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SCHOOL OF ARCHITECTURE AND BUILT ENVIRONEMENT (SABE)

THESIS REPORT

Characterization of a catchment erosion potential through hypsometric analysis: Case of Yanze Watershed, Rwanda

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Declaration

This research is my original work and has not been presented to any other institution for any academic award. No part of this research should be reproduced without the author's consent or that of the University of Rwanda.

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Approval

It is hereby confirmed that this thesis entitled "**Characterization of a catchment erosion potential through hypsometric analysis: Case of Yanze Watershed, Rwanda**" submitted by Faustin GASHAKAMBA has been assessed and accepted by the post-graduate coordination team in the school of Architecture and Built Environment.

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Abstract

Implementing a watershed erosion control program necessitates extensive and time-consuming preliminary investigations to strategically prioritize interventions, so that sub-catchments that are likely to yield the most effective results are targeted. This study aims at exploring and documenting the efficacy of utilizing hypsometric analysis to prioritize erosion control measures, using Yanze watershed in central Rwanda as a case study.

Utilizing a 30-meter resolution Digital Elevation Model (DEM) of the watershed and employing ArcGIS and R software, we calculated hypsometric integral values of each sub-catchment of Yanze watershed. We then calculated annual soil loss estimates using the Revised Universal Soil Loss Equation (RUSLE) model. Data from diverse sources were used during the soil loss modeling, including the Rwanda Meteorological Agency (rainfall data), ISRIC (soil data), and Sentinel-2 images (land cover maps).

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

The results of the soil loss 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 that has been estimated at 62 $tonnes.ha^{-1}.year^{-1}$

Correlation analysis between the hypsometric integral values and mean soil loss values of Yanze sub-catchments revealed no significant correlation. From the results of this study, we conclude that in watersheds where lithology significantly affects soil erosion, 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

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AfSIS: Africa Soil Information Service

AHP: Analytic Hierarchy Process

CRAN: Comprehensive R Archive Network

CSV: Comma-Separated Values

DEM: Digital Elevation Model

EICV5: Fifth Integrated Household Living Survey

ENACTS: Enhancing National Climate Services

EPIC: Erosion Productivity Impact Calculator

ESA: European Space Agency

FONERWA: Fond National pour l'Environnement du Rwanda (Rwanda Green Fund)

GIS: Geographic Information System

GLASOD: Global Assessment of Human-Induced Soil Degradation

GMES: Global Monitoring for Environment and Security

HI: Hypsometric Integral

ISRIC: International Soil Reference and Information Centre

MCDA: Multi-Criteria Decision Analysis

NISR: National Institute of Statistics of Rwanda

NTU: Nephelometric Turbidity Unit

REMA: Rwanda Environment Management Authority

RHPC4: Rwanda 4th Population and Housing Census

RUSLE: Revised Universal Soil Loss Equation

RWFA: Rwanda Water and Forestry Authority

UNEP: United Nations' Environment Programme

W4GR: Water for Growth, Rwanda

WHO: World Health Organization

WTP: Water Treatment Plant

CHAPTER 1. INTRODUCTION

In this chapter, the importance of Yanze watershed as the main source of water supply for the City of Kigali and as for the provision of many ecosystem services to the population that live within the watershed will be discussed. The soil erosion and water pollution problem in this watershed will also be described and key initiatives that were taken by various stakeholders to curb this issue will be documented. Then after, the key problem that this study has sought out to solve and the objectives of the study will be stated. Finally, the scope of the study will be defined to clarify the expectations that the reader of this report should reasonably have regarding the results of the study.

1.1. Background

Yanze is one of the most important watersheds in Rwanda that provides many ecosystem services to the population living within it. It is also the main source of water supply for the City of Kigali. It provides up to 80% of the water requirements for the city through Kimisagara Water Treatment Plant[9] . However, this watershed is over-exploited due to the high population pressure that leads to need for more agricultural land. In addition there is an increase in human economic activities within the watershed such as quarrying and mining, and these activities resulted in land degradation which is threatening the ability of the watershed to provide the essential ecosystem services it used to provide[9].

The degradation of Yanze Watershed is particularly linked with soil erosion and that degradation has, in recent decades, brought the long-term reduction of the quantity and quality of water resources, thus affecting the ability of this watershed to continue providing its water supply service to Kigali city[33].

The threat to the water supply of the City of Kigali as a result of land degradation in Yanze watershed is manifested through the increase in the operation cost of Kimisagara Water Treatment Plant (WTP) due to high turbidity of the raw water drawn from Yanze River[9]. Other impacts of the degradation of Nyanze watershed include modification of the physico-chemical properties of the water and the clogging of the gills of fish which stunts their growth and decreases their resistance to diseases. This significantly, reduces the amount of ecosystem services that the watershed provides to downstream communities especially in Nyabugogo plain where the river constitutes an important source of fish for the local population. The degradation also reduces the recreational value of the river benefited by local businesses.

In order to mitigate the above-mentioned problems, the government of Rwanda and its partners have implemented various projects and initiatives. These soil erosion and water pollution control measures include, widening of river channel, riverbank protection, construction of dykes, and covering vulnerable farmed land with radical terraces. Some results from these initiatives include establishment of 1.5 km buffer zone around Cyonyonyo, Mulindi and Yanze river streams, construction of 493 hectares of bench terraces, riverbank stabilization around Mulindi tributary, as well as construction of gabion walls and leaky weirs on key waterways. These interventions were conducted in the framework of a project implemented by the Dirstrict of Rulindo, a project that was funded by Rwanda's environment and climate change fund (FONERWA) and targeted at reducing sedimentation of Yanze River through terracing and agroforestry[33].

In addition, a Nyabugogo catchment management plan was developed by Water for Growth Rwanda (W4GR), a project that was funded the Dutch Embassy through Rwanda Water and Forestry Authority (RWFA) and which run from year 2016 to 2019[32].

Despite these various efforts that were taken to curb soil erosion within Yanze watershed in order to reduce sediment loads in Yanze River and enhance ecosystem services it provides; the watershed still remains one of the major erosion hotspots within Nyabugogo watershed. This shows that there is still a need for more effort in protecting the catchment. The main challenge for conducting effective interventions is that the available resources are always little 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 these available resources are used efficiently, a prioritization mechanism is called for to ensure the activities undertaken as part of such a programme are spatially targeted onto areas where they can have the highest long-lasting impact. This requires a detailed assessment of the watershed for identification of hotspots and prioritization of intervention activities, a process that is normally conducted following a Multi-Criteria Decision Analysis (MCDA) framework using tools such as Analytical Hierarch Process (AHP)[5, 16]. This study explores the use hypsometric analysis as a mechanism to assess watershed erosion potential and to document its effectiveness as an approach to prioritize sub-watersheds for erosion control measures in a faster and cost-effective way.

1.2. Problem Statement

Yanze watershed is a very important ecosystem when it comes to the provision of potable water to the City of Kigali. The watershed currently, provides about 80% of all the water used in the city[33]. However, the watershed is in a degraded state despite various efforts put in in place to rehabilitate it. There is a high level of erosion in the watershed leading to a high amount of sediment load in Yanze River. The high level of erosion in the watershed is associated with the nature of the physical environment of its landscape characterized by a very rugged topography with steep slopes coupled with high intensity of rainfall and highly erodible soils. This also makes soil and water conservation interventions in the watershed very costly. The degraded status of the watershed has a serious negative impact on the water supply of the City of Kigali. Some of the problems associated with the degraded condition of the Yanze watershed include: (1) Increase in the cost of operation of the water treatment plant, (2) increase in time required to treat water, (3) modification of the physico-chemical properties of the water, (4) clogging of the gills of fish which stunts their growth and decreases their resistance to diseases, (5) reduction of the recreational value of the river downstream.

The solution to this problem requires a detailed watershed erosion risk assessment and prioritization of sub-catchments study which is a resource-intensive time-consuming endeavor. This study intends to contribute to the solution of this problem by exploring and documenting the use of hypsometric analysis as an approach to identify sub-catchments that are most susceptible to soil erosion within a watershed.

1.3. General and Specific Objectives of the Study

The main objective of this study is to explore and document the significance of using hypsometric parameters (i.e., hypsometric curve & hypsometric integral) as estimators of the erosion status in a landscape.

The specific objectives are the following:

1. To examine the morphometric characteristics of Yanze watershed using GIS;
2. To determine the erosion potential of the watershed using RUSLE and develop its soil erosion risk map;

3. To establish the correlation between the hypsometric parameters of Yanze sub-catchments and their estimated soil losses due to erosion.

1.4. Scope and Limitations of the Study

Several studies have evaluated the ability of soil erosion models to realistically predict measured rates of erosion, mainly on agricultural landscapes and it was found that there is often a wide discrepancy between predicted and observed erosion rates[2].

Given the fact that this study has not included extensive field measurements that are recommended for better calibration of empirical parameters used by RUSLE models, its results - and the recommendations derived thereof - are thus not intended to be taken as prescriptive measures to be adopted into public policy or based upon during the development of regulatory instruments aiming at curbing soil erosion in the study area.

The present study mainly aims at demonstrating and examining the adequacy of using hypsometric analysis as an estimator of future erosion hotspots at a long-term time scale. The study results should therefore only be considered as a benchmark that can be built upon by future researchers who can use the methodology pioneered here and expand on it to derive a more comprehensive framework that integrates hypsometric analysis techniques within an exhaustive process of assessing erosion in a watershed based on actual data collected on field.

1.5. Conclusion

This research aims at exploring and documenting the use of hypsometric analysis as a predictor of soil erosion in a watershed thus allowing quick and cost-effective prioritization for erosion control interventions. Given its importance as the main source of water supply for the City of Kigali, Yanze watershed was selected as the test bed for this potential method. The results of this study will be used by researchers and planners who will apply this method during feasibility studies of new soil erosion control programmes targeting watersheds similar to Yanze.

CHAPTER 2. LITERATURE REVIEW

2.1. Chapter Overview

This chapter explains the existing literature about the viability of using hypsometric analysis for sub-watershed prioritization. In addition, the adequacy of some of the tools that were used in this study and how they were applied by other researchers will be described. Those tools include the Revised Universal Soil Loss Equation (RUSLE) which was used to model soil erosion and the hypsometric curve/integral which were used to an analyze the morphologic patterns in Yanze watershed.

2.2. Soil Erosion as the Main Cause of Land Degradation and Water Pollution

Soil erosion as a part of the larger problem of land degradation constitutes one of the most serious environmental issues that the world is facing today. In 2003, According to the Global Assessment of Human-Induced Soil Degradation (GLASOD) prepared jointly by the International Soil Reference and Information Centre (ISRIC) and the United Nations' Environment Programme (UNEP); soil erosion by water is by far the most important type of soil degradation, affecting about 1,100 million ha worldwide (56% of the total area affected by human-induced soil degradation) at an estimated rate of 1,150 t/km^2 globally[28].

As soil constitutes the basis of all terrestrial ecosystems, a degraded soil means lower fertility, reduced biodiversity, and human poverty. While natural erosion is a long-term process with less impact on the overall soil balance of a site under consideration, accelerated soil erosion on the other hand comes with human interventions mainly in the form of land use and land cover change[22].

In Sub-Saharan Africa, the population is growing with the highest birth-rate compared to any other region – 2.4% compared to a world average of 1.3% – and it is projected to grow to two billion by 2050[3].

Accelerated soil erosion is amplified by human activities and, among these, agriculture is the primary cause of soil degradation[19]. Given the high dependence of population on agriculture in Rwanda (83.4% of Rwanda's population depend on subsistence agriculture[24]), soil erosion as a major cause of land degradation becomes even more serious problem due to its impact on agricultural productivity[41]. The unabated population growth (2.7%[24]) exacerbates this problem as the amount of land available to agriculture becomes more and more limited and agricultural expansion increasingly takes place on marginal lands.

This results in a situation where land becomes very fragmented and overexploited which leads to unprecedented erosion rates that make a big chunk of the land unsuitable for sustainable agriculture.

The high level of soil erosion explains the severe water pollution and excessive turbidity of streams in Yanze watershed where the levels in Nyabarongo river are 737.28 - 571.03 NTU (Nephelometric Turbidity Units) and 28.79 - 20.94 mg/L of Nitrate–Nitrogen (NO_3–N) compared to 1 NTU and 11 mg/L respectively set as the standard limits according to WHO Drinking Water Guidelines[26].

2.3. Overview of Soil Erosion Modeling Using RUSLE

With growing pressure on natural resources and landscapes, there is an increasing need to predict the consequences of any changes to the environment[11]. Soil erosion models are useful during the estimation of soil loss and runoff rates from agricultural land. The Universal Soil Loss Equation (USLE) is one of the earliest of such models and was developed in 1978 by Wischmeier and Smith[11]. Since then, several USLE-family models have been developed to simulate the soil erosion process and predict soil losses through erosion. They all consider slope steepness, slope length, vegetative cover, rainfall, soil properties and erosion control methods as parameters which influence erosion[38].

One of these, RUSLE, is the revised version of the original USLE model and it was introduced by Kenneth G. et al, 1991[31]. It maintains the basic structure of USLE but is a computerized version that incorporates the results of additional research and experience obtained since the 1978 publication of USLE[11].

RUSLE falls into a family of models called empirical models and the models in this category are known to be simple compared to conceptual or physically-based ones as they can be implemented in situations with limited data and parameter inputs[11].

Originally, USLE was developed mainly for soil erosion estimation in croplands or gently sloping topography[7]. The RUSLE quantifies soil erosion as the product of six factors representing rainfall and runoff erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), cover and management practices (C), and supporting conservation practices (P)[11].

Present RUSLE soil loss equations are substantially less accurate for prediction of specific events than for the prediction of long time averages[44]. This justifies its choice for this specific study since our objective is not to simulate soil erosion event-wise but rather, to approximate soil erosion estimates on a long-time scale.

2.4. Morphometry as an Approach of Analyzing Patterns in a Watershed

Morphometry is defined as a formal or mathematical analysis of the configuration of the earth's surface, shape, and dimension of its landforms[1]. A watershed is the appropriate unit to study several processes of land surface and is considered to be a fundamental erosional landscape element, where conspicuous interaction of land and water resources takes place[1]. Given this importance of a watershed as a unit of analysis in hydrology, the definition of morphometric indices at the watershed level, rather than at individual streams level is more natural and useful in revealing relevant patterns.

Hypsometric analysis (area-elevation analysis) is a branch of morphometry that deals with elevation distribution across an area of land surface and is useful when studying erosion processes in an area given that it allows the researcher to quantitatively express the overall slope of a catchment. When analyzing soil erosion, the hypsometric indices that define the overall shape of the watershed can reveal very valuable insights that can point the analyst in the right direction to improve their study.

