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Assessing the importance of hypsometry for catchment soil erosion: A case study of the Yanze watershed, Rwanda

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Abstract

Implementing a watershed erosion control programme requires resource-intensive and time-consuming preliminary studies to prioritize such interventions and to focus on those sub-catchments where they are most likely to yield the most effective results.

In this study, we explore and document the effectiveness of using hypsometric analysis as a method to prioritize erosion control measures and apply it to the Yanze watershed located in central Rwanda.

Based on a 30m-resolution DEM of the watershed and using ArcGIS and R software, we made estimates of hypsometric integral values and calculated soil loss estimates through RUSLE modelling and by using data from different sources, namely the Rwanda Meteorological Agency (rainfall data), ISRIC (soil data), and Sentinel-2 images (land cover maps).

The hypsometric integral values of the Yanze sub-catchments were high, ranging from 0.5 to 0.936. This, combined with the overall convex upward hypsometric curves, indicates that the Yanze watershed is still at a youthful stage in its erosional cycle.

The results of the RUSLE model showed that the average potential soil loss in the Yanze watershed is 55.63 tonnes.ha^{-1}.year^{-1}, which is comparable to the national average estimated at 62 tonnes.ha^{-1}.year^{-1}.

The correlation analysis that we conducted between the hypsometric integral values of the Yanze sub-catchments and their respective mean soil loss values revealed no correlation between the two variables. From the results of this study, we conclude that in watersheds where lithology affects soil erosion significantly, morphology can indeed indicate the potential for erosion. However, we further concluded that future studies to characterize erosion potential using morphometry should employ additional morphometric parameters in the regression model.

Keywords: *Hypsometric analysis, Morphometry, RUSLE, GIS, watershed management, soil erosion, Rwanda, Yanze*

1. Introduction

Soil erosion as part of the larger problem of land degradation constitutes one of the most serious environmental issues the world is facing today. As soil constitutes the basis of all terrestrial ecosystems, a degraded soil means lower fertility, reduced biodiversity, and human poverty.

The main challenge for conducting effective erosion control is that the available resources are invariably limited compared to what is needed to maintain a long-term, catchment-wide, and integrated watershed management programme within the watershed.

In order to ensure that the available resources are used efficiently, a prioritization mechanism is required to ensure that the activities undertaken as part of such a programme are spatially focused on areas where they could have the greatest impact and be long lasting. This requires a detailed assessment of the watershed for the identification of hotspots and the prioritization of intervention activities, a process that is normally conducted following a Multi-Criteria Decision Analysis (MCDA) framework, where tools such as the Analytical Hierarchy Process (AHP) are used (Chowdary *et al.*, 2013; Kulimushi *et al.*, 2021). During this process, soil erosion modelling, the first step in assessing those areas most prone to erosion, and the Universal Soil Loss Equation (USLE), the most popular model used in various studies across the country (Karamage, Zhang, *et al.*, 2016; Byizigiro *et al.*, 2020; Niyonsenga, Mugabowindekwe and Mupenzi, 2020), are applied.

In watersheds, where the influence of lithology on soil erosion is significant, morphometry can be used as a proxy indicator of erosion potential. Morphometry is defined as a formal or mathematical analysis of the configuration of the earth's surface and the shape and dimensions of its landforms (Altaf, Meraj and Romshoo, 2013). Hypsometric analysis (area-elevation analysis) is a branch of morphometry that deals with elevation distribution across an area of land, and given that it allows the researcher to quantitatively express the overall slope of a catchment, is useful when studying erosion processes in an area.

The two most considered metrics during hypsometric analysis are the "Hypsometric or Hypsographic Curve" (area-altitude curve) and the "Hypsometric Integral". The former is a graph that shows the proportion of the surface area of the earth at various elevations by plotting relative area against relative elevation. The latter is the area beneath the hypsometric curve whose value varies from 0 to 1(Sharma *et al.*, 2018). In terms of its interpretation, given a hypothetical Hypsometric Integral of 0.35, for example, this would mean that only 35 per cent of the land masses in that basin would remain susceptible to erosion.

The hypsometric integral is important for estimating the erosional status of the watershed, and helps to prioritize watersheds for making proposals in respect of soil and water conservation activities (Sharma and Mahajan, 2020). It also provides a simple morphological index that can be used in surface runoff and sediment yield predictions concerning watersheds (Sharma *et al.*, 2018; Sharma and Mahajan, 2020).

Many studies have already explored the use of morphometry and hypsometric analysis to prioritize soil erosion control interventions in a watershed (Singh, Sarangi and Sharma, 2008; Chowdary *et al.*, 2013; Choudhari *et al.*, 2018; Sharma and Mahajan, 2020). In Rwanda, only one study(Kulimushi *et al.*, 2021) has attempted to conduct a soil erosion prioritization process for a watershed where morphometry has been used; however, many additional indices and processes have also been applied and therefore the methodology followed in that study cannot be considered adequate in terms of its simplicity and cost-efficiency as a quick prioritization method in a resource-restrained environment.

This study conducted a hypsometric analysis of the Yanze watershed and estimated soil loss in that same watershed. It then explored the correlation between the hypsometric integral values of the Yanze sub-catchments and their respective mean soil loss values to establish whether hypsometric analysis can be used as a proxy for watershed prioritization in these sub-catchments.

