservation and for reducing the intensity of runoff and erosion. The map for factor (P) was drawn up by analyzing the same images as the previous factor. Table 1(*below*) presents this factor.

3. Results

3. 1. Erosivity factor « R »

To obtain this parameter, we adopted the formula of Nguyen (1996). The spatial distribution of precipitation (mean annual rainfall) over the basin is shown in Figure 3, below. An increase in the average rainfall value (from 2007 to 2022) can be seen for the year 2022. It ranges from 1185 to 1453 mm, whereas for 1990 and 2006, precipitation oscillates between 1134 and 1371 mm and 1073 and 1352 mm respectively.

Figure 4 shows the erosivity factor results for 1990, 2006 and 2022, from left to right. It shows that for 1990, the "R" factor varies from 560 MJ.mm/ha.h.yr downstream to 690 MJ.mm/ha.h.yr upstream and in some western parts of the basin.

The spatial distribution of this factor for 2006 changes as follows: the minimum value of around 530 MJ.mm/ha.h.y is distributed between the northern and eastern parts of the basin, while the maximum value of around 680 MJ.mm/ha.h.y is observed in the western part of the basin. The same applies to 2022, with an increase from 590 to 740 MJ.mm/ha.h.yr. Given the formula used to determine this factor, this increase is due to the rise in precipitation.

3. 2. Soil erodibility « K »

The value of K ranges from 0.18 to 0.31 according to the FAO classification. The spatial distribution of this factor is shown in Figure 6. It can be deduced that highly erodible soils occupy only a few areas (around 1%) of the basin characterized by reddish-brown to yellowish-red weakly desaturated ferralitic soils, while over 43% of the basin is characterized by erodible soils, corresponding to weakly desaturated ferralitic soils, typically beige on charnockites. The hydromorphic soils that spread out and cover the Commune Antanetibe Anativolo valley have a low K value.

3. 3. The « LS » topographical factor

The LS factor shows the importance of slope inclination and slope length in sheet and gully erosion processes. It therefore depends on the variation in basin topography. The steeper the slope, the more significant the value. It ranges from less than 1 to more than 7. Figure 8 shows the spatial distribution of this factor. We can conclude that low slopes occupy 25% of the basin with LS<2, 61% for medium slope (2<LS<5) and 14% for steep slopes (5<LS). This last could generate the abundance of soil loss.

3. 4. « C » factor: vegetation cover index

As shown in Figure 9, the value of this parameter varies from year to year. This explains the changes in land use in the basin. In 1990, the cover index ranged from 0.045 to 0.83. 9% of the basin's surface area is covered either by degraded forest, gallery forest or reforestation in more or less extensive. Bare land and water bodies, characterized by a high C value of over 0.33, occupy 27% of the basin. The remainder is grassy savannah with bare soil. In 2006, this index ranged from 0.26 to 0.58. As before, the area covered by vegetation is only 7% of the basin. We can therefore see that deforestation and/or land clearing occurred between these two years. The latter could be due to bush fires or anthropogenic activities (charcoal production, timber harvesting, etc.).

As a result, the bare surface area increases to 36% of the basin, and is distributed over the center of the basin. In 2021, the C factor varies from 0.31 to 0.71, of which 8% of the basin is covered by vegetation, the result of the fact that there could be reforestation, and 30% is occupied by bare land and the rest by savannah

3. 5. Anti-erosion factor, « P »

The P factor takes into account existing management techniques at Antanetibe when estimating soil losses, since each anti-erosion measure has an impact on soil degradation processes whose coefficient is established according to its effectiveness in reducing or mitigating water erosion (Ouadjane et al., 2021). In other words, the impact of anti-erosion practices makes it possible to minimize the action of runoff by modifying its direction and reducing the inclination and length of the slope and, consequently, limit the ablation and transport of soil particles (El Hage Hassan et al., 2018). The result obtained showed that the areas that did not benefit from any intervention, have a surface area, respectively of 82.67%, 85.84%, and 81.04% of the Antanetibe Anativolo basin for the years 1990, 2006, 2022. Given this lack of anti-erosion development in the basin, the value 1 represents the absence of anti-erosion interventions and projects. This factor is shown in Figure 10.

3. 6. Estimated soil losses

As shown in Figure 11, soil losses in the basin are grouped into 5 classes. Areas with low slopes have a low erosion rate. In 1990, this ranged from 0 to over 300 t/ha/year. Significant or very significant erosion covers 6.28% of the Antanetibe basin, with values in excess of 250 t/ha/year. This class is concentrated in the center of the basin, on the northern and north-western edges of the basin and in the mountainous area near the chief town of Antanetibe Commune. This area is nearly bare.

Heavy erosion covers 24.26% of the basin surface. It can be observed on the left bank of the Amparihibe river and in some parts west of Sadabe. The tonnage of erosion varies from 150 to 250 t/ha/year. This is an area covered by savannas, but dominated by savannas with bare soils. The upstream part of the basin, from Sadabe to Talata Volonondry, shows average erosion ranging from 50 to 150 t/ha/year. It is spread over 45.58% of the basin. Although rainfall erosion is abundant in this area, the amount of soil loss remains average. As a result, this is an area of degraded forest and/or more or less extensive reforestation.