Hypsometric analysis of a watershed has generally been used to reveal the stages of geomorphic development (stabilized, mature and young) and it describes the elevation distribution across an area of land surface[35].

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 surface area of earth at various elevations by plotting relative area against relative elevation. The non-dimensional hypsometric curve is the standardized form usually used by hydrologists and it is drawn by scaling elevation and area by the maximum values. The Hypsometric Integral is the area beneath the hypsometric curve whose value varies from 0 to 1[35]. In terms of its interpretation, given a hypothetical Hypsometric Integral of 0.35 for example, that would mean that only 35 per cent of the land masses in that basin remain to be eroded.

The hypsometric integral is important for estimation of erosion status of watershed, and it helps in prioritization of watersheds for proposing soil and water conservation activities[34]. It also provides a simple morphological index that can be used in surface runoff and sediment yield prediction from watersheds[34, 35]. Given the dimensionless nature of the above-mentioned hypsometric parameters, their use in the characterization of the erosion status of a watershed has an added advantage of allowing comparison between the different sub-watersheds of the basin irrespective of their true absolute scale[37].

2.5. Conclusion

Soil erosion poses a serious threat to the livelihoods of people and integrity of ecosystems in Rwanda in general and in Yanze watershed in particular. Many soil erosion modeling studies have been conducted in Rwanda using RUSLE and at least one was specifically conducted in Nyabugogo watershed which encompasses Yanze sub-watershed. In terms of watershed prioritization, one study was conducted in Nyabugogo to group its sub-catchments (including Yanze) into clusters according to their erosion potential using five erosion hazard parameters that were assessed using Multi-criteria Decision Analysis (MCDA) based on Analytic Hierarchy Process (AHP). However, hypsometric analysis was not included among these parameters, and this represents a notable gap which this study aims to close.

CHAPTER 3. MATERIALS AND METHODS

3.1. Chapter Overview

In this chapter, Yanze watershed (our study area) will be described to present its physiographical and socio-economic situation. Afterwards, the conceptual framework of the study will be introduced, and the methodological process followed to answer each research question will be specified.

3.2. Description of the Study Area

3.2.1. Localization of study area

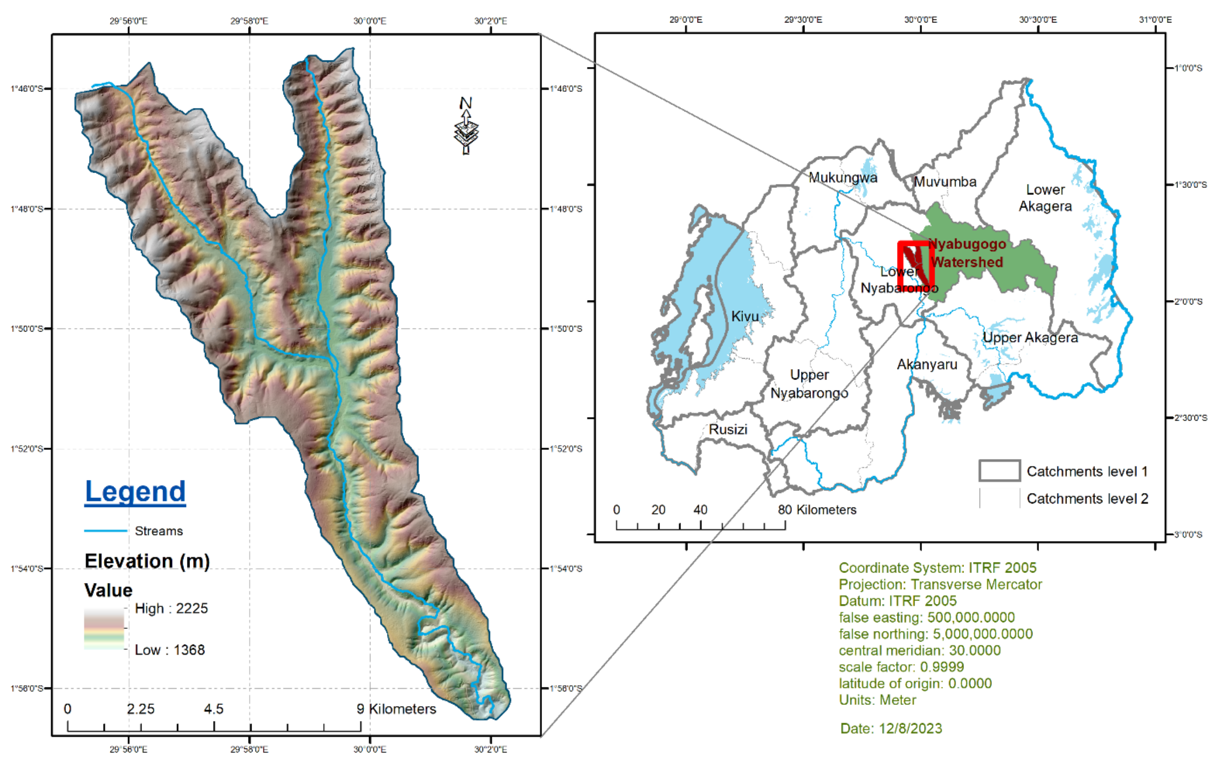

Figure 1: Location of Yanze catchment in Rwanda and in relation to Nyabugogo watershed (Source: Rwanda Land Management and Use Authority, 2018)

Yanze is a relatively small watershed located in north-west of The City of Kigali, Rwanda. It straddles 3 administrative districts namely Nyarugenge and Gasabo (in The City of Kigali) as well as Rulindo (in Northern Province).

The watershed is part of a bigger Nyabugogo watershed which was identified by the Rwanda Water Resources Board (former Rwanda Water and Forestry Authority) as one of the five most important watersheds in the country[32].

The watershed is composed of 3 main sub-catchments namely Cyonyonyo, Mulindi, and Yanze Downstream; and together they total an area of 9,687.39 Ha (Figure 3).

Sub-catchments	Area in Hectares
Cyonyonyo	3,617.52
Yanze Downstream	3,455.46
Mulindi	2,614.41
TOTAL	**9,687.39**

Source: Rwanda Environment Management Authority, 2013

3.2.2. Ecological and Biophysical Environment

a. Climate

The average rainfall in Kigali is 997mm per year[21]. The closest meteorological stations for Yanze watershed are Kigali Airport, Kabuye, Rulindo and Gicumbi stations and of these, only the Kigali Airport station offers a long-term record of about 30 years (only missing data for 5 months from May 1994 to September 1994).

Similar to much of the territory of Rwanda, the rainfall regime in Kigali and surrounding areas follows bimodal pattern having two rainy periods, the first from March to May and the less intense second wet season from October to December. Rainfall is abundant with an average of around 250mm/month and the average annual temperature ranges between 16°C and 20°C without any significant variations[21].

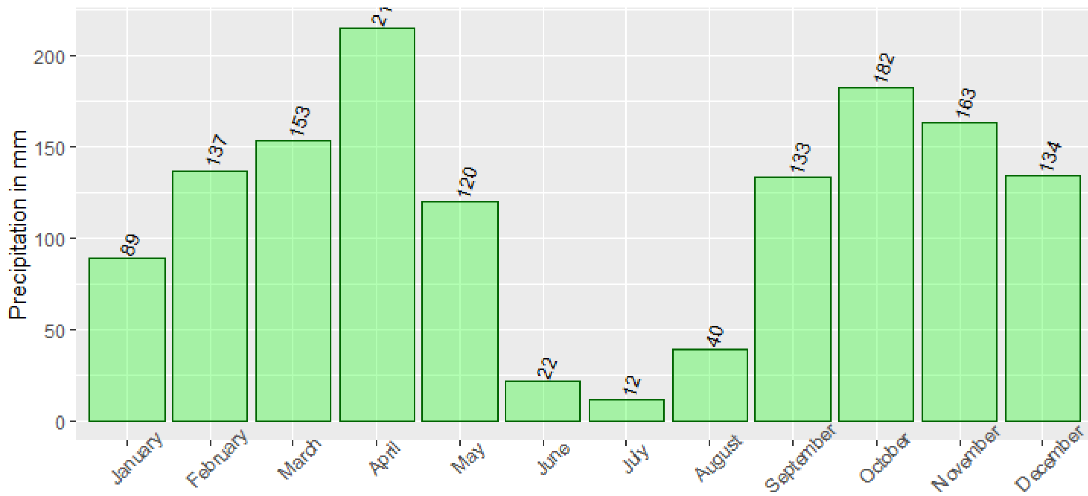

Figure 2: Average monthly rainfall at Kabuye Station from 1981 to 2017 (Source: Rwanda Meteorology Agency, 2018)

b. Soils and Geology

The geology of the part of Rwanda where Yanze watershed is located comprises mesoproterozoic metasediments, largely 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 are generated by physico-chemical alteration of basic schistose, quartzite, gneissic, granite rocks that make up the superficial geology in this region.

c. *Topography and Slope Characteristics*

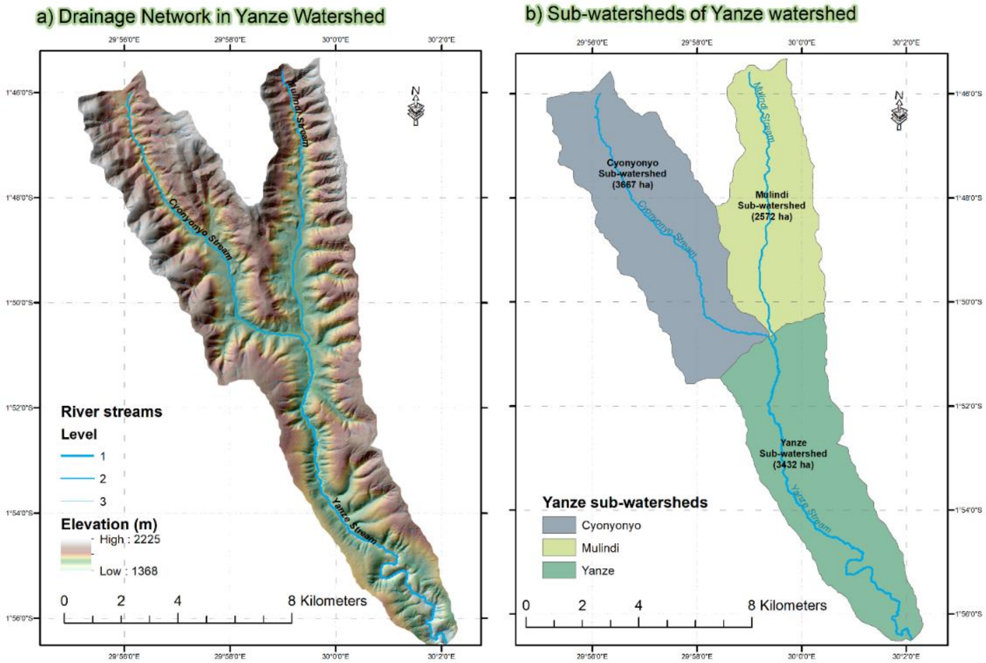

Figure 3: Yanze sub-watersheds, its drainage network, and elevation map (Source: Rwanda Land Management and Use Authority, 2018)

The elevation in Yanze watershed ranges between 1370m and 2225m above the sea level. The watershed forms a depression between two high elevation zones namely Mount Jali and Shyorongi highland on the eastern and western sides of the watershed, respectively.

The watershed is characterized by steep slopes on hillsides separated by V-shaped valleys with an average slope of 38.7%.

Table 1: Slope values in Yanze watershed at sub-watershed level

Sub-watershed	Total area (Ha)	Area with slope 0-5%	Area with slope 5.1-15%	Area with slope 15.1-30%	Area with slope 30.1-50%	Area with slope >50%
Mulindi	2614.41	15.8	17.3	44.0	22.1	0.7
Cyonyoyo	3617.52	13.1	21.5	49.5	15.6	0.3
Yanze Downstream	3455.46	53.2	16.4	22.7	7.5	0.1
Average percentage at watershed level		27.3	18.4	38.7	15	0.3

Source: Author, 2020

d. *Hydrology and Drainage Patterns*

Yanze River has one gauging station which was installed in January 2011 and the station records the water level variation not the discharge, but the latter has been estimated for the main stream (Yanze River) at 2,500m^3/h in the rainy season and 800m3/h in the dry season[20].

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

3.2.3. Socio-economic Environment

a. *Population*

According to the Fourth Rwanda Population and Housing Census (RPHC4) conducted by the National Institute of Statistics of Rwanda in 2012, the resident population in the sectors comprising Yanze watershed is 159,797 inhabitants with an average household size of 4.4 for Rulindo district[25]. Generally, Yanze watershed is characterized by a rural population, largely dependent on subsistence agriculture and heavily on fuel wood for cooking[9].

Table 2: Distribution of resident population in Yanze watershed in 2012 by Sector, Sex and density

Sector	District	Both sexes	Male	Female	Density (People / km^2)
Cyinzuzi	Rulindo	13,662	6,392	7,270	408
Mbogo	Rulindo	16,795	8,026	8,769	411
Ngoma	Rulindo	10,881	5,072	5,809	346
Rusiga	Rulindo	10,888	5,116	5,772	347
Shyorongi	Rulindo	23,545	11,114	12,431	504
Gatsata	Gasabo	37,110	19,445	17,665	6,163
Jali	Gasabo	25,057	12,121	12,936	671
Kanyinya	Nyarugenge	21,859	10,777	11,082	904
All sectors		**159,797**	**78,063**	**81,734**	**1,219**

Source: NISR, 2012

Table 3: Distribution of resident population in Yanze watershed in 2012 by their employment status

Sector	Employed			Unemployed			Inactive			Total count
	Male	Female	Both sexes	Male	Female	Both sexes	Male	Female	Both sexes	
Cyinzuzi	2,870	3,534	6,404	32	51	83	631	841	1,472	7,959
Mbogo	3,403	3,991	7,394	35	81	116	845	1,180	2,025	9,535
Ngoma	2,350	2,902	5,252	33	55	88	460	538	998	6,338
Rusiga	2,302	2,707	5,009	15	16	31	532	799	1,331	6,371
Shyorongi	4,063	4,222	8,285	141	235	376	2,237	3,055	5,292	13,953
Gatsata	10,275	5,589	15,864	411	977	1,388	2,481	4,466	6,947	24,199
Jali	4,886	4,570	9,456	232	385	617	1,880	2,990	4,870	14,943
Kanyinya	3,824	2,217	6,041	107	170	277	2,367	4,005	6,372	12,690
All sectors	**33,973**	**29,732**	**63,705**	**1,006**	**1,970**	**2,976**	**11,433**	**17,874**	**29,307**	**95,988**

Source: NISR, 2012

b. Land use and Tenure System

Land use in the catchment is composed of forest plantations, open agriculture dominated by seasonal crop land, and closed agriculture mainly occupied by intercropping agriculture system. The major crops cultivated in Yanze watershed are beans, cassava, sweet potato and irish potato. Maize, irish potatoes and vegetables are cultivated along the valley and low-lying areas while cassava and beans are cultivated on the hillside.