2. Materials and Methods

2.1. Study Area

Yanze is a relatively small watershed located north-west of the City of Kigali, Rwanda. It straddles three administrative districts, namely Nyarugenge and Gasabo in the City of Kigali, as well as Rulindo in Northern Province.

The watershed is part of the bigger Nyabugogo watershed which was identified by the Rwanda Water Resources Board (Figure 1) as one of the five most important watersheds in the country (Rob, Benon and Ebel, 2018).

The watershed is composed of three main sub-catchments, namely Cyonyonyo (3667Ha), Mulindi (2572Ha), and Yanze Downstream (3442Ha); together, they total an area of 9,681Ha.

The elevation of the Yanze watershed ranges between 1370m and 2225m above sea level and forms a depression between two high elevation zones, namely, Mount Jali and the Shyorongi Highland on the eastern and western sides of the watershed, respectively. The watershed is characterized by steeply sloping hillsides separated by V-shaped valleys, with an average slope of 38.7%. The geology of that portion of Rwanda where the Yanze watershed is located comprises mesoproterozoic metasediments - largely the quartzites, sandstones, and shales of the Burundian supergroup which are locally intruded by granite (Thomas Schlüter, 2006). The soils within the watershed are naturally fragile. They have been generated through the physico-chemical alteration of the basic schistose, quartzite, gneissic, and granitic rocks that make up the superficial geology in this region.

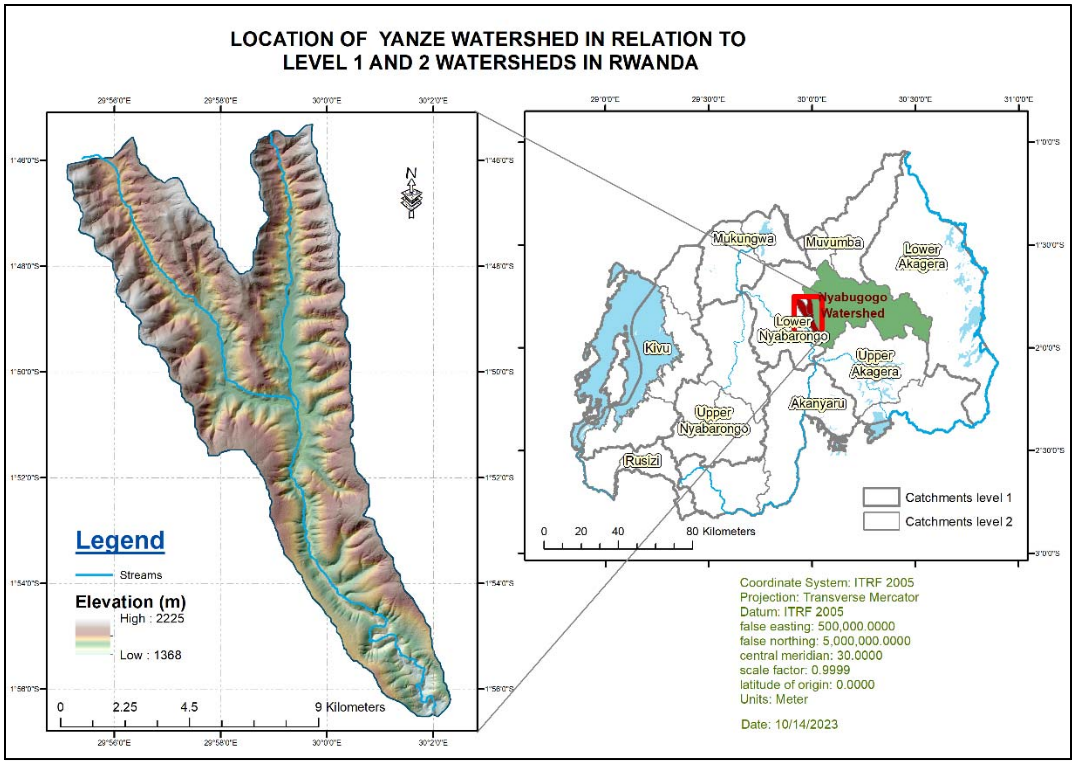

Figure 1: Location of the Yanze catchment in Rwanda.
The country is subdivided into nine primary (Level 1) catchments which are divided into 20 Level 2 sub-catchments. These are further divided into 580 Level 3 sub-catchments, one of which is Yanze.

The drainage pattern in the Yanze watershed is characterized by dendritic streams with a third-order permanent stream flow system. The main tributaries, namely, the Cyonyonyo and Mulindi, feed into the Yanze stream and are themselves fed by streams that have their sources in the surrounding hillsides. These third-order streams include the Nyakabingo, Ruhonwa, Ntakaro, Munyarwanda, and Kinywamagana.

2.2. Methodology used in the study

This study was subdivided into two main components, namely, soil erosion modelling based on the Revised Universal Soil Loss Equation (RUSLE) and a hypsometric analysis of the watershed. A correlation analysis was then conducted between the soil erosion risk map and the hypsometric integrals emanating from these components.