The low-erosion zone, with values ranging from 2 to 50 t/ha/year, is found in the south-western part of the basin and around Ambohitsinjorano. This is a gently sloping area covering 22.9% of the basin. Very low erosion is spread over an area of less than 1% of the basin. It can be observed in all the low-lying areas of the basin, which are presumed to be silting zones. Soil loss tonnage in these areas is less than 2 t/ha/year. The soil loss classification for the other two years is the same as above. We can see that the surface area occupied by the different erosion risk classes varies from one year to the next. For the year 2006, the most abundant erosion is spread over

16.31% of the basin, while for the year 2022, it covers up to 33.03% of the basin. The heavy erosion of 2006 is spread over 32.78% of the basin, while for 2022 it is only 27.06%. Next, for the third- or medium-class erosive risk, the area covered in 2006 is 36.34%, while in 2022 it will be 25.11%. The low erosion class covers 13.53% of the basin in 2006, falling to 14.11% by 2022. The area occupied by very low erosion in 2006 is around 1%, and less than that in 2022.

4. Discussion

Implementation of the universal soil loss equation using a Geographic Information System has enabled a quantitative assessment of eroded areas in the Antanetibe Anativolo watershed. The effect of the erosion process is remarkable on bare slopes. An increase in the amount of rain falling in the basin amplifies the risk of erosion. This increase is also caused by deforestation and forest clearance. In addition, on hills and steep slopes, with the two criteria mentioned above, the rate of erosion is high. Downstream of the basin, the landscape is based on thick alluvial formations, generally covered by irrigated crops. The land is flat with gentle slopes. The superposition of these characteristics means that this area is considered to be at low risk of erosion, as it receives sediments and alluvial formations from upstream in the basin. Finally, the amount of water erosion in this basin increases from year to year.

Rigorous validation requires the matching of erosion measurements obtained in the field with model estimates. However, few erosion measurements have been carried out in the Antanetibe Anativolo watershed. A study by Rakotomamonjy T. E., in 2016, shows that soil loss in the Avaratrambolo Fokontany, which makes up this watershed, averages 30t/ha/year **[17]**.

Therefore, taking into account all the parameters considered above, it is recommended to reforest the entire basin, especially the erosion-sensitive parts, in order to mitigate the risk at basin level. In addition, where technically possible, ploughing should be carried out perpendicular to the slope. The latter would slow down the runoff phenomenon by preventing the formation of preferential paths for water accumulation. Earthworks are concrete proof of the effectiveness of this type of ploughing.

5. Conclusion

The aim of this study was to estimate water erosion by applying the GIS/RUSLE approach in the Antanetibe Anativolo watershed. This made it possible to map the various erosion factors, such as rainfall aggressiveness, soil erodibility, the topographical factor, the vegetation cover index and the agricultural practices implemented by a heavily farming population. Superimposing these factors gives average erosion rates of 21,30 t/ha/yr, 28,83 t/ha/yr and 43,08 t/ha/yr respectively for the years 1990, 2006 and 2022. The water erosion map of the Antanetibe Anativolo watershed is a decision-making tool for good community water management and soil conservation practices.

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7. Tables

Table 1 : The P factor according to land use and corresponding slope

Land use	Slope (%)	P Factor
Agricultural land	0-5	0.10
	5-10	0.12
	10-20	0.14
	20-30	0.19
	30-50	0.25
	50-100	0.33
Other land	All	1

(Source: *Wischmeier and Smith, 1978*)