Other significant land uses in the catchment include perennial crops (dominated by coffee and banana plantations), irrigated lands along the main streams i.e., Yanze, Cyonyonyo and Mulindi, built-up areas (occupied by rural settlements and part of Gatsata informal settlement) and grazing zones represented by farmland in Gako cell within Rusiga Sector along Kigali-Musanze road.

3.3. Theoretical Framework

The theoretical framework we adopted in this study provides a logical structure through which key concepts of this study and their relationships were organized to provide a context for interpreting the findings. It was derived from the adaptation of existing Soil Erosion Models used by other similar studies.

As can it be seen in Figure 4, the study is subdivided into two main components. First, the Revised Universal Soil Loss Equation (RUSLE) model was used to develop the soil erosion risk profile of the watershed. The methodology used for this component was adapted from previous studies that were conducted at larger-scale both at country level[23] and at Nyabarongo river basin[13].

The output of this component is a map that shows which zones in the study area are most prone to soil erosion. The subdivision of these zones was done such that they coincide with the delineated sub-watersheds that were used during the hypsometric analysis stage.

The second component of the study consists of carrying out a hypsometric analysis of the watershed to determine the hypsometric curves and integrals of each of the sub-watershed (level 5) in the study area.

Finally, a correlation analysis using the linear regression technique was conducted to establish whether there is any positive relationship between the soil erosion risk and the hypsometric stage each sub-watershed is at.

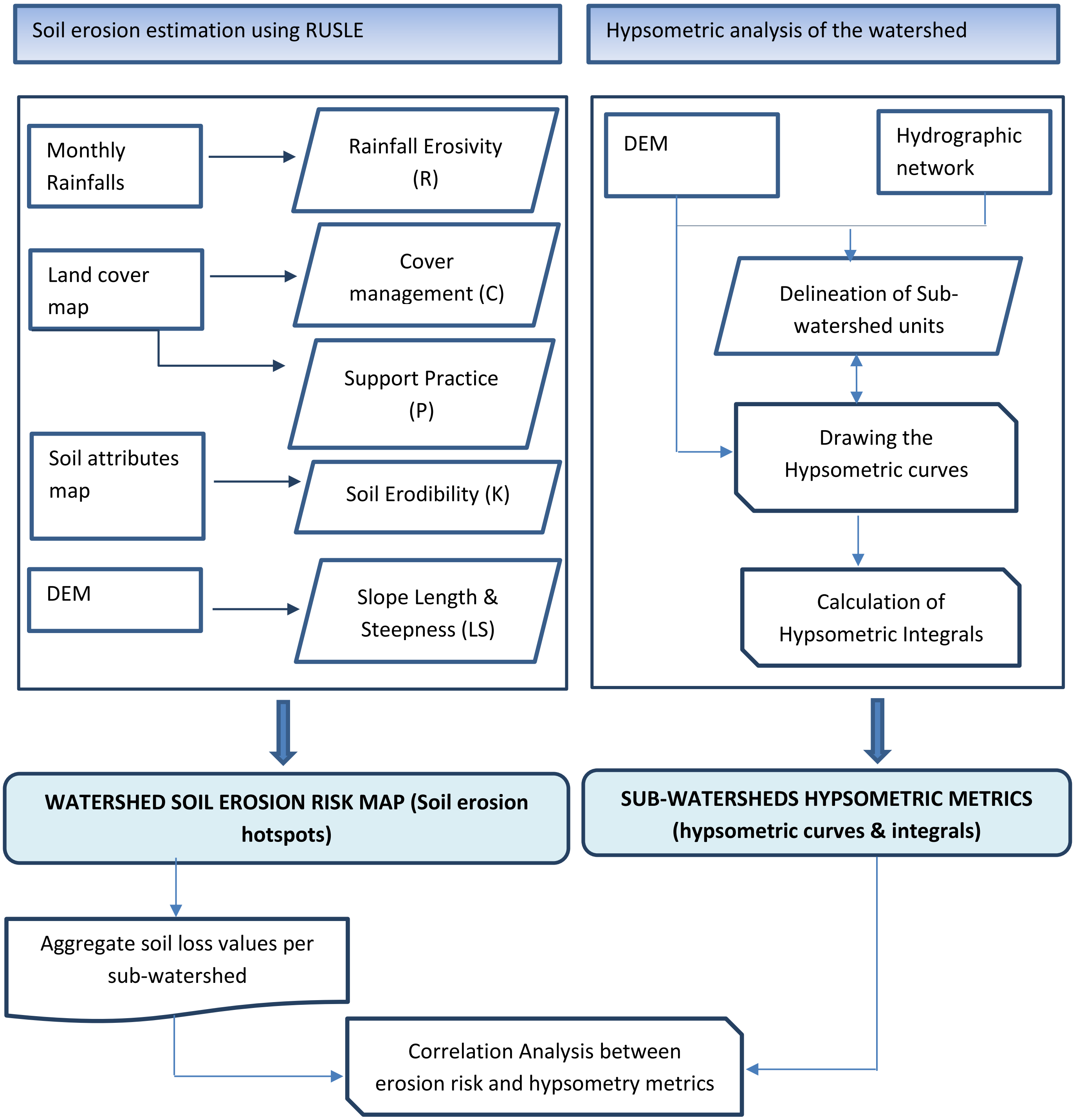

Figure 4: Theoretical framework of the study (*adapted from*[7])

3.4. Detailed Methodology per Study Objective

3.4.1. Delineating sub-catchments within Yanze watershed

Using ArcMap's hydrology tool and the DEM of Rwanda clipped to the boundaries of Yanze watershed, the latter was subdivided into 93 sub-catchments of different areas ranging from 20 to 300 Ha (Figure 7). Each sub-catchment was then given a 5-character code to serve as the unique ID throughout the remaining steps of the process.

3.4.2. Morphometric Analysis of Yanze Watershed Using GIS

The process of determining the hypsometric characteristics of Yanze watershed was conducted in two steps:

Step one consisted of delineating micro-catchments within Yanze watershed. This was done using ArcGIS' hydrology tools where the main input data was the DEM of Yanze watershed that was obtained by masking Rwanda's DEM dataset with Yanze watershed's vector boundary layer.

The second step consisted of drawing a hypsometric curve for each delineated micro-catchment and calculating its corresponding hypsometric integral. This was done using ArcMap and R software. The hypsometric curves were drawn using an R script to process the data produced by an ArcMap model that was developed to produce tables containing areas covered by different contour lines in each sub-catchment (Figure 5).

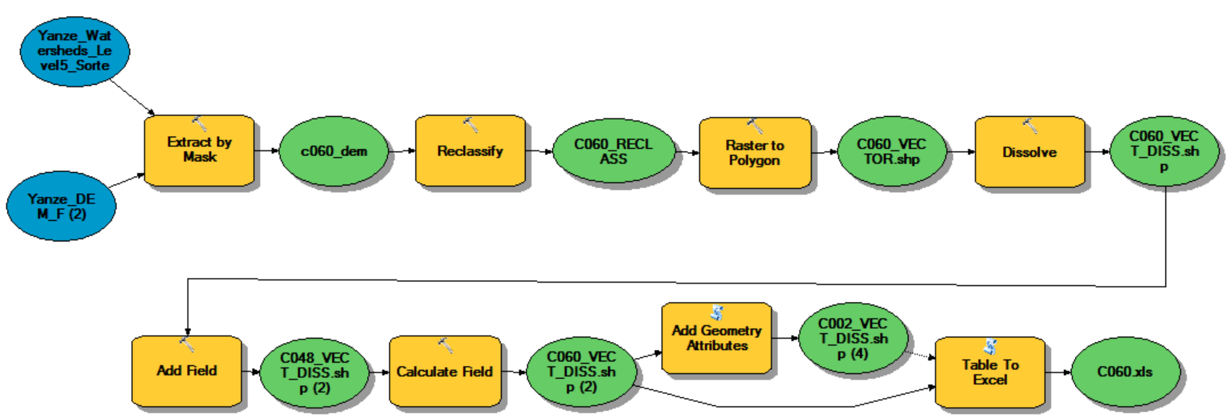

Figure 5: Diagram of ArcMap's model to produce data for HI calculation

This ArcMap model performs the following tasks: 1) it extracts the DEM of the sub-catchment, 2) reclassifies the DEM into 30 equal classes, 3) converts the reclassified DEM to vector using the "Value" field, 4) dissolves the features using the "Value" field, 5) calculates the area of each polygon, and 6) exports the table to a text file (CSV).

The hypsometric integrals were calculated by fitting a 3rd degree polynomial equation to the normalized contour lines area-elevation data and integrating it within the limits of 1 and 0[35]. For instance, by analyzing the whole watershed of Yanze watershed using this method, it was found that the watershed as a whole has a hypsometric integral of 0.695 which means that it is still at the young stage of its geomorphological evolution (Figure 6).

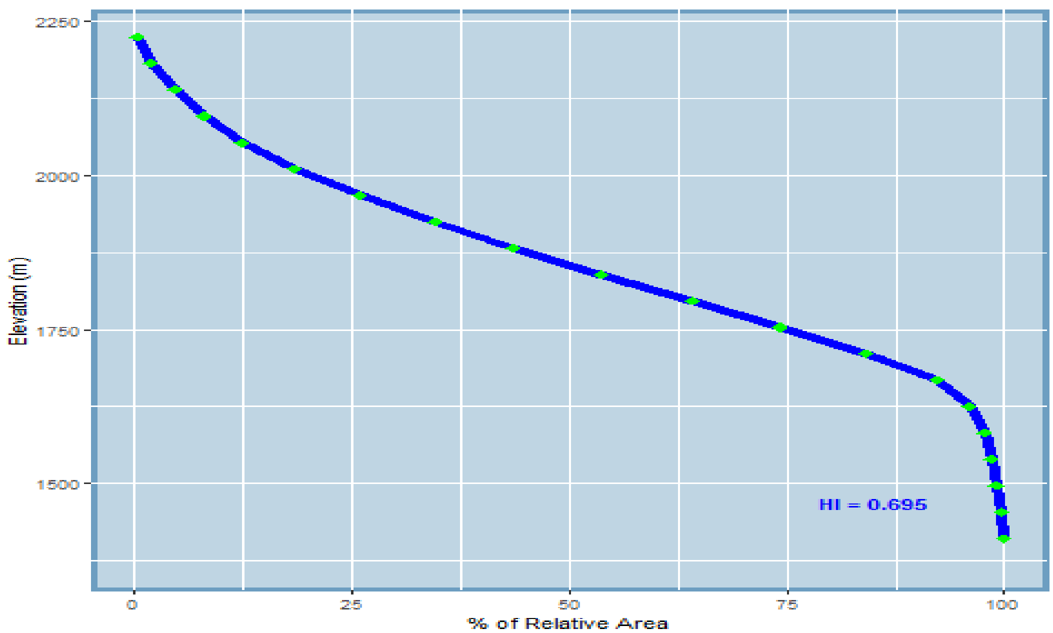

Figure 6: Hypsometric curve and integral of Yanze watershed (Source: Author, 2018)

3.4.3. Development of a soil erosion risk profile of Yanze watershed using RUSLE

The RUSSLE model uses a simple equation with six factors as presented in Equation(1). These six factors were incorporated into a GIS environment using the raster calculator function of 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 factor reflects the effect of rainfall intensity on soil erosion. Normally, it is defined as the total of the product of storm rainfall energy (E) and the maximum 30-min rainfall intensity (I30) for all rainfall events in the area[17]. Its calculation thus requires at least 10 years of detailed and continuous precipitation data showing both the intensity and duration of each rainfall event[7]. Also known as the rainfall erosion index, it measures the aggregate erosion potential of rainfall events by combining each storm event's energy and intensity through relatively rigorous mathematical equations that were built empirically through continuous observations by scientists over decades of research. Such hyetograph data or high-resolution rainfall data (pluviograph data) is rarely available for most rural areas where RUSLE is usually applied[42].

In response to this, various studies have tried to estimate the R factor using the more readily available monthly and annual precipitation data instead[8]. The methods applied depend on which climatic zone the study area is found in[8]. For Rwanda, the equation [Equation (2)] which was developed for wet tropical regions and applied in Hawaii[18] has been demonstrated to give reasonable estimates for the R factor[12–14, 27].

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

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 was 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[27]. It is defined as the rate of soil loss per erosion index unit as measured on a unit plot. The latter has been arbitrarily defined as a 21.1m long plot with a uniform lengthwise slope of 9%, kept in continuous fallow, and tilled up and down the slope[44].

The factor K accounts for soil texture, structure, organic matter, and permeability. Similar to the R-factor, the quantitative value of the K-factor is also empirically determined[27].

For our study, the estimation of the K-factor done using soil properties (sand, clay, silt, and organic carbon fractions) compiled through the Africa Soil Information Service (AfSIS) project by ISRIC with a spatial resolution of 250m[10, 39]. The K values were then computed using Equation 3 developed during the development of the Erosion Productivity Impact Calculator (EPIC) model[43] that was used by[12, 23] in the region:

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

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

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). The constant value of 0.1317 is used to convert the K factor from the American imperial unit system to the international/metric unit system[23, 30].
The computation of this equation again was done using ArcGIS' raster calculator function.

c. Topographic factor (LS)

The topographic factor characterizes the ratio of soil loss at a site with "standard" slope steepness (S) of 9% and slope length (L) of 22.6 m[7]. It is defined as the expected ratio of soil loss per unit area from a field slope to that from a 22.12848m length of uniform 9-percent slope under otherwise identical conditions[44].
From the equation (4) derived from [44], we estimated the LS factor using ArcMap's Hydrology tools to calculate the flow accumulation value for each cell in our study, and then used the software's ArcAnalyst tools to derive the slope map from our DEM. Finally, we fed the resulting rasters into the software's Raster Calculator tool to produce the final LS factor layer.

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

where **LS** is the slope length and gradient factor (dimensionless), **S** is the slope gradient in percentage, and **m** is a slope angle contingent variable reflecting the soil's susceptibility 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[30, 44] as below:

Table 4: 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 continuous fallow[6]. It represents the ratio of soil erosion from land cropped under specific conditions and it determines how natural vegetation or crop cover reduces rainfall energy and overflows or intercepts rainfall energy and increases infiltration[4].

The value of C is set to 1 under standard fallow conditions where the vegetation cover has been totally stripped off. As vegetative cover approaches 100%, the C factor value approaches 0. The Cover Management (C) factor along with the Support Practice factor (P) are the two most important factors in the RUSLE equation and they indeed set apart the potential soil loss estimation from the actual soil loss. This is because they are the factors that are controlled by human intervention whereas the other factors are geophysical and human intervention affect them only at a certain level.