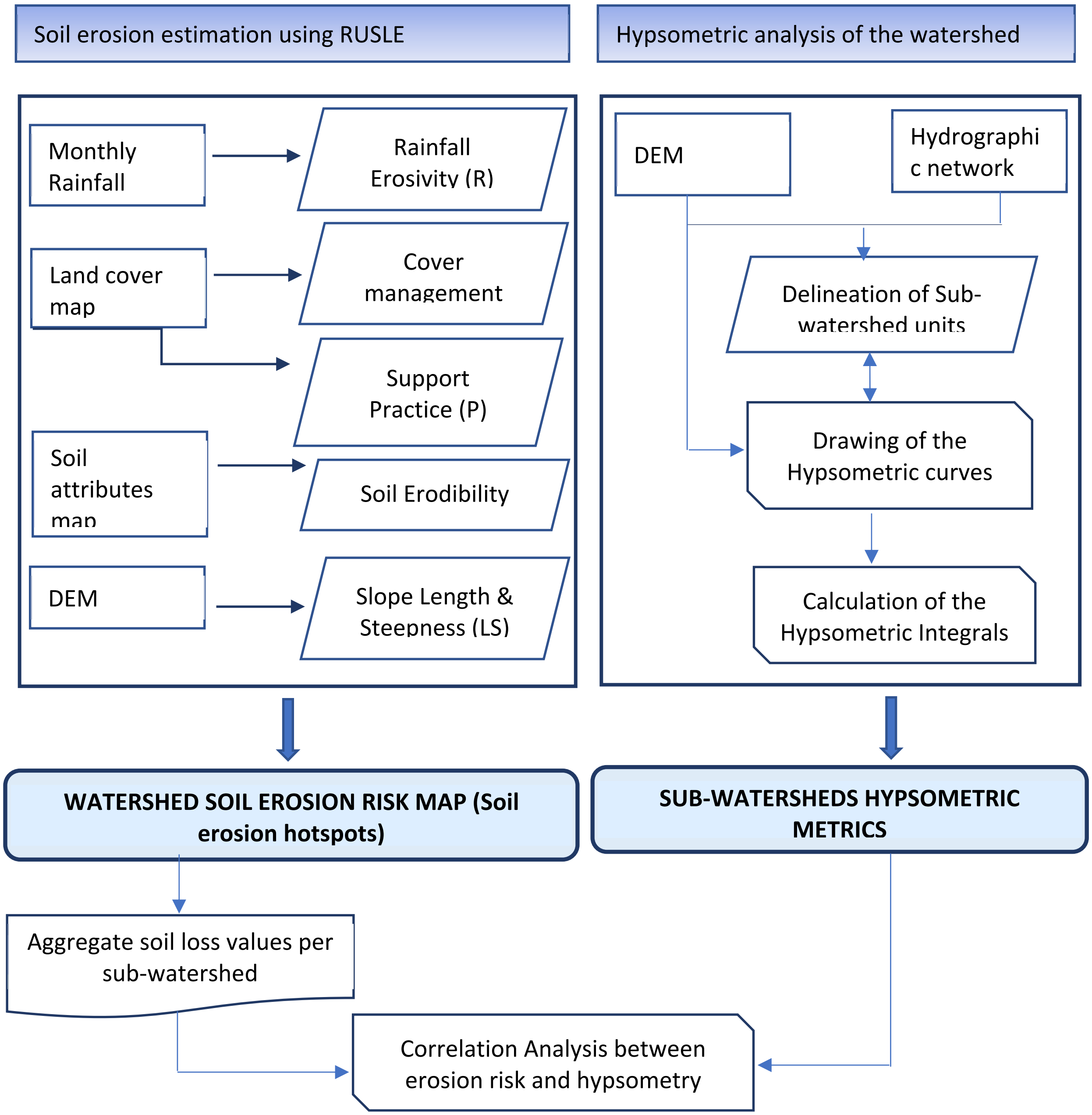

Figure 2: Methodology flowchart

2.3. Delineation of sub-catchments within the Yanze watershed

Using ArcMap hydrology tools, the DEM of the Yanze watershed was subdivided into 93 sub-catchments for the respective areas, which range from 20 to 300ha. Each sub-catchment was then given a five-character code to serve as the unique ID throughout the remaining steps of the process.

2.3.1. Drawing hypsographic curves and calculating the hypsometric values of the Yanze sub-catchments

Using R (programming language), the elevation tables of the Yanze sub-catchments were produced by reclassifying the DEM of each sub-catchment into 30 equal elevation range classes and calculating the area covered by each range class. The hypsometric integrals were then calculated by fitting a third- degree polynomial equation to the normalized contour area-elevation values and integrating it within the limits of 1 and 0 (Sharma et al., 2018).