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8. **Figures**

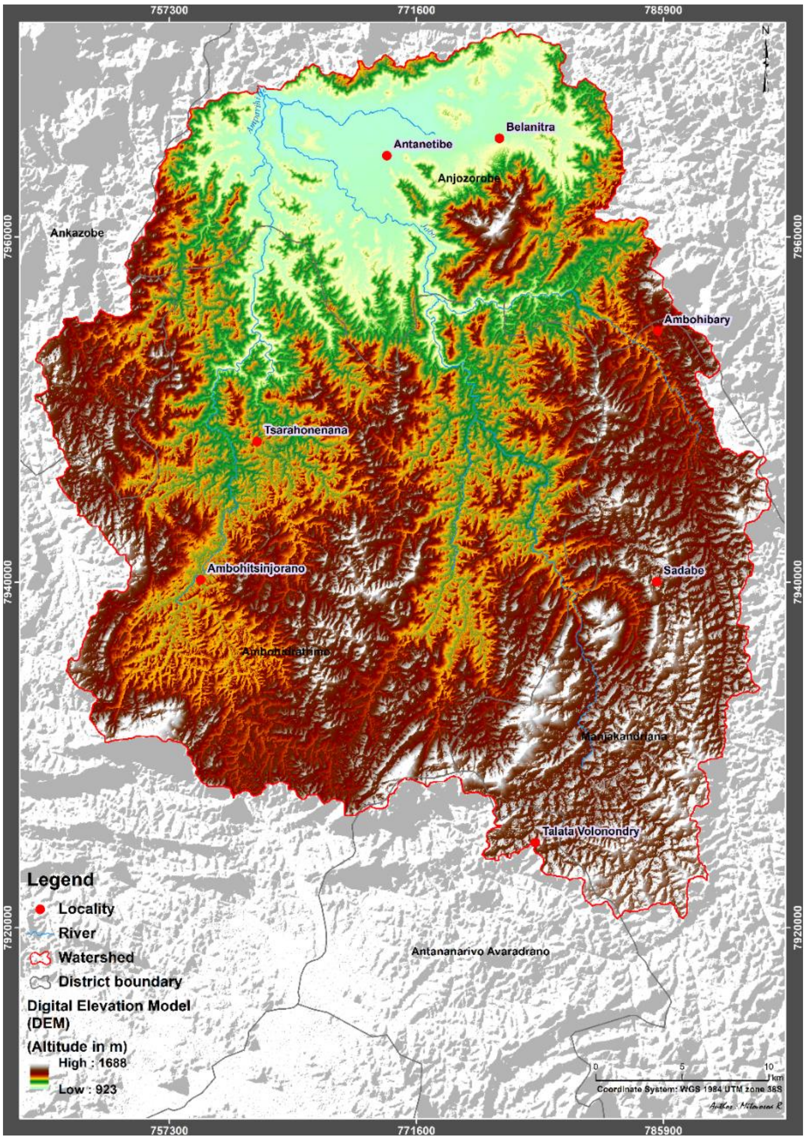

Figure 1 : Localization of the Antanetibe Anativolo Watershed

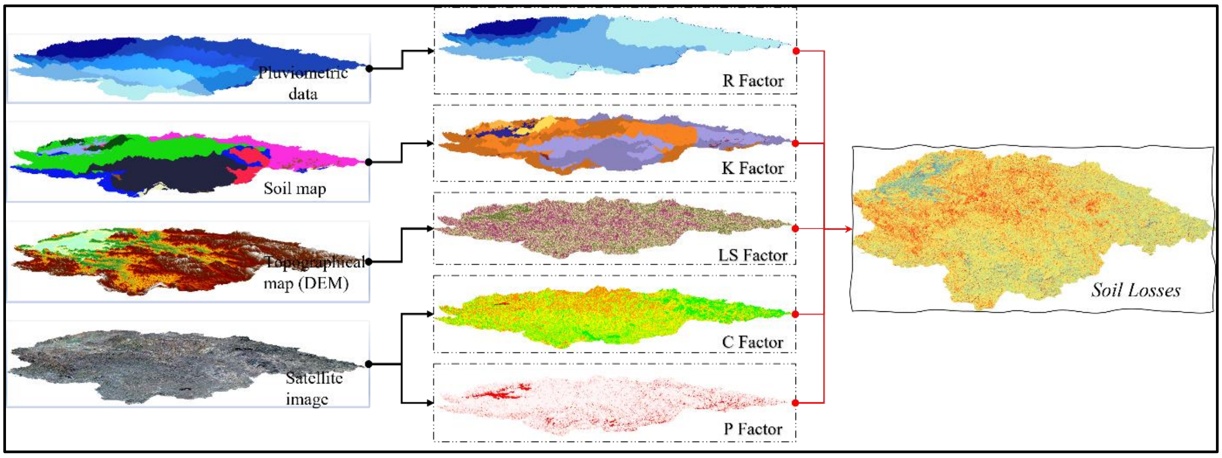

Figure 2 : Methodology