For our study, the LULC map of Yanze watershed was produced using Sentinel-2 images taken in the rain season of year 2020 (March-May) and C values were assigned to each landcover class using a lookup table through ArcMap's raster reclassification tool. These values were derived from[15, 29] and were used in previous RUSLE studies conducted in Rwanda[4].

Table 5: Assignment of C factor values to Landuse Classes

Land Use	C Factor	Land Use	C Factor
Forest	0.03	Barren Land	0.45
Shrubland	0.03	Built-Up	0
Grassland	0.01	Water Body	0
Agricultural Land	0.21		

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[27]. The P factor is dependent on the slope and the cultivation method such as contour tillage and planting, strip-cropping, terracing, grassed waterways, and subsurface drainage[27].

Its values range from 0 to 1 and are calculated as the ratio of the rate and amount of soil loss due to a specific support practice to the soil loss due to row farming in upward and downward of the slope condition[8]. If no conservation practice is present, the P factor is taken as 1. If a soil conservation practice exists at a given area, then a proper P factor value is assigned for that particular area with respect to the slope.

Wischmeier and Smith[44] provides tables to estimate the P factor based on the slope gradient and different support practices. Unfortunately, the establishment of a P factor map at a watershed scale with a complex land-use system is nearly impossible to be assessed using these tables.

For our study, we classified the watershed's 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 6) established by[36] and used by[4]. For the remaining area where no soil conservation practices exist, a value of 0.75 was assigned according to[13]. The extent of soil conservation practices in the area was digitized manually from Google Earth images and cross-checked with ancillary data obtained from local authorities.

Table 6: 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

3.4.4. Regression analysis between the hypsometric parameters of Yanze sub-catchments and their estimated soil losses due to erosion

To answer the main research question of documenting and quantifying the level at which hypsometric analysis predicts soil erosion in a watershed, the soil erosion risk profile map of the study area was reclassified using ArcGIS' zonal statistics tools so that each sub-catchment is given a score that is equal to the mean value of all the cells in that sub-catchment.

Finally, the two variables (hypsometric integral & erosion risk score) were subjected to a regression analysis to quantify the correlation between them. A linear regression model was then built using R scripting language for this process.

3.5. Data Acquisition and Processing

The main ancillary datasets that were used in this study are the following:

Table 7: Ancillary datasets used in the study

No	Dataset	Source
1	Officially delineated boundary of Yanze watershed	Rwanda watersheds map (Level 1 to 5) prepared by the Water for Growth Rwanda (W4GR) project under former Rwanda Water and Forestry Authority
2	Digital Elevation Model (DEM) of Yanze watershed	High-resolution DEM data for Rwanda sourced from Rwanda Land Management and Use Authority
3	Land Use Land Cover (LULC) data for Yanze watershed	Rwanda land cover maps (2000-2015) developed by Rwanda Land Management and Use Authority and the new (year 2018) high resolution map developed by the Water for Growth Rwanda (W4GR) project
4	High to medium resolution satellite images of Yanze watershed	Cloud-free composite Sentinel-2 images processed using the Google Earth Engine
5	Rainfall data covering Yanze watershed	37 years' time series (1981-2017) of daily rainfall data provided by Rwanda Meteorology Agency. The data was recorded at 30 meteorological stations located in and around Yanze watershed. For the periods where records were missing, the data was reconstructed from remote sensing and other proxies as part of the ENACTS Data Library initiative.
6	Soil properties data for Yanze watershed	Clipped from the Africa Soil Information Services (AfSIS) data downloaded from ESRIC's Africa Soil Profiles Database

Apart from this secondary data acquired from different sources, primary data was also collected using unstructured interviews with local leaders in charge of land management in the districts and the sectors that comprise Yanze Watershed. Additional interviews were also conducted with selected staff of central government authorities in charge of water and land management (MoE, REMA, RWFA, etc) as well as projects that are active in the watershed in the environmental management sector.

3.6. Conclusion

The methodology used for soil erosion modeling in Yanze watershed was borrowed from other similar studies that were conducted in Rwanda and Nyabugogo basin. This is an important point since the application of empirical equations for the calculation of RUSLE factors requires that such equations were tested and validated in a region that has similar characteristics. The data used was also gathered from local sources except for soil characteristics where locally produced data is not yet available. For hypsometric analysis, all the existing tools available were explored and found not to be suitable for this study. Therefore, a tool built around R was developed to draw hypsographic curves and calculate hypsometric integrals for the sub-watersheds within Yanze watershed all at once. This tool has also been bundled into an R package and submitted to the Comprehensive R Archive Network (CRAN) repository so that other researchers can access and use it as well.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Chapter Overview

In this chapter, the results obtained from the hypsometric analysis conducted in Yanze watershed will be presented and their interpretation attempted. Also, the findings from soil erosion modeling in the watershed will be specified and summary statistics outlined. Finally, the outcome of the regression analysis between hypsometric integrals and soil erosion risk will be presented and discussed.

4.2. Hypsometric analysis of Yanze watershed

Using an ArcMap-based model developed for the purpose of producing data to be used for hypsometric integral calculation (Figure 5), a table was produced for each sub-catchment which specifies the minimum and maximum elevation for the sub-catchment and the areas between each consecutive contours (Table 8). For reproducibility purpose, an R script that replicates the results of this model was also developed and presented in (APPENDIX 1).

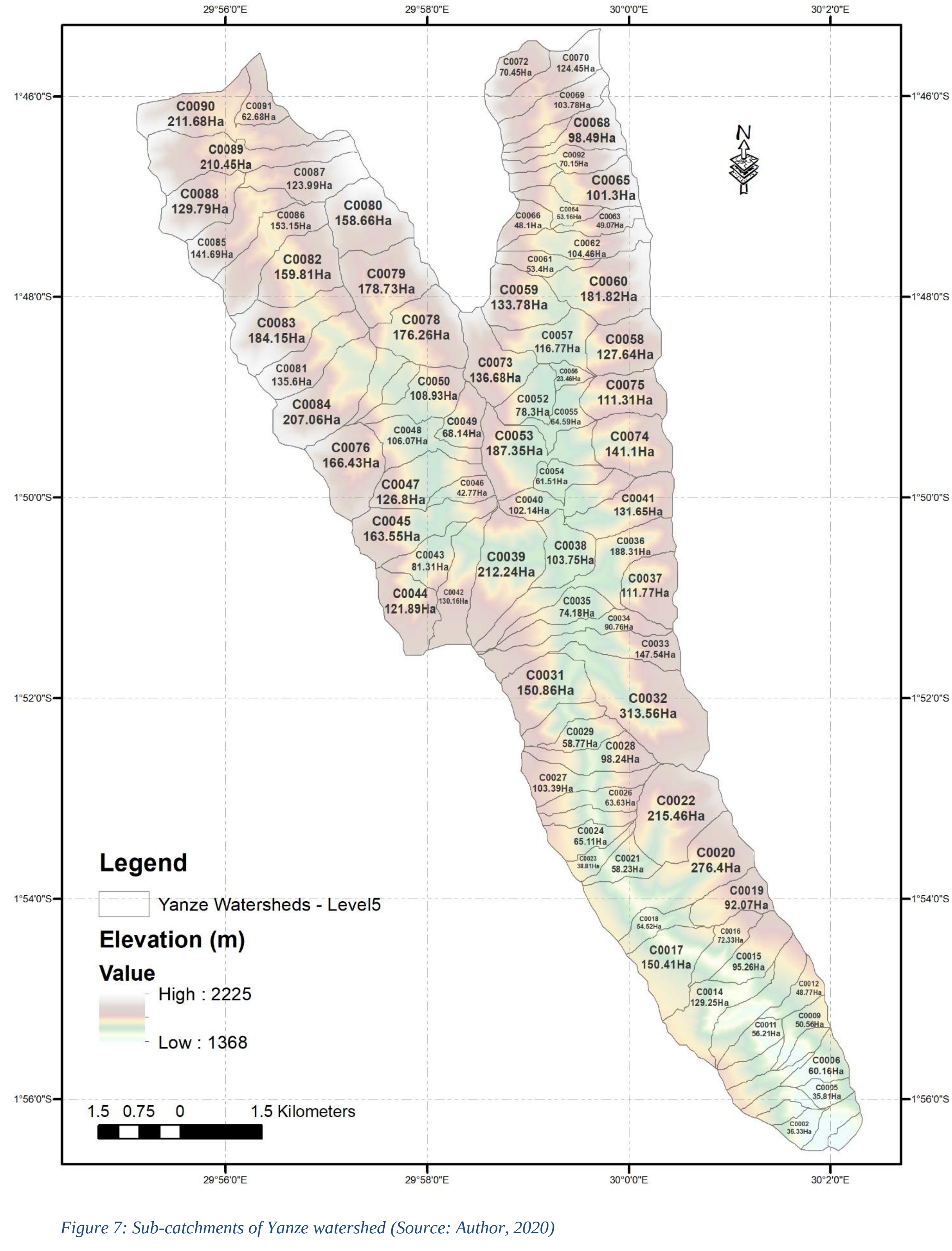

Figure 7: Sub-catchments of Yanze watershed (Source: Author, 2020)

Table 8: Calculated HI values for some sub-catchments of Yanze watershed

Class ID	Countour Elevation	Area Between Countours (Ha)
0	1,368.00	-
1	1,376.07	4.98
2	1,384.13	1.70
3	1,392.20	1.47
4	1,400.27	0.90
5	1,408.33	0.95
6	1,416.40	0.87
7	1,424.47	0.84
8	1,432.53	0.84
9	1,440.60	0.79
10	1,448.67	0.64
11	1,456.73	0.52
12	1,464.80	0.42
13	1,472.87	0.50
14	1,480.93	0.37
15	1,489.00	0.45
16	1,497.07	0.32
17	1,505.13	0.33
18	1,513.20	0.33
19	1,521.27	0.30
20	1,529.33	0.33
21	1,537.40	0.33
22	1,545.47	0.32
23	1,553.53	0.29
24	1,561.60	0.33
25	1,569.67	0.30
26	1,577.73	0.37
27	1,585.80	0.37
28	1,593.87	0.31
29	1,601.93	0.20
30	1,610.00	0.18

Afterwards, an R script (APPENDIX 1) was developed to use this data and draw the hypsometric curve and calculate the hypsometric integral for each sub-catchment.

In short, the script performs the following tasks:

1) **Normalization of the data**: For elevation, we first subtract the minimum elevation from each contour elevation and then divide the result by the range. For area, we divide the cumulative area at each contour area starting from the top contour by the total area of the sub-catchment(6).

$$normalizedElevation = \frac{countourElevation - minElevation}{maxElevation - minElevation} \quad (5)$$

$$normalizedArea = \frac{cumulativeSumArea}{totalArea} \quad (6)$$

2) **Plotting of the hypsometric curve**: The normalized data is plotted on a 2D chart showing the relative area on the X-axis and the relative elevation on the Y-axis.
3) **Calculation of the hypsometric integral**: a 3-degree polynomial equation is fitted to the data and is integrated within the limits of 0 and 1.
4) **Outputting the summary table and charts**: each of the generated charts are saved on disk and a summary table is produced.

Table 9: Hypsometric integrals of Yanze sub-catchments

ID	MIN (m)	MAX (m)	AREA (Ha)	HI
C0001	1370	1667	43.69	0.683
C0002	1378	1717	35.13	0.714
C0003	1394	1785	23.81	0.885
C0004	1396	1805	36.34	0.837
C0005	1400	1674	35.87	0.725
C0006	1410	1760	60.33	0.777
C0007	1420	1810	44.72	0.886
C0008	1435	1826	42.79	0.865
C0009	1428	1777	50.38	0.896
C0010	1424	1760	27.49	0.765
C0011	1437	1827	56.32	0.773
C0012	1451	1849	48.52	0.936
C0013	1454	1890	117.18	0.809
C0014	1504	1823	129.44	0.797
C0015	1534	1952	95.33	0.795
C0016	1540	1934	72.52	0.77
C0017	1546	1781	150.75	0.893
C0018	1556	1761	54.62	0.757
C0019	1681	1996	92.31	0.795
C0020	1561	2055	276.95	0.721
C0021	1565	1807	58.38	0.727
C0022	1632	2071	215.66	0.811
C0023	1569	1837	38.85	0.814
C0024	1571	1843	65.29	0.821
C0025	1575	1855	45.77	0.825
C0026	1580	1910	63.85	0.862
C0027	1584	1984	103.58	0.898
C0028	1586	1967	98.51	0.84
C0029	1589	1894	58.9	0.733
C0030	1594	1923	55.82	0.782
C0031	1599	1976	150.85	0.775
C0032	1604	2048	313.76	0.82
C0033	1606	2008	147.43	0.835
C0034	1607	2010	90.98	0.807
C0035	1609	1952	74.38	0.596
C0036	1611	2011	188.76	0.724
C0037	1656	1963	111.95	0.862
C0038	1613	1783	103.92	0.62
C0039	1621	2011	212.68	0.693
C0040	1622	1956	102.42	0.68
C0041	1621	1946	131.89	0.805
C0042	1632	2007	130.44	0.795
C0043	1637	2002	81.43	0.633
C0044	1688	2008	122.11	0.886
C0045	1639	2047	163.94	0.706
C0046	1643	1950	42.85	0.778
C0047	1646	2044	126.99	0.613
C0048	1655	1945	106.34	0.557
C0049	1664	1995	68.27	0.794
C0050	1661	2006	109.18	0.635
C0051	1670	1785	29.51	0.61
C0052	1639	1933	78.43	0.521
C0053	1631	1959	187.96	0.636
C0054	1624	1889	61.57	0.532
C0055	1633	1874	64.73	0.5
C0056	1647	1871	23.53	0.545
C0057	1653	2075	116.94	0.547
C0058	1675	2092	127.88	0.835
C0059	1666	2133	133.85	0.706
C0060	1673	2168	182.28	0.765
C0061	1683	2140	53.59	0.646
C0062	1690	2171	104.65	0.629
C0063	1700	2171	49.19	0.803
C0064	1704	2107	53.28	0.633
C0065	1714	2153	101.25	0.767
C0066	1721	2138	48.17	0.759
C0067	1728	2118	27.82	0.737
C0068	1743	2168	98.34	0.84
C0069	1767	2185	103.89	0.741
C0070	1799	2225	124.47	0.772
C0071	1750	2130	29.82	0.62
C0072	1826	2167	70.43	0.776
C0073	1660	2140	136.76	0.817
C0074	1660	1962	141.07	0.856
C0075	1664	2033	111.39	0.85
C0076	1709	2129	166.7	0.889
C0077	1677	1998	50.02	0.525
C0078	1694	2140	176.37	0.742
C0079	1727	2125	178.83	0.81

C0080	1888	2216	158.66	0.811
C0081	1696	2179	135.98	0.736
C0082	1718	2080	160.22	0.756
C0083	1708	2183	184.49	0.813
C0084	1683	2138	207.39	0.729
C0085	1754	2150	141.64	0.694
C0086	1742	2148	153.33	0.795
C0087	1764	2216	124.23	0.797
C0088	1765	2177	129.53	0.799
C0089	1772	2203	210.67	0.707
C0090	1779	2199	211.79	0.618
C0091	1782	2031	62.4	0.833
C0092	1734	2150	70.13	0.722
C0093	1368	1610	20.85	0.589

The results of the hypsometric analysis of Yanze watershed showed that all its sub-catchments are at young and equilibrium stages with hypsometric integrals ranging from 0.5 to 0. 0.936 and an average of 0.75 (Figure 8). The vertical blue lines in Figure 8 indicate the breakpoints separating hypsometric integrals representing the monadnock stage from the mature stage (0.4) and young stage (0.6) respectively. This means that almost all the sub-catchments of Yanze watershed are still in the young stage and therefore have a potential to undergo intensive erosion if not enough soil conservation measures are undertaken. However, there is still a variability in this potential, and this is what was explored in the next component of this study.