2.3.2. Development of a RUSLE model of the Yanze watershed

As presented in Equation (1), the RUSLE model uses a simple equation with six factors. These six factors were incorporated into a GIS environment using the raster calculator function of the ArcGIS software.

$$A = R \times K \times LS \times C \times P \tag{1}$$

The values of the six factors of the model were derived as follows:

a) Rainfall-runoff erosivity factor (R)

The rainfall erosivity index measures the aggregate erosion potential of rainfall events by combining the energy and intensity of each storm event through relatively rigorous mathematical equations that were built empirically through continuous observations by scientists over decades of research. Given the limited availability of adequate hyetographic data, various studies have attempted to estimate the R factor using more readily available monthly and annual precipitation data (Ghosal and Das Bhattacharya, 2020). The methods applied depend on the climatic zone in which the study area is located (Ghosal and Das Bhattacharya, 2020). For Rwanda, the equation [Equation (2)] which was developed for wet tropical regions and applied in Hawaii (Lo *et al.*, 1985) has been demonstrated to give reasonable estimates for the R factor(Karamage, Shao, *et al.*, 2016; Karamage, Zhang, *et al.*, 2016; Karamage *et al.*, 2017; Niyonsenga, Mugabowindekwe and Mupenzi, 2020).

$$R = 38.46 + 3.48 \ * P \tag{2}$$

Here, R is the rainfall erosivity factor (MJ mm ha−1 h−1 year−1 and P is the mean annual rainfall (in mm). The mean annual rainfall was computed from a 30-year dataset provided by the Rwanda Meteorology Agency. The point data were interpolated using geostatistical methods in an ArcGIS environment to produce gridded data for use in the RUSLE function.

b) Soil erodibility factor (K)

Soil erodibility is a measure of a soil's resistance to the erosive powers of rainfall energy and runoff. It accounts for soil texture, structure, organic matter, and permeability. Comparable with the R factor, the quantitative value of the K factor is also empirically determined (Niyonsenga, Mugabowindekwe and Mupenzi, 2020).

For our study, we estimated the K factor by using soil properties (sand, clay, silt, and organic carbon fractions) with a spatial resolution of 250m that were compiled through the Africa Soil Information Service (AfSIS) project by ISRIC (Hengl *et al.*, 2015; ISRIC, 2017). We then computed the K-values by using Equation 3, which was established during the development of the Erosion Productivity Impact Calculator (EPIC) model (WIlliams, 2014) that was applied to the region by Karamage, Shao, *et al.* (2016) and Nambajimana *et al.* (2020):

$$K = K_{USLE} \times 0.1317 \tag{3}$$

$$K_{USLE} = \left[0.2 + 0.3\exp\left(-0.0256\,SAN\left(1-\frac{SIL}{100}\right)\right)\right] \times \left[\frac{SIL}{(CLA+SIL)}\right]^{0.3} \times \left[1-\left(0.0256\frac{C}{C+\exp(3.72-2.95C)}\right)\right] \times \left[1-\left(0.7\frac{SAN1}{SN1}+\exp(-5.51+22.9SN1)\right)\right]$$

where SAN denotes the percentage of the sand content (0.05–2.00 mm diameter); SIL stands for the percentage of the silt content (0.002–0.05 mm diameter); CLA represents the percentage of the clay content (<0.002 mm diameter); C stands for the percentage of the organic carbon content; and SN1 = 1 - (SAN/100). We used the constant value of 0.1317 to convert the K factor from the American imperial unit system to the international/metric unit system (Renard *et al.*, 1997; Nambajimana *et al.*, 2020).

c) Topographic factor (LS)

The topographic factor is defined as the expected ratio of soil loss per unit area from a field slope to that from a 22.12848m length of a uniform nine-percent (9%) slope under otherwise identical conditions (Wischmeier and Smith, 1978).

From Equation (4), derived from Wischmeier and Smith (1978), we estimated the LS factor using the ArcMap hydrology tools to calculate the flow accumulation value for each cell in our study area; we then used the software raster calculator tool to produce the final LS factor layer by applying the equation below:

$$LS = \left(\text{flow accumulation} \times \frac{\text{resolution}}{22.1}\right)^{m} \times 0.065 + 0.0455S + 0.0065S^2 \tag{4}$$

where **LS** is the slope length and gradient factor (dimensionless), **S** is the slope gradient as a percentage, and **m** is the slope angle contingent variable reflecting the susceptibility of the soil to erosion. Its value varies between 0.5 (slopes of 5% or more) and 0.2 (slopes of 1% or less) and for the purpose of our study, we used the table derived from Wischmeier and Smith (1978) and Renard *et al.* (1997), as presented below:

Table 1: Assignment of values to the slope angle contingent variable (m) according to slope gradient

Slope (%)	Value of (m)
>5	0.5
3-5	0.4
1-3	0.3
<1	0.2

d) Cover management factor (C)

The C factor is defined as the ratio of soil loss from an area with a specific cover and tillage practice to that from an identical area in tilled but continuously fallow land (Clay and Lewis, 1990). It represents the ratio of soil erosion from land cropped under specific conditions and determines how the natural vegetation or the crop cover reduces rainfall energy and overflows or intercepts rainfall energy and increases infiltration (Byizigiro et al., 2020).

For our study, C values were assigned to each land-cover class using a look-up table through ArcMap's raster reclassification tool. These values were derived from Panagos et al. (2015) and Koirala et al. (2019) and were used in previous RUSLE studies conducted in Rwanda (Byizigiro et al., 2020).