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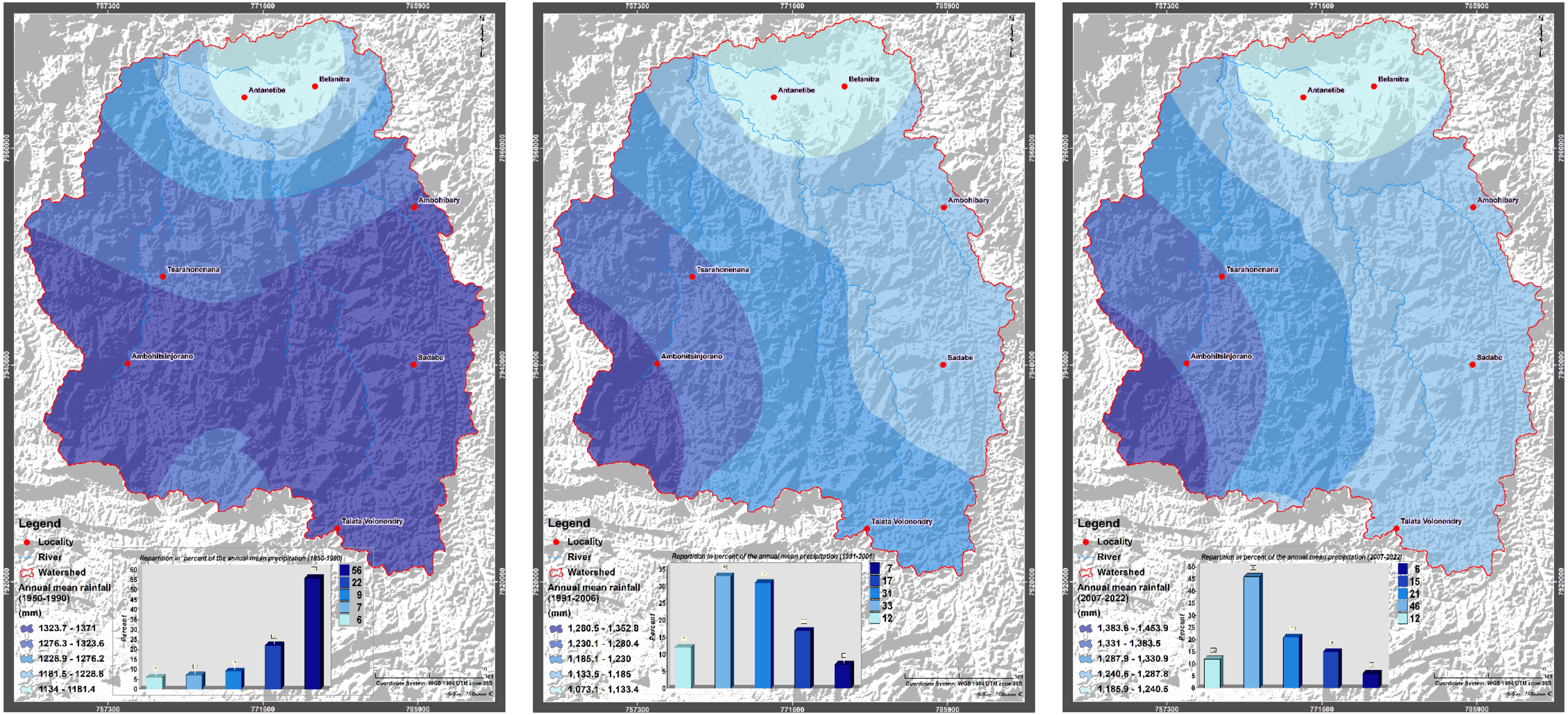
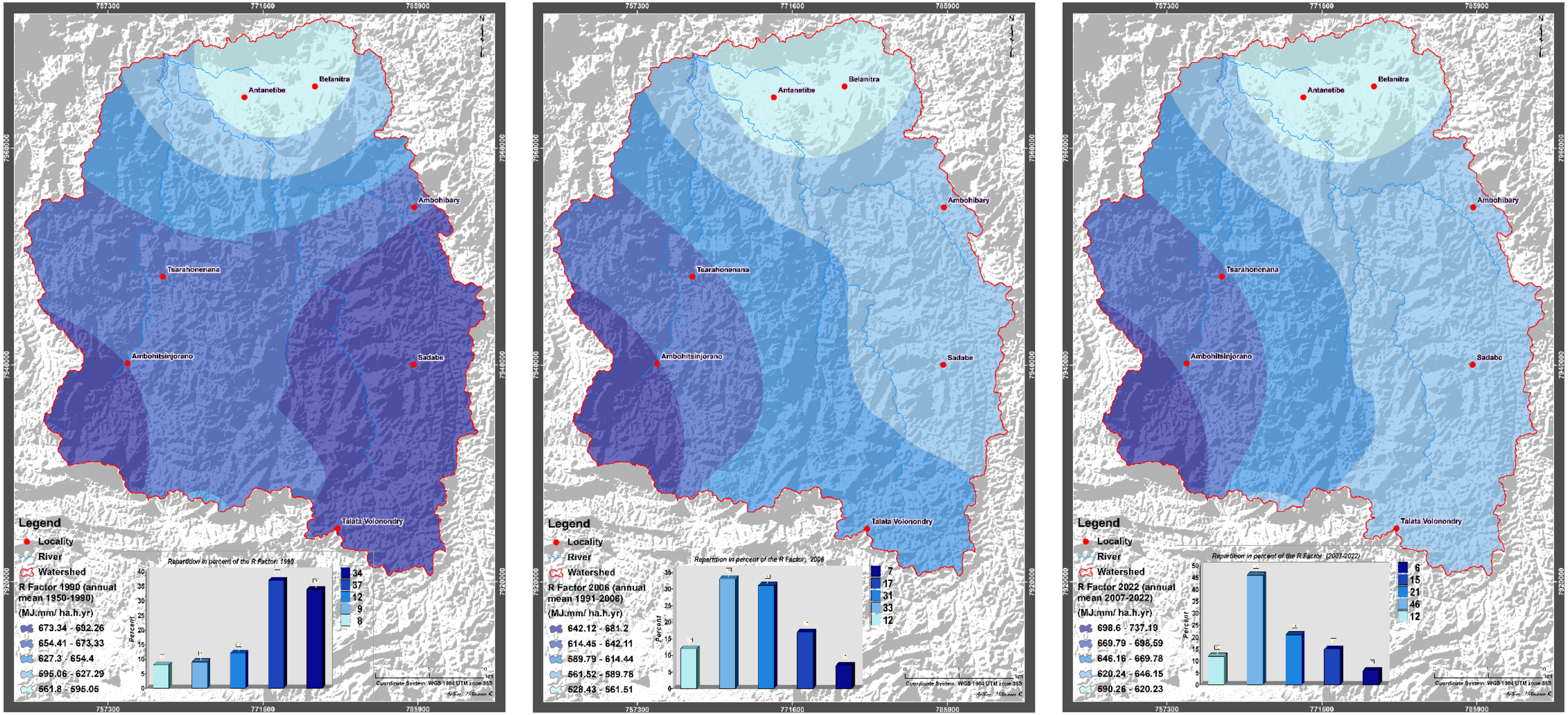


(a) (b) (c)

Figure 3 : Interannual mean precipitation: (a): 1950-1990, (b): 1991-2006, (c):2007- 2022



(a) (b) (c)