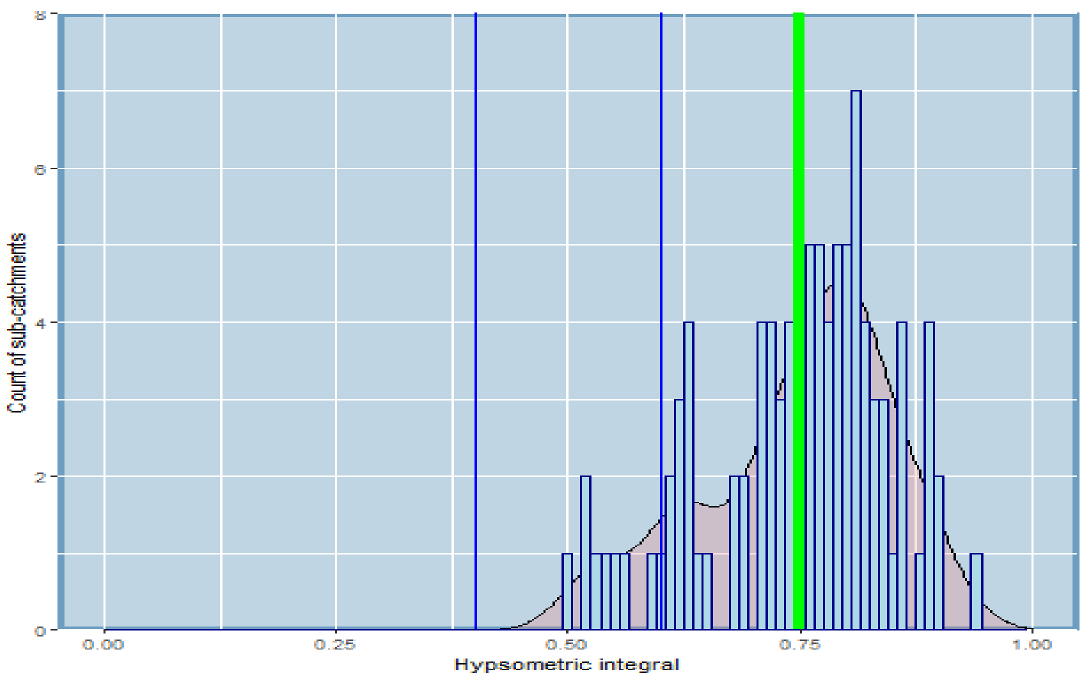

Figure 8: Distribution of hypsometric integrals of Yanze sub-catchments (Source: Author, 2018)

As it can be seen from the hypsometric curves of the sub-catchments of Yanze watersheds (APPENDIX 2), the majority have a convex-upward shape which suggests they are still at young stage and therefore still have to undergo further erosion. The ones that have a concave shape are located in the downstream part of the watershed which suggests that much future erosion is expected more in the upstream part of the watershed (Figure 9).

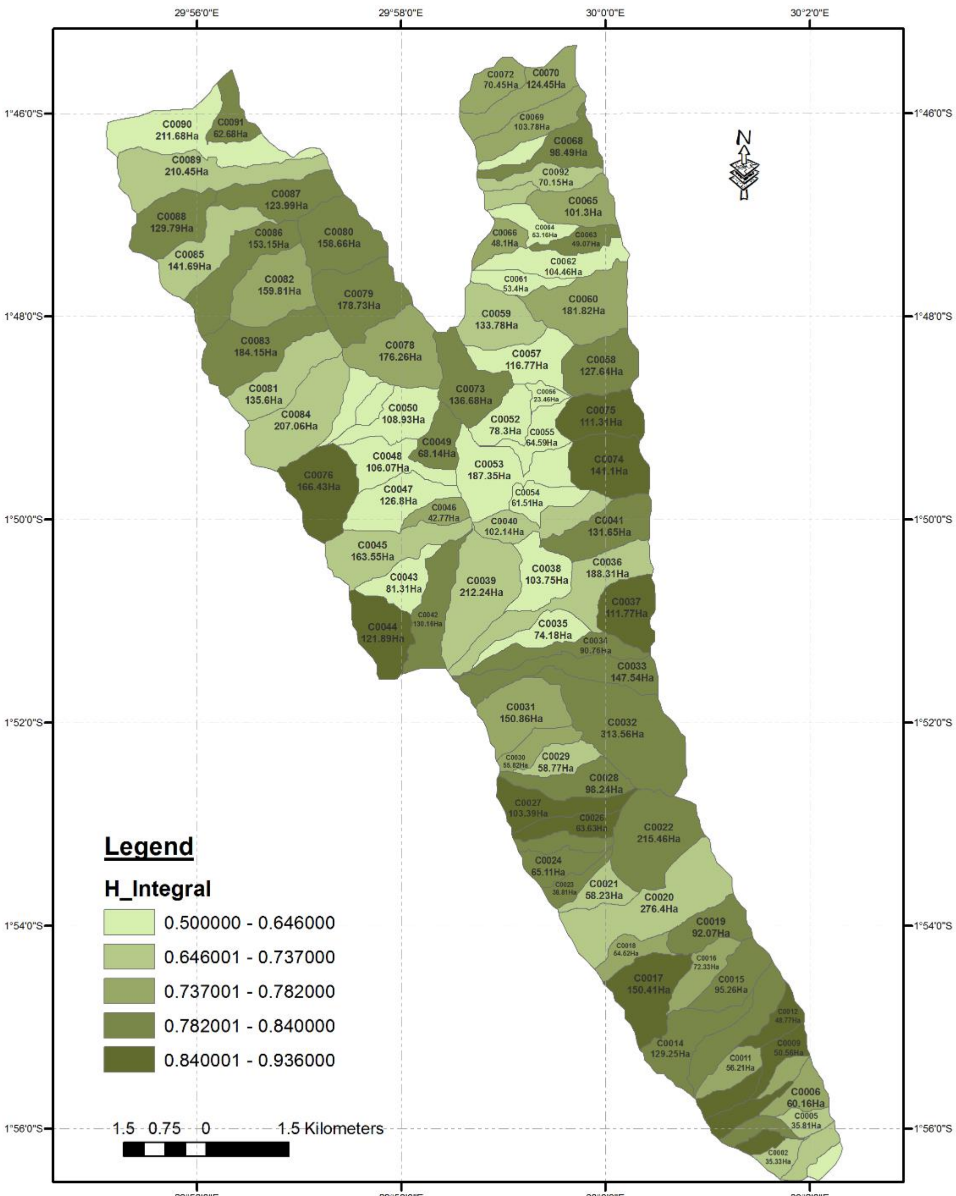

Figure 9: Spatial distribution of hypsometric integral values of Yanze sub-catchments ((Source: Author, 2018)

4.3. Soil Erosion Risk in Yanze Watershed

The risk profile map of Yanze watershed was developed using a RUSLE model. The final values of RUSLE factors were computed and formatted into rasters and each resampled to a 10x10m grid. For the R factor, values range from 3,500 to 5,380 MJ.mm.ha^{-1}.h^{-1}.year^{-1} which reflects the high level of erosivity typical to tropical wet climates. For the K factor, values range from 0.253 to 0.148 Tonnes.ha.h.ha^{-1}.MJ^{-1}.mm^{-1} and its spatial distribution in the watershed shows some higher values upstream and lower values downstream (Figure 9Figure 10).

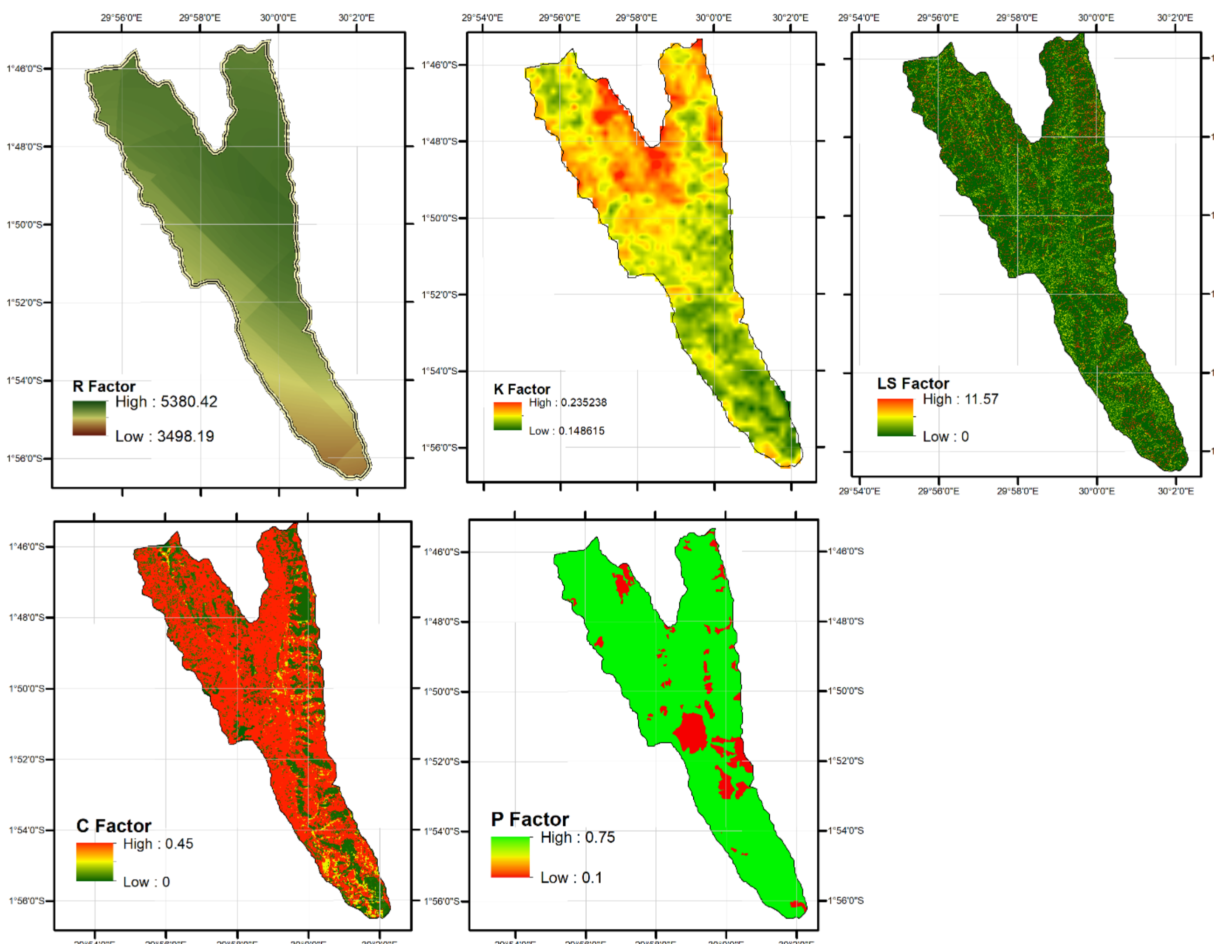

Figure 10: Spatial distribution of RUSLE factor values in Yanze watershed (Source: Author, 2018)

The product of all of 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 Yanze watershed (Figure 11).

The table from this soil risk profile map was then exported as a text file to be used in the regression analysis between soil erosion risk and hypsometric integrals.

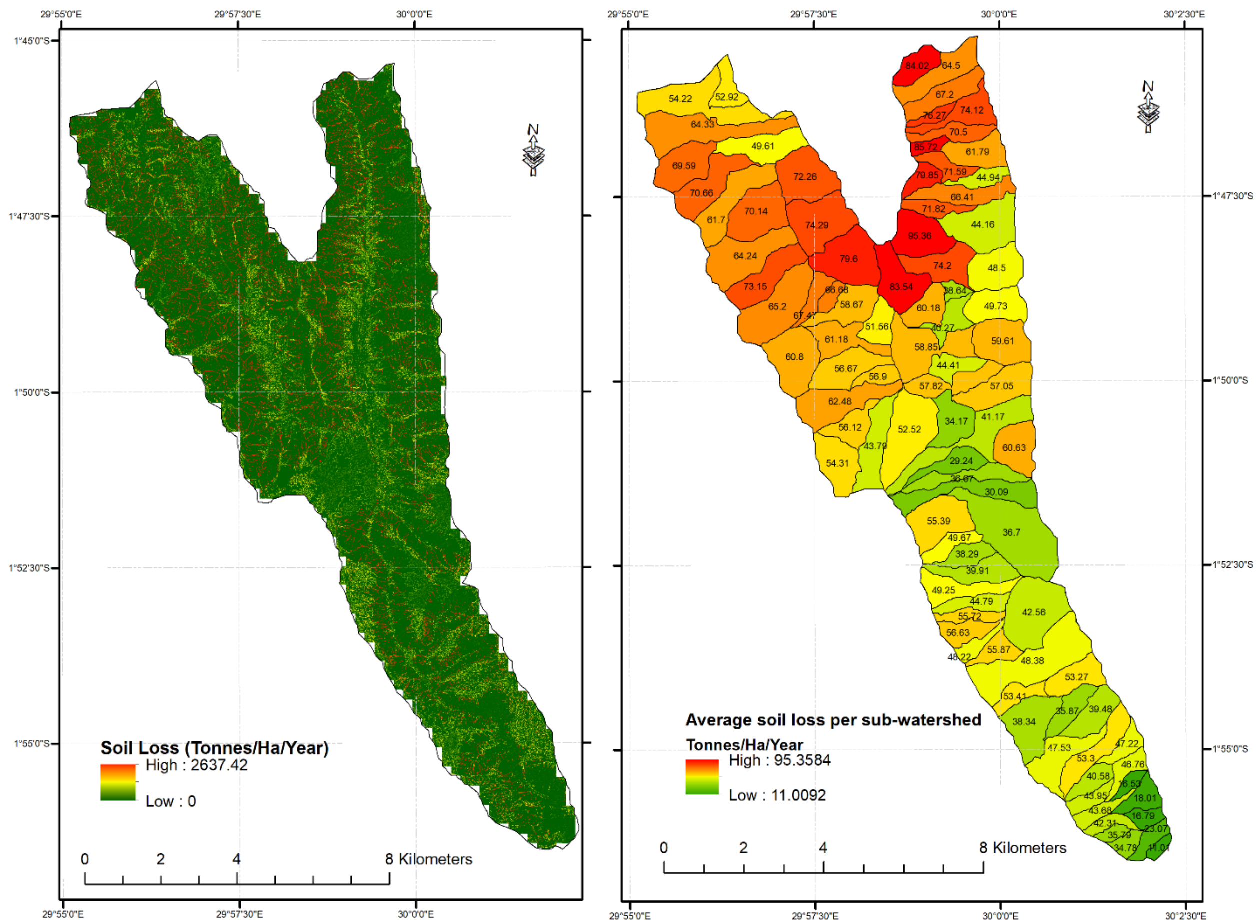

Figure 11: Soil loss map of Yanze watershed (Source: Author, 2018)

4.4. Correlation between Hypsometric Integrals and Soil Erosion Risk in Yanze Watershed

A correlation analysis between the hypsometric integrals of Yanze sub-catchments and their corresponding soil erosion risk index was conducted using linear models' algorithms in R. The results of the best fitting model showed 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) is explained by the predictor (hypsometric integral). The P-Value of the relationship is also very high (0.25) which means even this little observed relationship probably derives from chance.