Table 2: Assignment of C factor values to land-use classes

Land Use	Area covered (Ha)	% of land covered	C Factor
Forest	1,378.56	14.23	0.03
Shrubland	424.24	4.38	0.03
Grassland	531.24	5.48	0.01
Agricultural Land	7,260.24	74.93	0.21
Built-up	94.28	0.97	0
Water / wetland	0.20	0.00	0

e) Support practice factor (P)

The support practice factor (P) is defined as the ratio of soil loss with a specific support practice to the corresponding soil loss with straight-row upslope and downslope tillage (Niyonsenga, Mugabowindekwe and Mupenzi, 2020). Its values range from 0 to 1 and are calculated as the ratio of the rate and amount of soil loss as a result of a specific support practice to the soil loss issuing from row farming in an upward and downward slope condition (Ghosal and Das Bhattacharya, 2020). If no conservation practice is applied, the P factor is taken as 1. However, if a soil conservation practice is conducted in a given area, then a proper P factor value is assigned to that particular area with respect to the slope.

Wischmeier and Smith (Wischmeier and Smith, 1978) provides tables to estimate the P factor based on the slope gradient and different support practices. Unfortunately, it is virtually impossible in the case of a complex land-use system to establish a P factor map at a watershed scale from these tables.

For our study, we classified the watershed slope map into five slope angle classes (<7% as very gentle to flat, 7% to 11.3% as gentle, 11.3% to 17.6% as moderate, 17.6% to 26.8% as steep and >26.8% as very steep) and assigned P values following the model in Table 3, established by Shin (1999) and used by Byizigiro et al. (2020). For the remaining area where no soil conservation is practiced, a value of 0.75 was assigned according to the recommendations of Karamage, Zhang, et al. (2016). The distribution of soil conservation practices in the area was digitalized manually from Google Earth images and cross-checked with ancillary data obtained from the local authorities.

Table 3: Estimated P-factor values according to slope and key soil conservation measures

Slope %	Strip Cropping	Contour Cropping	Terrace Cropping	
			Bench	Broad-based
0-7.0	0.27	0.55	0.1	0.12
7.0-11.3	0.3	0.6	0.1	0.12
11.3-17.6	0.4	0.8	0.1	0.16
17.6-26.8	0.45	0.9	0.12	0.18
> 26.8	0.5	1	0.14	0.2

2.3.3. Correlation analysis between the hypsometric parameters of the Yanze sub-catchments and their estimated soil loss

The soil erosion risk profile map for the study area was compiled with the aid of ArcGIS zonal statistics tools where the mean soil loss for each sub-catchment was calculated from the values provided by the RUSLE model. Using R (programming language), a second-order polynomial regression model was then fitted to these mean values for soil loss (the independent variable) and the hypsometric integral values (the dependent variable).

3. Results and Discussion

3.1. Hypsometric profile of the Yanze watershed

The hypsometric analysis of the Yanze watershed showed that all its sub-catchments are at either a young or an equilibrium stage, with the hypsometric integrals ranging from 0.5 to 0. 0.936 and an average of 0.75. This means that the majority of the Yanze sub-catchments are still in the youthful stage. As such, they have the potential to undergo intensive erosion if the soil conservation measures undertaken are inadequate.

Regarding the hypsometric curves of the Yanze sub-catchments, most of them have a convex-upward shape, which confirms that they are at the youthful stage in their evolution. Those that have a concave shape occur in the downstream portion of the watershed which is indicative of more future erosion being expected in the upstream portion of the watershed (Omvir Singh, 2008).

3.2. Soil erosion risk in the Yanze watershed

The risk profile map of the Yanze watershed was compiled by applying a RUSLE model. The final values of the RUSLE factors were computed and formatted into rasters and each resampled to a 30x30m grid. For the R factor, the values range from 3,500 to 5,380 $MJ.mm.ha^{-1}.h^{-1}.year^{-1}$, which reflects the high level of erosivity typical of tropical wet climates. For the K factor, the values range from 0.253 to 0.148 $tonnes.ha.h.ha^{-1}.MJ^{-1}.mm^{-1}$ and their spatial distribution in the watershed shows some higher values upstream and lower values downstream.

The product of all these factor values gives the average annual rate of soil loss, which was calculated to be in the range of 0 to 2,637 $tonnes.ha^{-1}.year^{-1}$, with a mean annual soil loss of 55.63 $tonnes.ha^{-1}.year^{-1}$. In order to develop a soil erosion profile map for each sub-watershed, ArcGIS zonal statistics tools were used to calculate the mean value of soil loss in each of the 93 sub-catchments of the Yanze watershed. The spatial distribution of the soil erosion risk in the Yanze watershed shows that compared to the downstream portion, the upstream portion of the watershed is at a much higher risk (Figure 6).