Figure 4 : Erosivity factor « R »: (a): 1990, (b): 2006, (c): 2022

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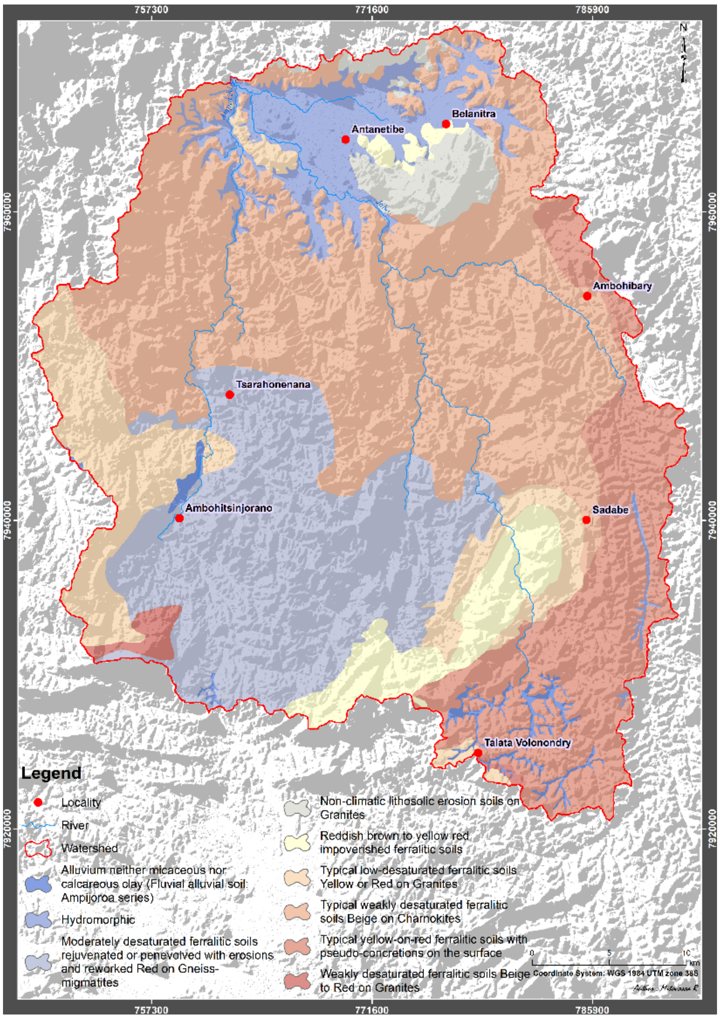