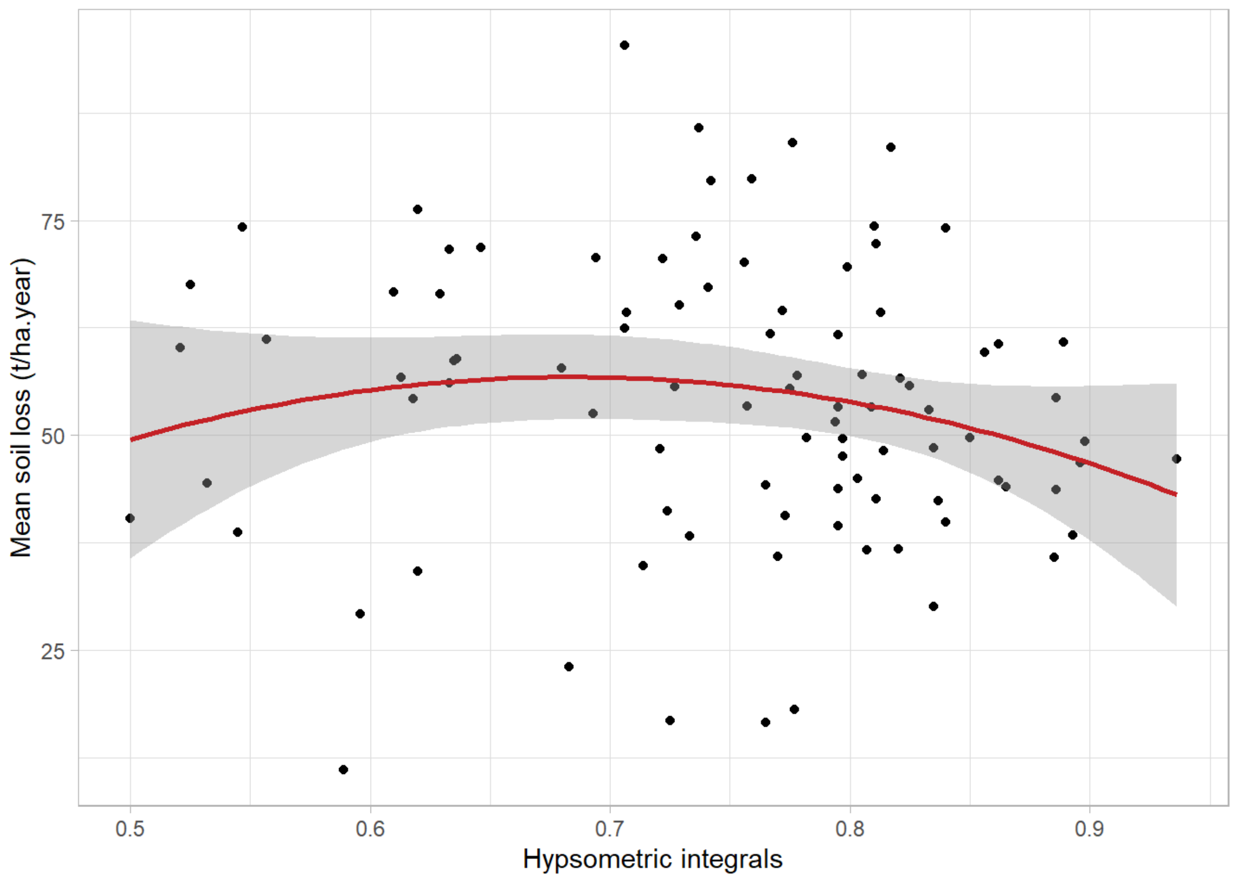

Figure 12: Relationship between soil loss and hypsometric integrals in Yanze watershed

4.5. Conclusion

The hypsometric analysis of Yanze watershed revealed that the watershed is still at its young geomorphological stage 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 compared to the national average. This hints to the fact that soil erosion in Yanze has a connection with the geomorphology of the watershed. However, the regression analysis conducted between hypsometric integrals of sub-catchments within the watershed and their respective mean soil loss values didn't yield any significant correlation. We therefore conclude that hypsometry is not the main driver of erosion in Yanze watershed and therefore other factors should be considered when conducting erosion prioritization in the watershed.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In this study, a morphometric analysis of Yanze watershed was conducted with an emphasis on estimating hypsometric parameters of its different sub-catchments. A thorough analysis of these hypsometric characteristics of the watershed was subsequently conducted to determine if they could provide valuable insights into identifying the watershed areas at higher risk of future soil erosion. This analysis involved a comparison with the soil erosion risk map generated from soil erosion modeling conducted for the watershed.

The morphometric analysis of Yanze watershed showed that this watershed is still at young stage of its geomorphological evolution and this is confirmed by the form of the hypsometric curves of its sub-catchments which are convex upward[34]. The mean hypsometric integral of its sub-catchments was calculated to be 0.75 which means that almost 75% of the land mass in the watershed is yet to undergo further erosion before it reaches the mature and then the monadnock stage[40].

It is important to clarify however that this interpretation of the hypsometric integral for a watershed applies to a geological time scale and therefore can sometimes have little to do with observed soil erosion at short time scales as it was demonstrated by this study.

Regarding soil loss prediction in Yanze watershed, it was found that soil erosion in Yanze watershed is high compared to the national mean soil loss value[23]. This can be attributed to the socio-economic factors of erosion such as overexploitation of farmland which are different in Yanze watershed given its proximity with the City of Kigali.

The lack of strong correlation between the hypsometric integral and short-term erosion potential suggests that hypsometry is not the main driver of erosion in the watershed and therefore should not be the main factor to be considered during erosion prioritization studies conducted in the watershed.

5.2. Recommendations

The exploration of the relationship between hypsometric parameters such as the hypsometric integral and soil erosion potential in Yanze watershed shows no correlation between these two. However, we believe there exist other morphometric parameters that can be better proxy indicators of soil erosion potential. We therefore recommend more studies to document further the relationship between morphometry and soil loss by incorporating more morphometric parameters in the model. Suggested parameters to be added are geometric parametric such as basin shape, elongation ratio, and shape/form factor as well as relief parameters such as basin shape, elongation ratio, and shape/form factor as well as relief parameters such as terrain ruggedness index, elevation-relief ratio, and gradient ratio.

Regarding the use of GIS tools as a basis of conducting soil loss prediction for a basin, this study demonstrated the effectiveness of such tools. However, for hypsometric analysis, we found there don't exist software that are adequate for studies related to watershed analysis as part of watershed management planning. The identified issues with existing tools include gaps in terms of (1) not being simple enough for use by non-specialist practitioners, (2) not being open-source for the purpose of transparency and ease of modification, (3) being provided as part of larger programs (sometimes expensive packages) which becomes a bloated solution for a simple problem, and (4) not being automated enough for easy integration into watershed analysis workflows conducted in an accessible environment such as R.

We therefore recommend that researchers involved in such studies should engage with developers' communities to develop an adequate tool to be used during comprehensive morphometric analysis of watersheds. During this study, a preliminary step has been taken in this direction by developing an R script that can draw hypsographic curves and calculate hypsometric integrals for the sub-catchments within a watershed all at once.

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APPENDICES

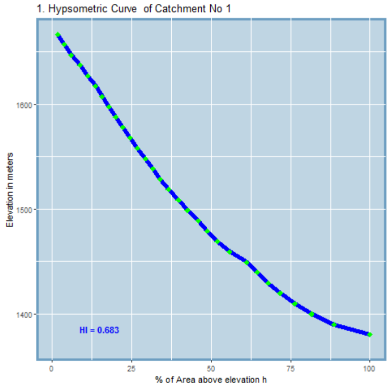
APPENDIX 1: Code snippet of an R scrip to calculate hypsometric integrals of sub-catchments

```
generateHypsoTables <- function(x, y) {
  #test the arguments of the function
  test_arguments(x, y)
  # Load data and set the number of contours to use
  DEM <- NULL
  DEM <- y
  watersheds <- x
  nbr_classes <- 30
  #alternatively, you can request the user to supply this data
  #nbr_classes = readline()
  #nbr_classes = as.integer(nbr_classes)

  #initialize min-max data frame and the data list
  min_max <- data.frame(X1=character(), X2=double(), X3=double())
  colnames(min_max) <- c("code", "min", "max")
  data_list <- list()

  #loop and calculate the hypso of each feature
  for(i in 1:nrow(watersheds)){
    #extract the DEM of the sub-watershed
    DEM_i <- crop(DEM, extent(watersheds[i,]))
    DEM_i <- mask(DEM_i, watersheds[i,])
    #calculate range step
    max <- maxValue(DEM_i)
    min <- minValue(DEM_i)
    range <- max - min
    step <- range/nbr_classes
    #update the min-max table
    min_max[i,] <- c(i, min, max)
    #create and update a temporary reclassification matrix
    reclass_df <- data.frame(X1=double(), X2=double(), X3=double())
    colnames(reclass_df) <- c("bottom_value", "top_value", "new_value")
    counter <- 1
    for(j in seq(from = min+step, to = max, by = step)){
      bottom_value <- j-step
      top_value <- j
      new_value <- j
      reclass_df[counter,] <- c(bottom_value, top_value, new_value)
      counter <- counter + 1
    }
    #reclassify DEM_i
    DEM_i_recl <- reclassify(DEM_i, reclass_df, include.lowest=TRUE)
    #calculate areas per class, give it a clearer name, and add it to the
data list
    table <- calc_areas(DEM_i_recl)
    data_list[[i]] <- table
    #reset the reclassification matrix
    rm(reclass_df)
  }
  return(list(min_max, data_list))
}
```

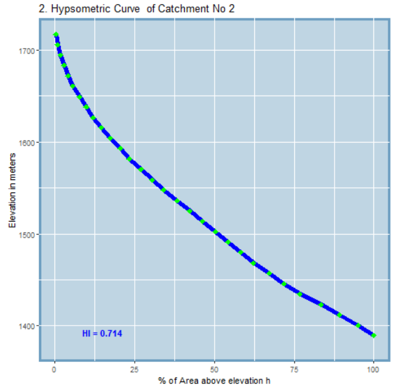
```
drawHypsoCurves <- function(x, y){
  AREA_NORM <- ELEV_NORM <- ELEV <- AREA <- NULL  #deal with the  R CMD check
  test_arguments(x, y)   #test the input arguments
  dir.create("HYPSO_OUTPUT") #create the output folder in the working directory
  final_table <- list() #initialize the catchment details list
  # get minimum-maximum elevation data and hypsometric tables for each sub-catchments
  watersheds <- x; DEM <- y
  temp <- generateHypsoTables(watersheds, DEM)
  min_max <- temp[[1]]
  data_list <- temp[[2]]
  for (i in 1:nrow(watersheds)){
    n <- i
    # Read in the data and preprocess it
    minimum <- as.double(min_max$min[i])
    maximum <- as.double(min_max$max[i])
    data <- as.data.frame(data_list[[i]])
    data <- data %>% select(ELEV, AREA)
    data <- mutate(data, ELEV_NORM = (ELEV - minimum)/(maximum - minimum))
    data <- mutate(data, AREA_NORM = rev(cumsum(rev(AREA)))/sum(AREA))
    # Build the Hypsometric curve object
    g <- ggplot(data = data, aes(x = AREA_NORM * 100, y = ELEV))
    g <- g + geom_line(color = "blue", size = 2)
    g <- g + geom_point(color = "green", size = 3, shape = 18)
    g <- g + labs(title = paste(i, ". Hypsometric Curve  of Catchment No ", n, sep = ""),
                  x = "% of Area above elevation h",  y = "Elevation in meters")
    g <- g + ylim(minimum, maximum)
    g <- g + xlim(0, 100)
    # Determine the Hypsometric Integral
    fit = lm(ELEV_NORM ~ poly(AREA_NORM, 3), data = data)
    x <- polynom()
    p = summary(fit)$coefficients[2,1] * x + summary(fit)$coefficients[3,1] * x^2 +
    summary(fit)$coefficients[4,1] * x^3
    HI <- integral(p, c(1,0))
    # Output the results
    g <- g + annotate("text", y=minimum + 15, x= 15, label = paste("HI = ", round(HI,3),
sep = ""), color="blue", fontface="bold")
    png(paste("HYPSO_OUTPUT/", n, ".png", sep = ""))
    print(g)
    dev.off()
    #Update the main data list
    catchment_details <- list("minimum" = minimum, "maximum" = maximum, "data" = data,
"equation" = p, "h_integral" = HI)
    final_table[[n]] <- catchment_details
  }
  # Generate the summary data
  summary_table <- data.frame(x1 = character(),x2 = numeric(),x3 = numeric(),x4 = nu-
meric(),x5 = numeric(),stringsAsFactors = FALSE)
  colnames(summary_table)<-c("SUB_CATCHMENT_CODE","MIN_ELEV", "MAX_ELEV", "TOTAL_AREA",
"H_INTEGRAL")
  for (i in 1:nrow(watersheds)){
    n <- i
    SUB_CATCHMENT_CODE <- n
    MIN_ELEV <- final_table[[n]]$minimum
    MAX_ELEV <- final_table[[n]]$maximum
    TOTAL_AREA <- round(sum(final_table[[n]]$data$AREA),2)
    H_INTEGRAL <- round(final_table[[n]]$h_integral,3)
    summary_table[i,] <- c(SUB_CATCHMENT_CODE, MIN_ELEV, MAX_ELEV, TOTAL_AREA, H_INTE-
GRAL)}
  # Print the summary table and export it to CSV
  write.csv(summary_table, file = "HYPSO_OUTPUT/summary_table.csv")
  return(summary_table)
}
```