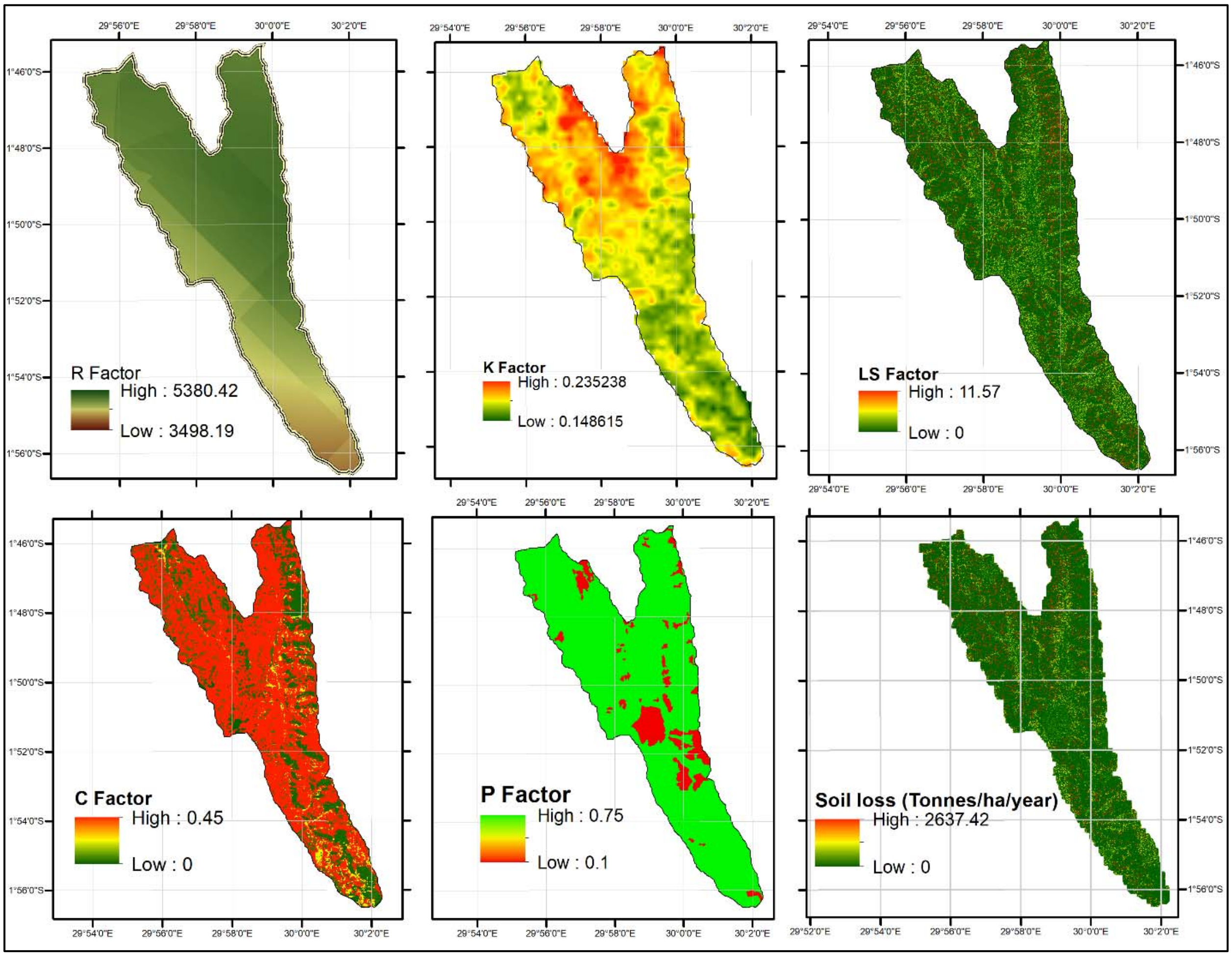

Figure 3: Spatial distribution of the RUSLE factor values and final soil loss map for the Yanze watershed

3.3. Correlation between hypsometric integrals and soil loss in the Yanze watershed

The results of the best fitting regression model between the hypsometric integrals and the soil loss values of the Yanze sub-catchments show that there is no significant relationship between the two variables. The coefficient of determination of the fitted model (R-Squared) is 0.0305, which means that only 3.05% of variability in the dependent variable (mean soil loss) can be explained by the predictor (hypsometric integral). The P value of the relationship is also very high (0.25) which means that this relationship that was observed to be limited probably derives from chance (Andrade Chittaranjan, 2019).