Figure 5 : Soil map

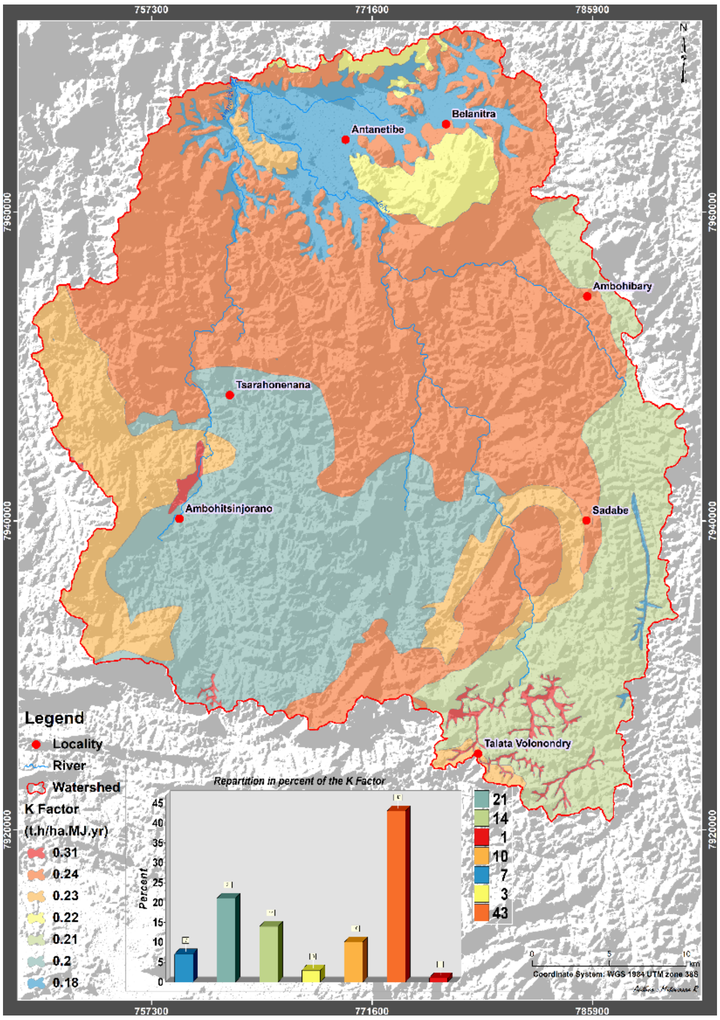

Figure 6 : « K » Factor

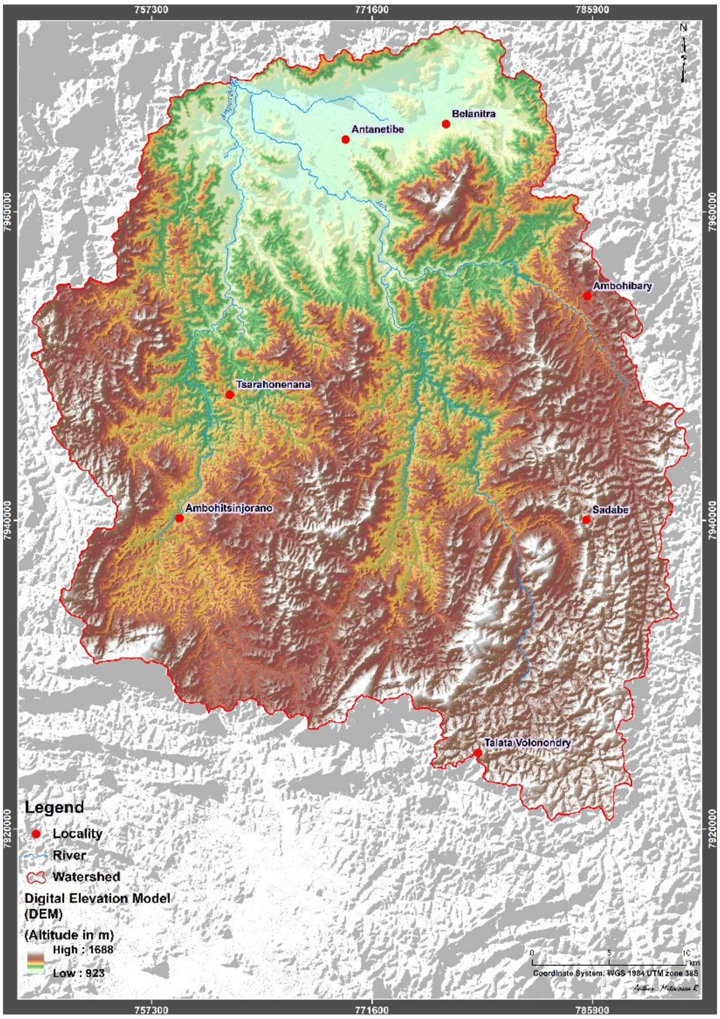

Figure 7 : Digital Elevation Model of the Antanetibe Anativolo Watershed

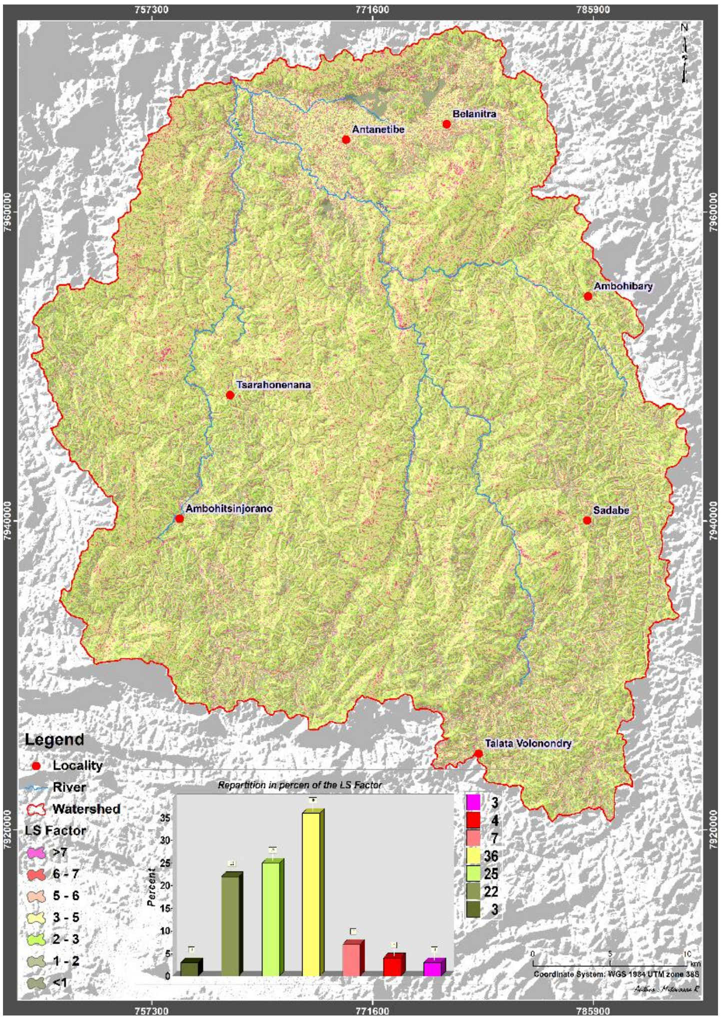

Figure 8 : Topographical factor, « LS »