APPENDIX 2: Hypsometric Curves of Yanze Sub-Catchments

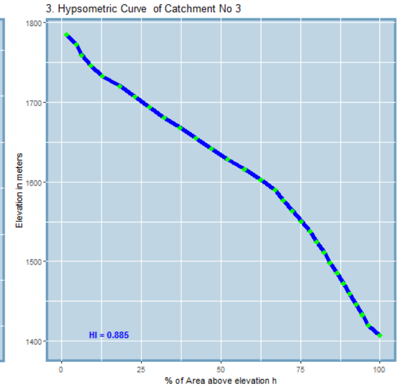
1. Hypsometric Curve of Catchment No 1



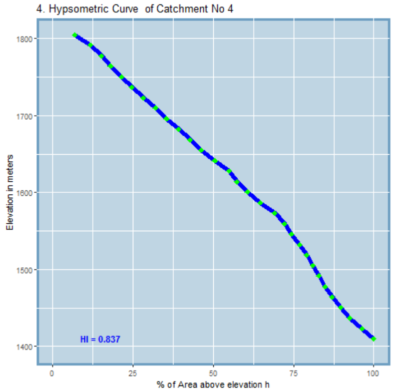
2. Hypsometric Curve of Catchment No 2



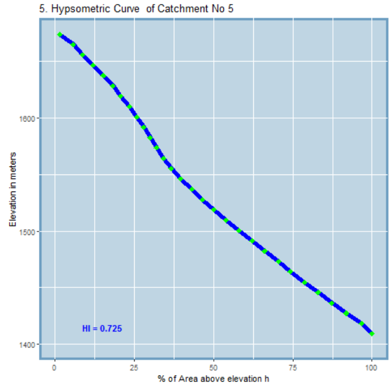
3. Hypsometric Curve of Catchment No 3



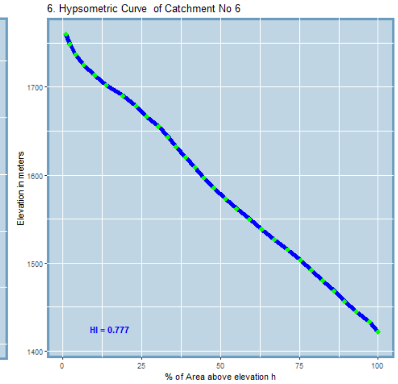
4. Hypsometric Curve of Catchment No 4



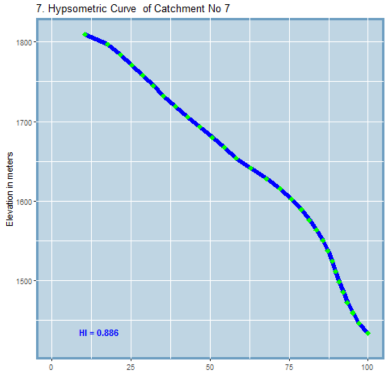
5. Hypsometric Curve of Catchment No 5



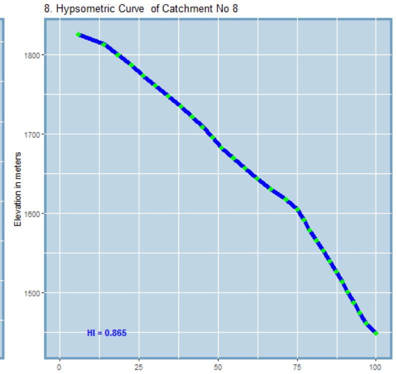
6. Hypsometric Curve of Catchment No 6



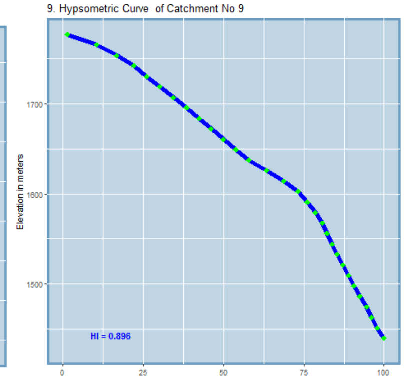
7. Hypsometric Curve of Catchment No 7



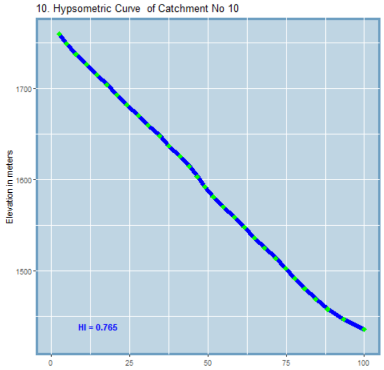
8. Hypsometric Curve of Catchment No 8



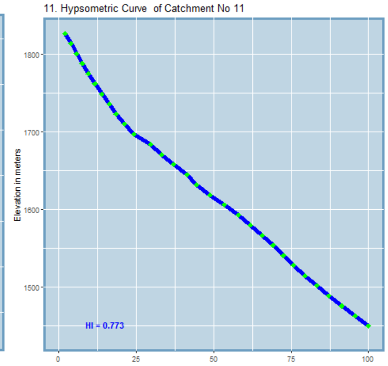
9. Hypsometric Curve of Catchment No 9



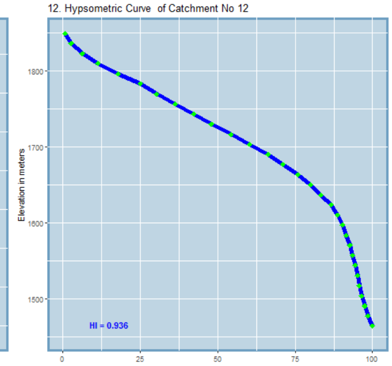
10. Hypsometric Curve of Catchment No 10



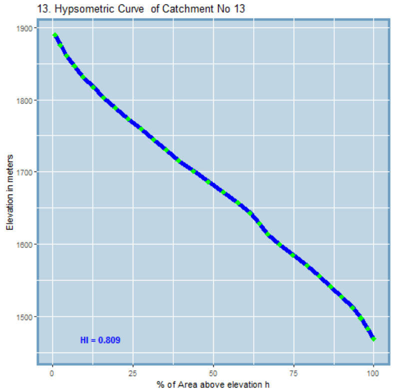
11. Hypsometric Curve of Catchment No 11



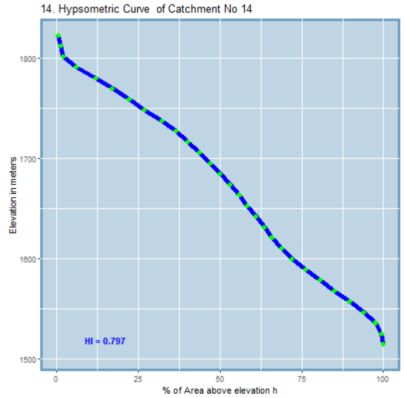
12. Hypsometric Curve of Catchment No 12



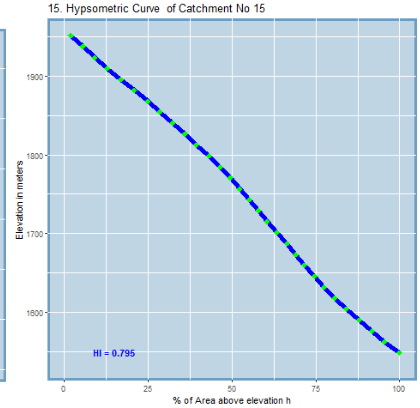
13. Hypsometric Curve of Catchment No 13



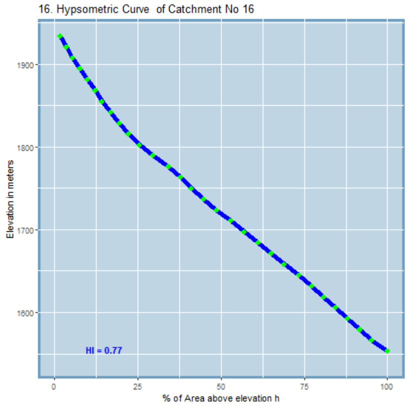
14. Hypsometric Curve of Catchment No 14



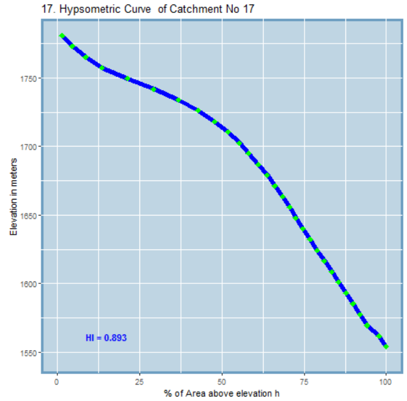
15. Hypsometric Curve of Catchment No 15



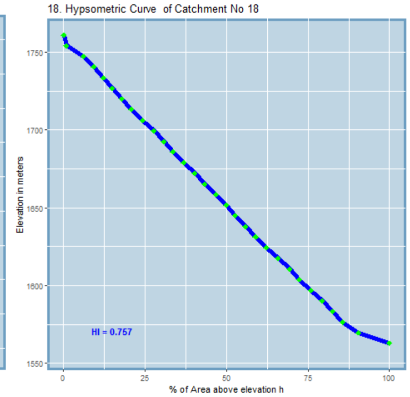
16. Hypsometric Curve of Catchment No 16



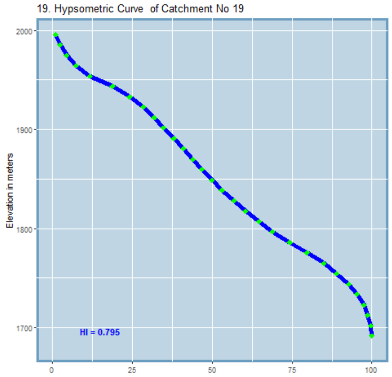
17. Hypsometric Curve of Catchment No 17



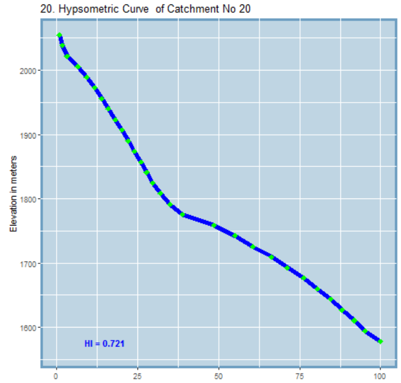
18. Hypsometric Curve of Catchment No 18



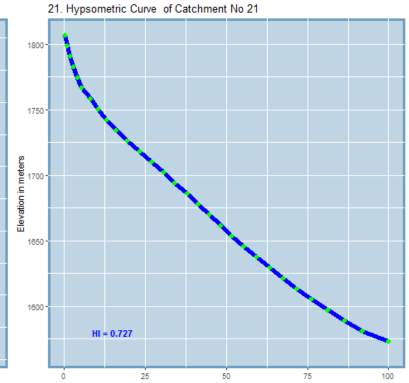
19. Hypsometric Curve of Catchment No 19



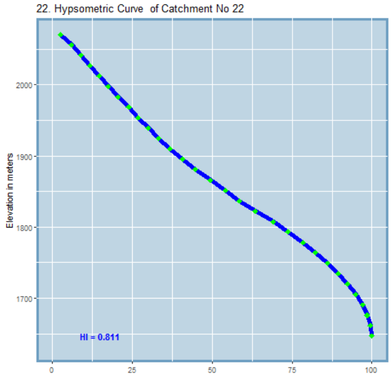
20. Hypsometric Curve of Catchment No 20



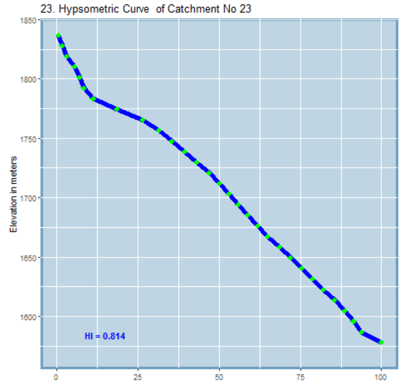
21. Hypsometric Curve of Catchment No 21



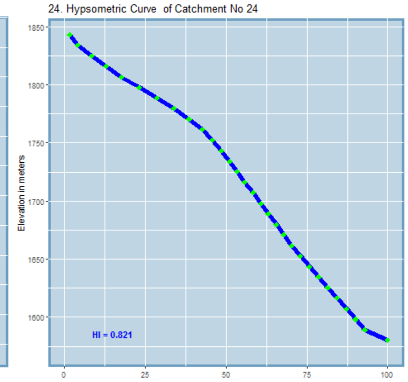
22. Hypsometric Curve of Catchment No 22

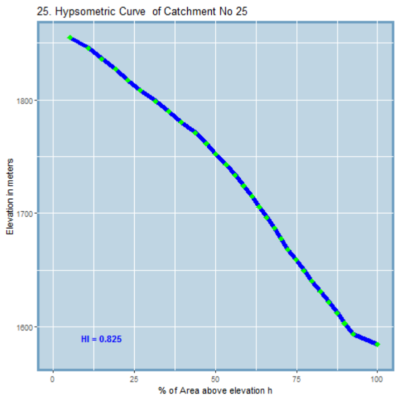


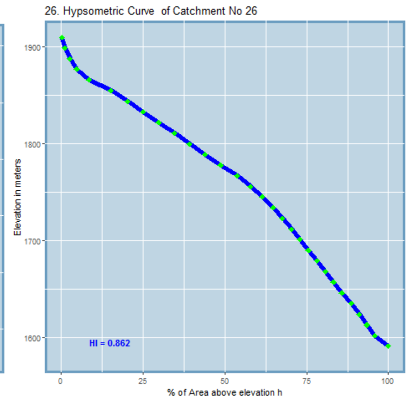
23. Hypsometric Curve of Catchment No 23