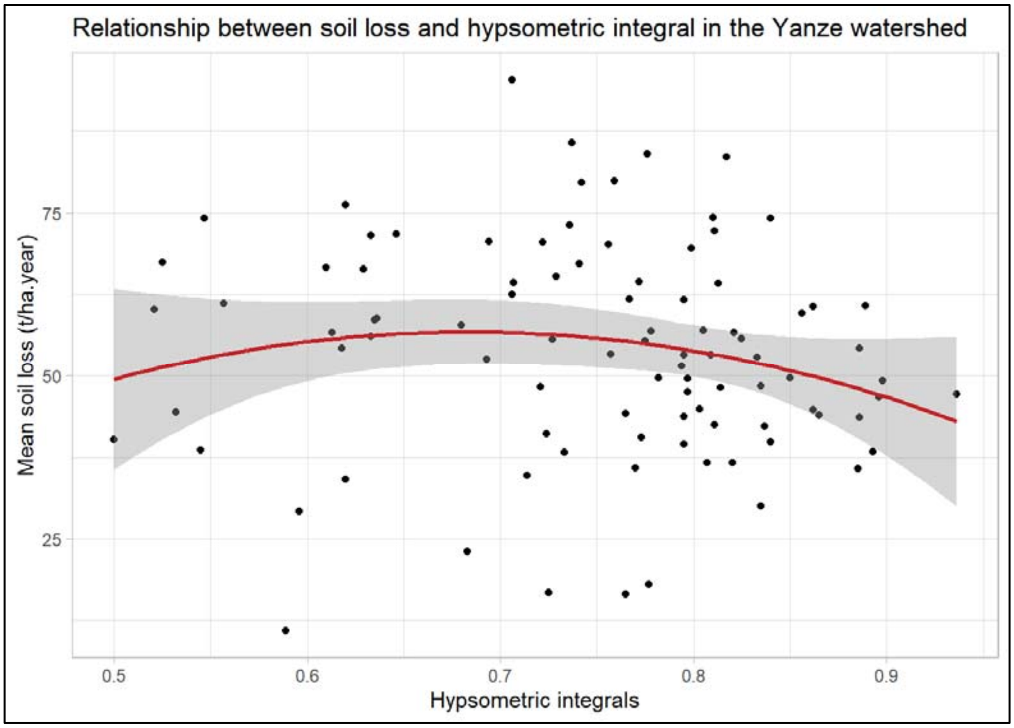

Figure 4: Polynomial linear model between hypsometric integrals and soil loss in the Yanze watershed