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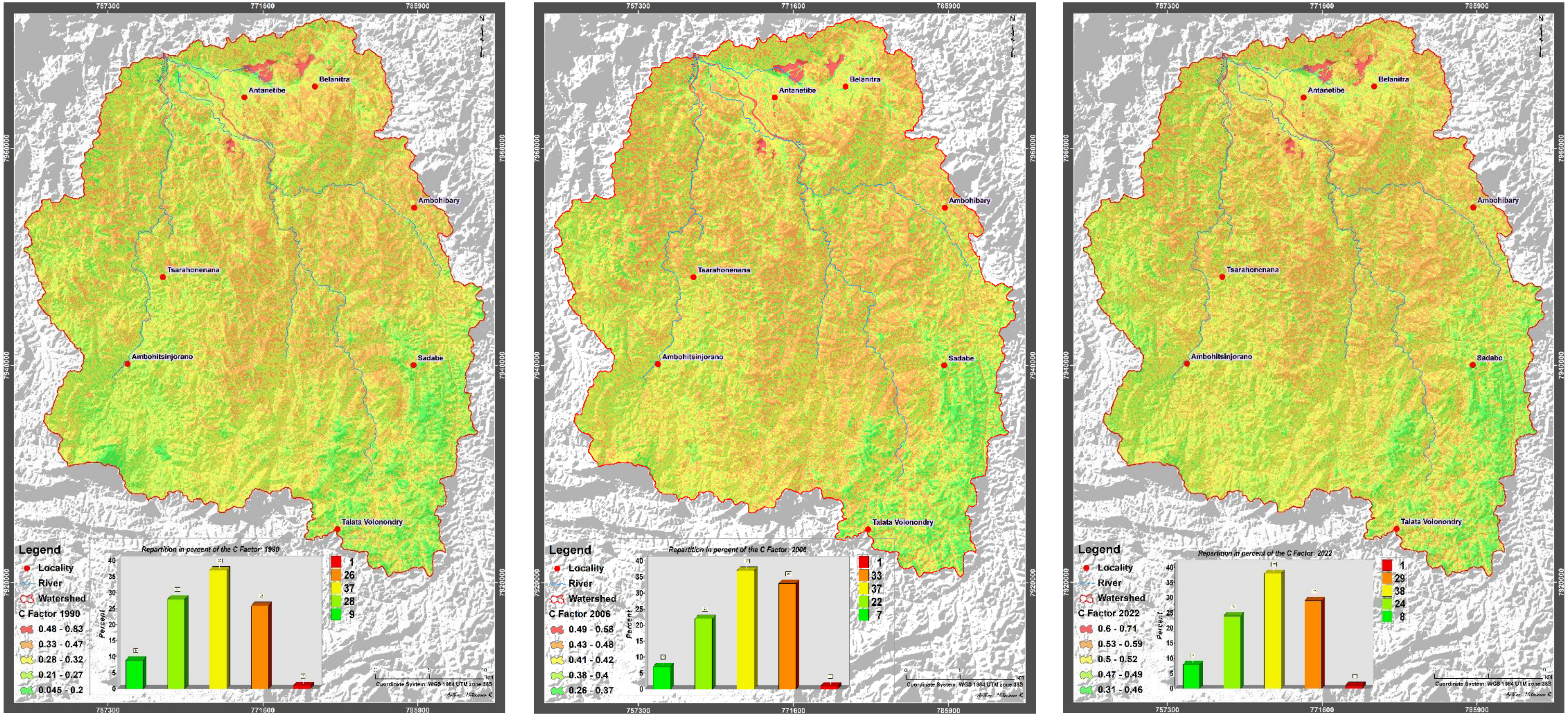

(a) (b) (c)