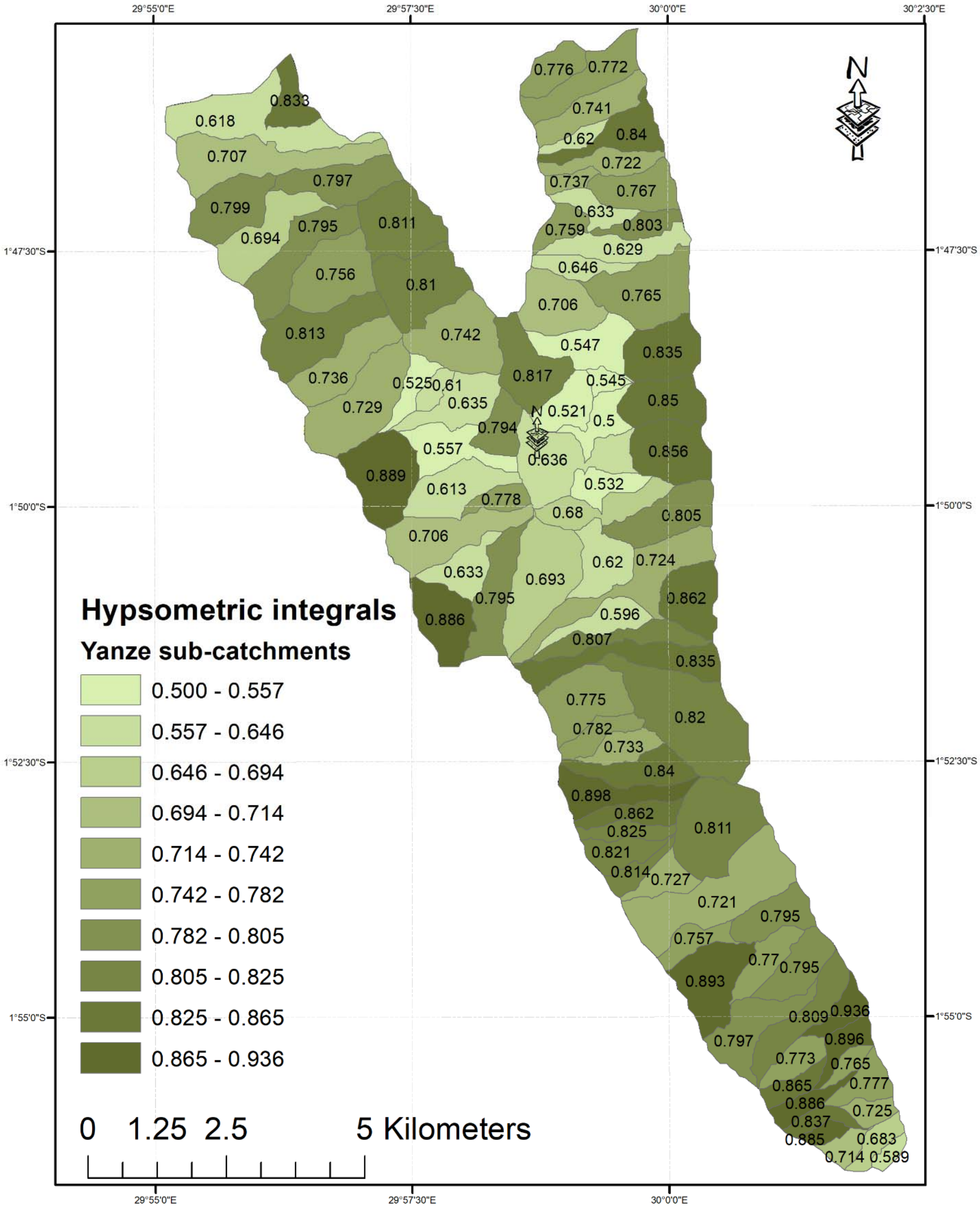

Figure 5: Map of hypsometric integrals of the Yanze sub-catchments

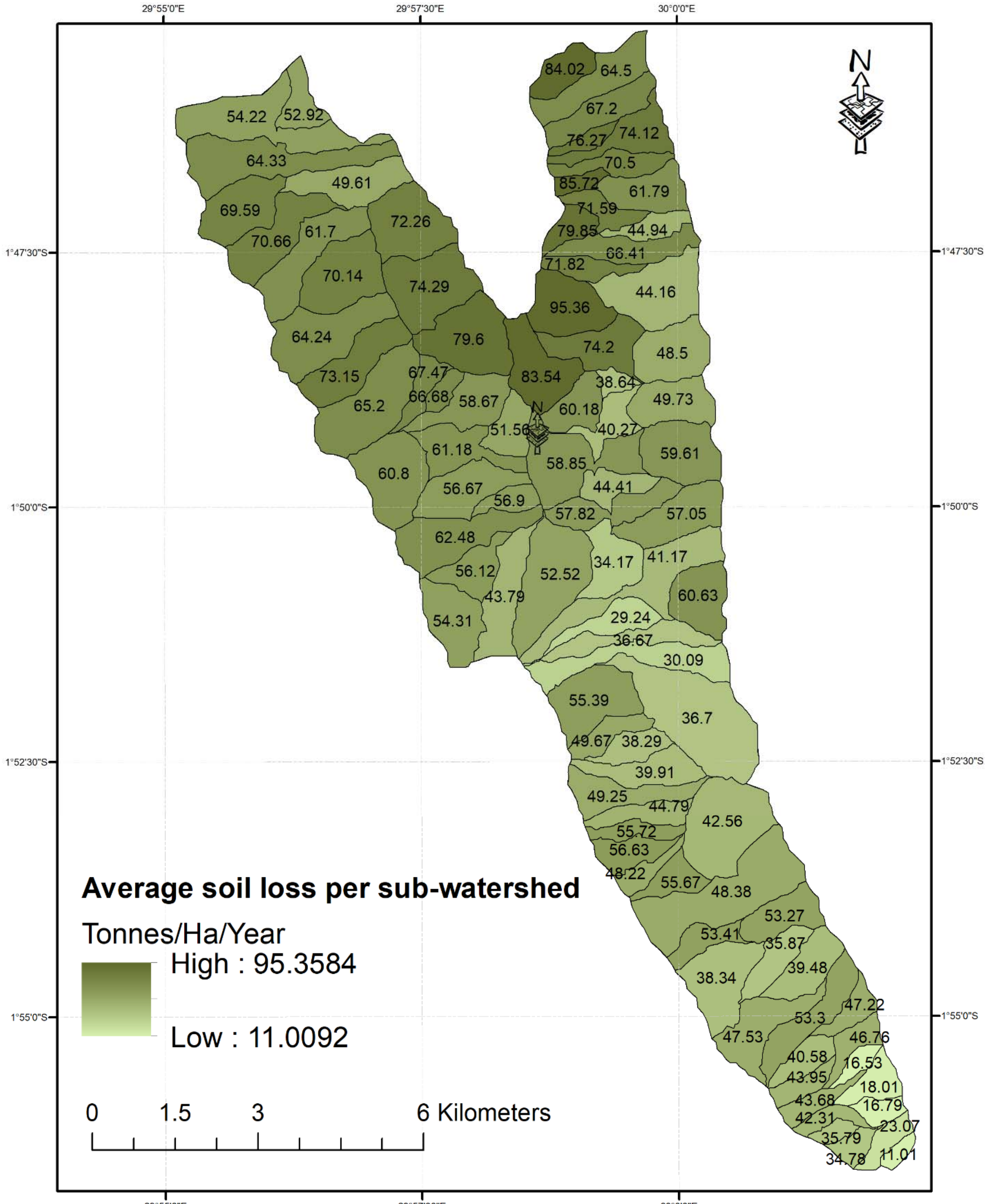

Figure 6: Map of average soil loss values in the Yanze sub-catchments

4. Conclusion

The hypsometric analysis of the Yanze watershed revealed that the watershed is still at the youthful stage in its geomorphological evolution which suggests that the landscapes in the watershed are still prone to erosion. Soil erosion modeling in the watershed also indicated that soil loss in the watershed is very high. From this evidence, we can deduce that soil erosion in the Yanze watershed is associated with the geomorphology of the watershed. However, the correlation analysis conducted between the hypsometric integrals of the sub-catchments within the watershed and their respective mean soil loss values did not yield any significant correlation. We therefore conclude that hypsometry is not the main driver of erosion in the Yanze watershed. As such, other factors should be considered when investigating measures to prioritize erosion control interventions in the watershed. Suggested additional parameters to consider include geometric parameters such as basin shape, elongation ratio, and shape/form factor; relief parameters such as basin shape, elongation ratio, and shape/form factor; and relief parameters such as the terrain ruggedness index, elevation-relief ratio, and gradient ratio.

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