Figure 9 : « C » factor, vegetation cover index, (a): 1990, (b): 2006, (c): 2022

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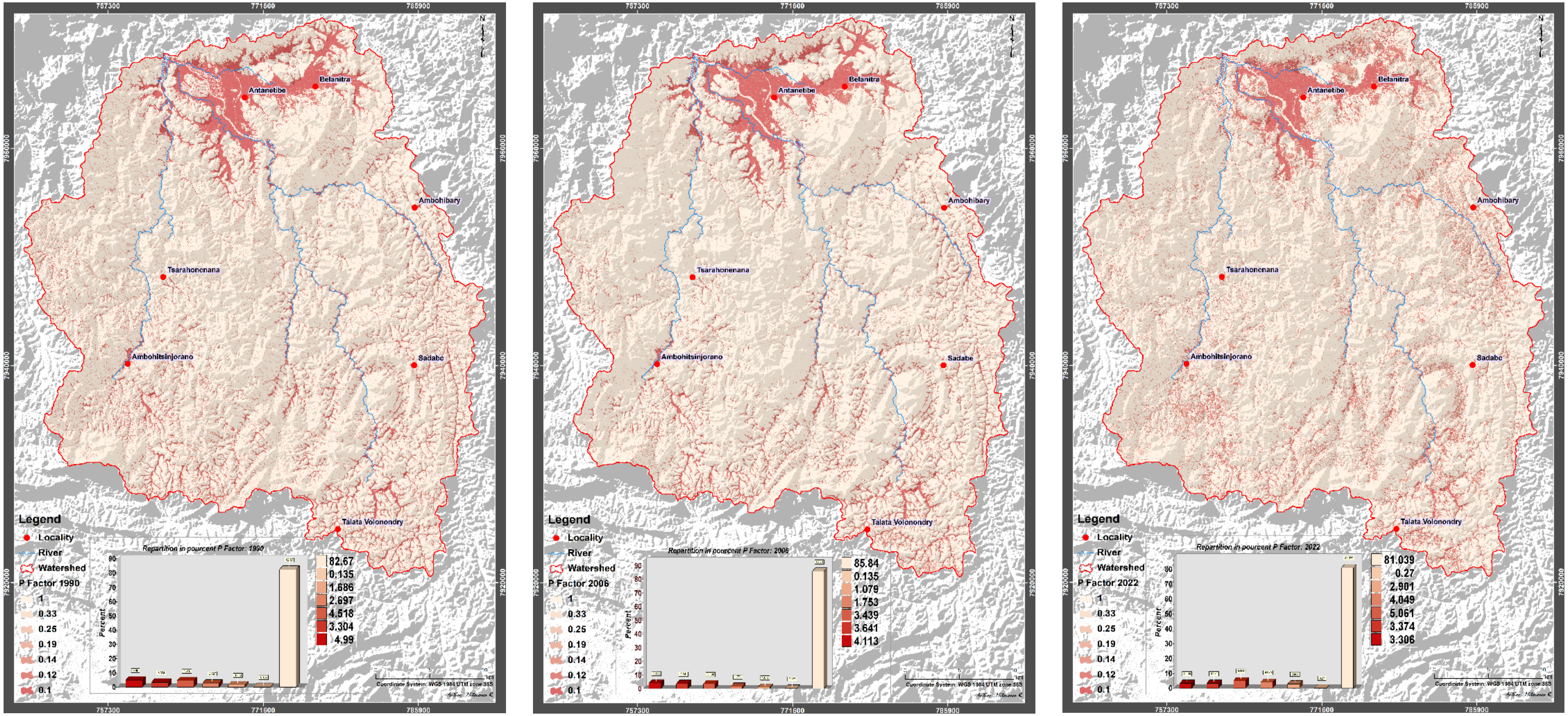
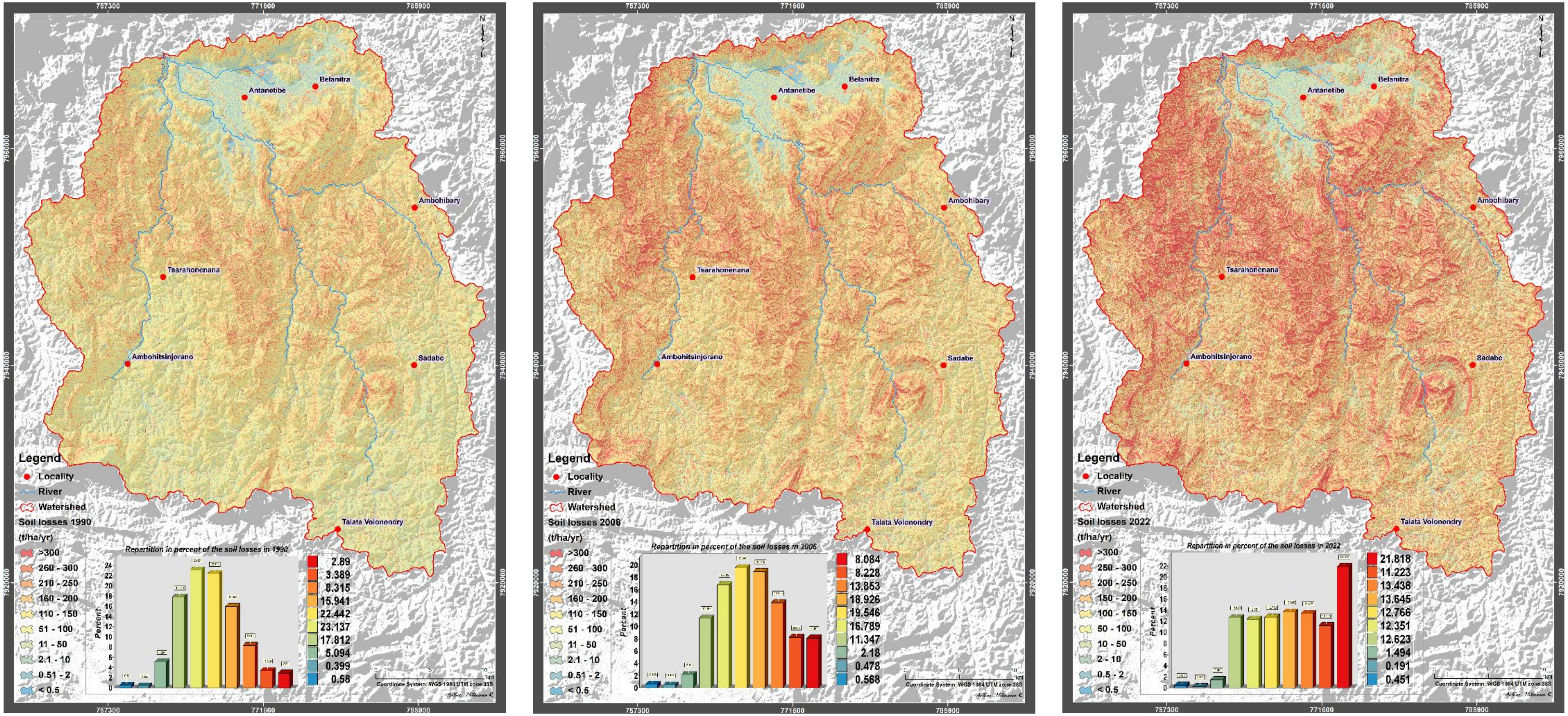


(a) (b) (c)

Figure 10 : Anti-erosion factor, « P », (a): 1990, (b): 2006, (c): 2022



(a) (b) (c)

Figure 11 : Soil losses in the Antanetibe Anativolo watershed: (a): 1990, (b): 2006, (c): 2022