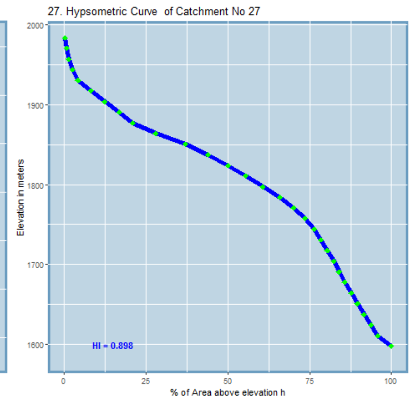


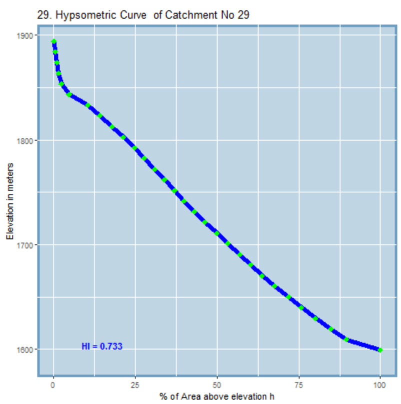
24. Hypsometric Curve of Catchment No 24

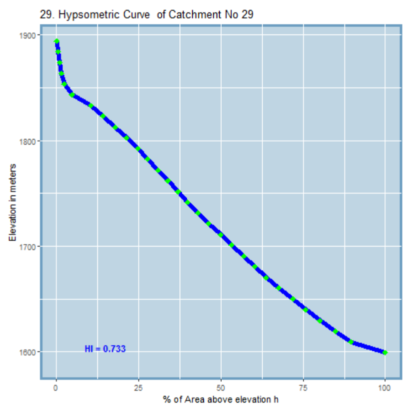


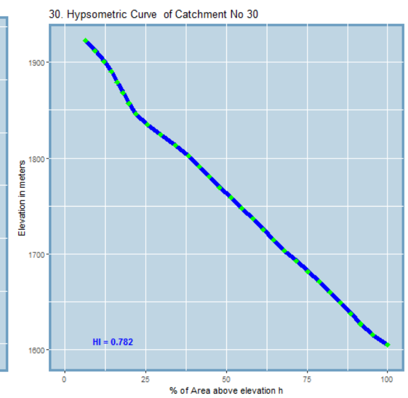

25. Hypsometric Curve of Catchment No 25
Elevation in meters
1800
1700
1600
HI = 0.825
0
25
50
75
100
% of Area above elevation h

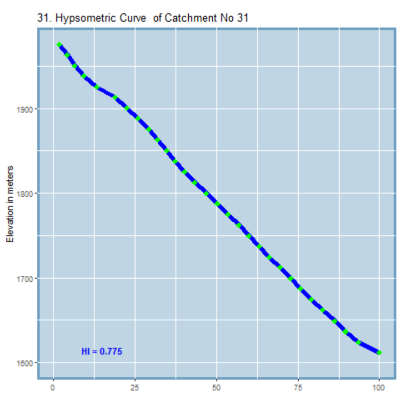

26. Hypsometric Curve of Catchment No 26
Elevation in meters
1900
1800
1700
1600
HI = 0.862
0
25
50
75
100
% of Area above elevation h

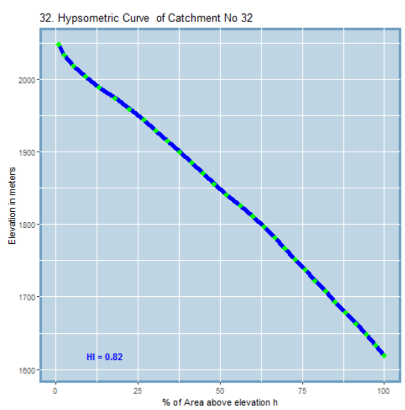

27. Hypsometric Curve of Catchment No 27
Elevation in meters
2000
1900
1800
1700
1600
HI = 0.898
0
25
50
75
100
% of Area above elevation h

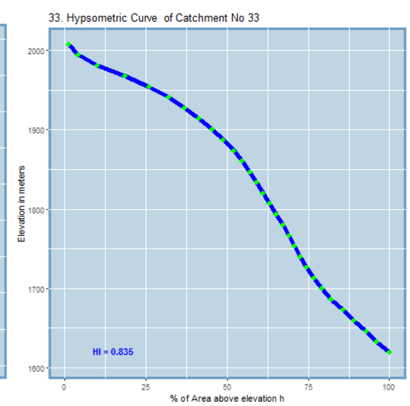

29. Hypsometric Curve of Catchment No 29
Elevation in meters
1900
1800
1700
1600
HI = 0.733
0
25
50
75
100
% of Area above elevation h

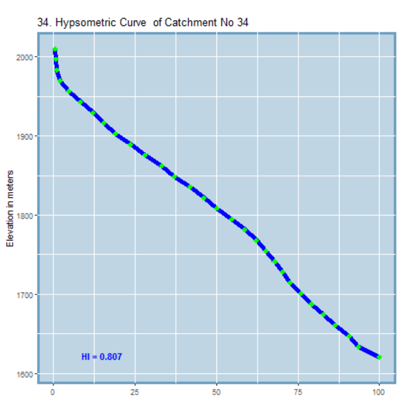

29. Hypsometric Curve of Catchment No 29
Elevation in meters
1900
1800
1700
1600
HI = 0.733
0
25
50
75
100
% of Area above elevation h

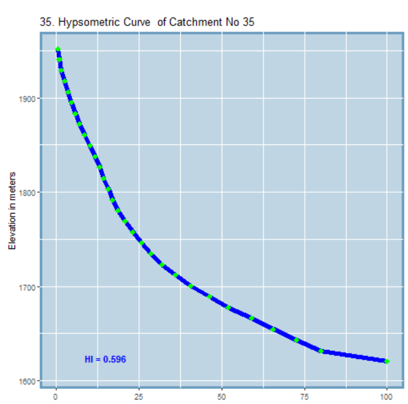

30. Hypsometric Curve of Catchment No 30
Elevation in meters
1900
1800
1700
1600
HI = 0.782
0
25
50
75
100
% of Area above elevation h

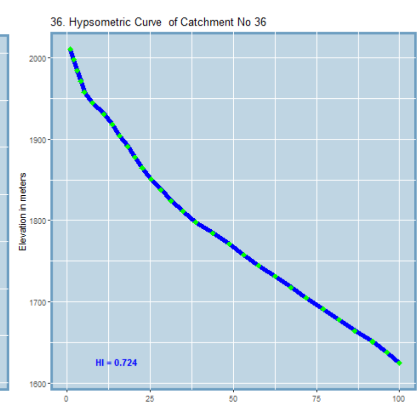

31. Hypsometric Curve of Catchment No 31
Elevation in meters
1900
1800
1700
1600
HI = 0.775
0
25
50
75
100
% of Area above elevation h

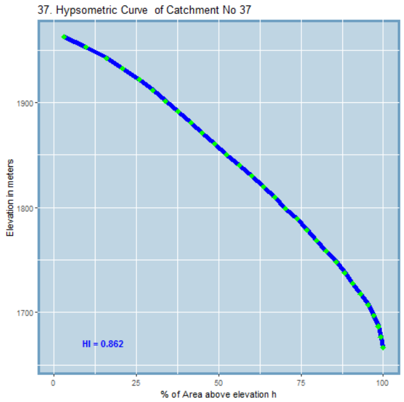

32. Hypsometric Curve of Catchment No 32
Elevation in meters
2000
1900
1800
1700
1600
HI = 0.82
0
25
50
75
100
% of Area above elevation h

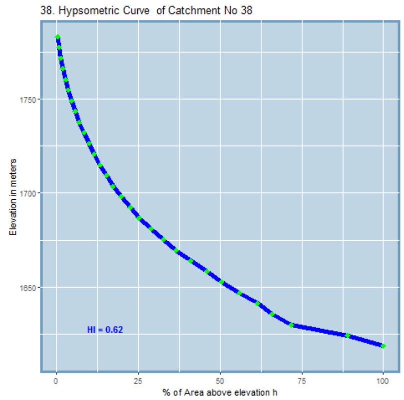

33. Hypsometric Curve of Catchment No 33
Elevation in meters
2000
1900
1800
1700
1600
HI = 0.835
0
25
50
75
100
% of Area above elevation h

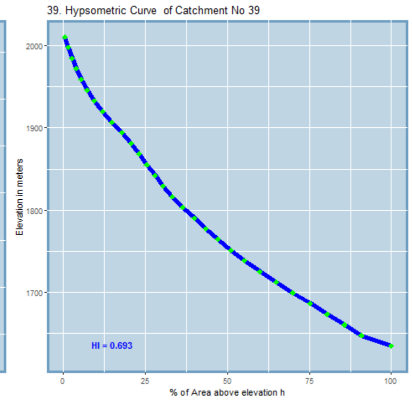

34. Hypsometric Curve of Catchment No 34
Elevation in meters
2000
1900
1800
1700
1600
HI = 0.807
0
25
50
75
100
% of Area above elevation h

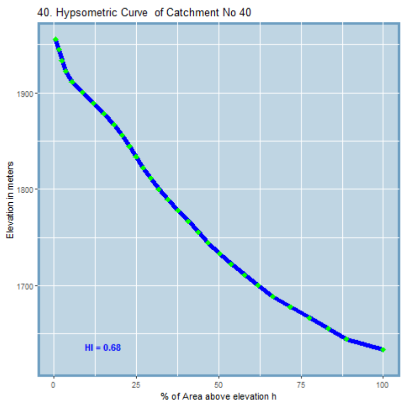

35. Hypsometric Curve of Catchment No 35
Elevation in meters
1900
1800
1700
1600
HI = 0.596
0
25
50
75
100
% of Area above elevation h

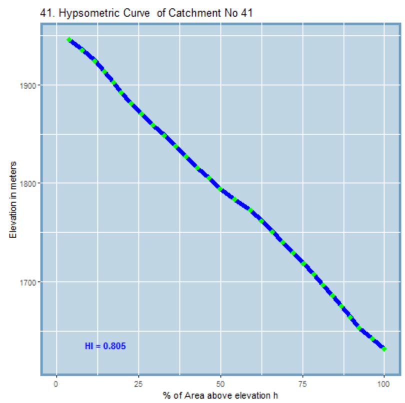

36. Hypsometric Curve of Catchment No 36
Elevation in meters
2000
1900
1800
1700
1600
HI = 0.724
0
25
50
75
100
% of Area above elevation h

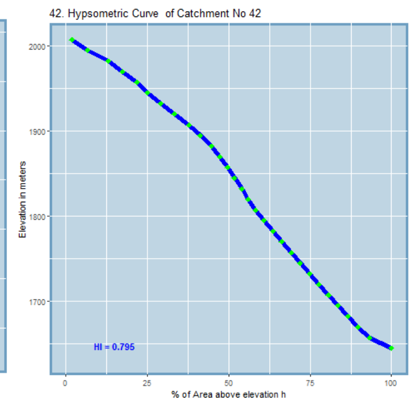

37. Hypsometric Curve of Catchment No 37
Elevation in meters
% of Area above elevation h
HI = 0.862

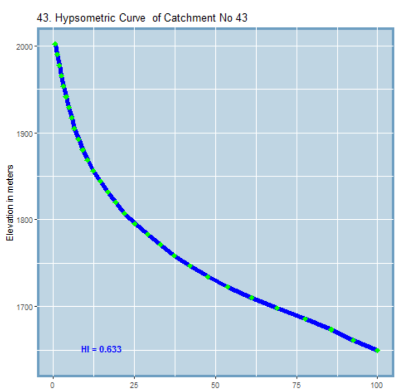

38. Hypsometric Curve of Catchment No 38
Elevation in meters
% of Area above elevation h
HI = 0.62

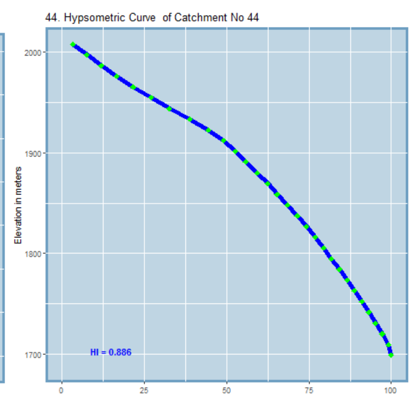

39. Hypsometric Curve of Catchment No 39
Elevation in meters
% of Area above elevation h
HI = 0.693

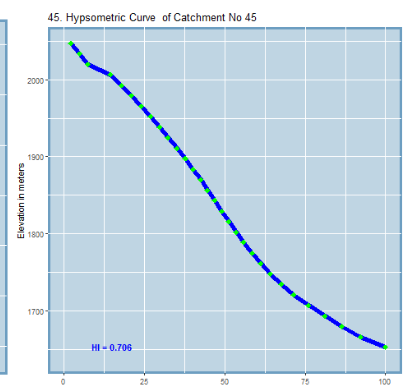

40. Hypsometric Curve of Catchment No 40
Elevation in meters
% of Area above elevation h
HI = 0.68

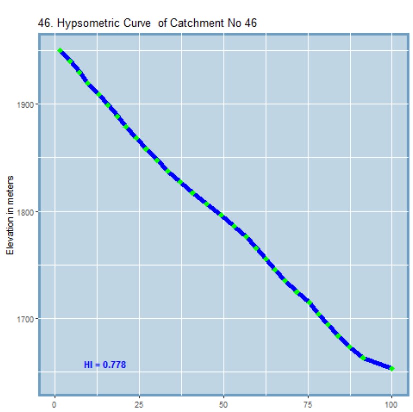

41. Hypsometric Curve of Catchment No 41
Elevation in meters
% of Area above elevation h
HI = 0.805

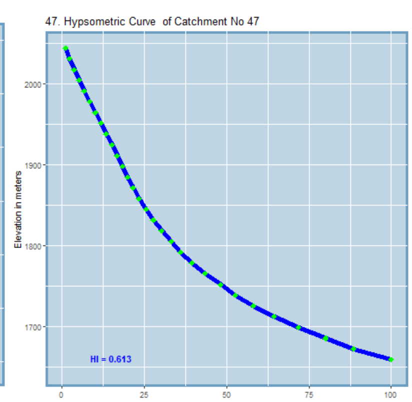

42. Hypsometric Curve of Catchment No 42
Elevation in meters
% of Area above elevation h
HI = 0.795

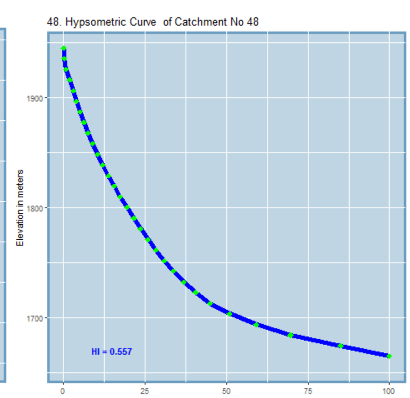

43. Hypsometric Curve of Catchment No 43
Elevation in meters
% of Area above elevation h
HI = 0.633


44. Hypsometric Curve of Catchment No 44
Elevation in meters
% of Area above elevation h
HI = 0.886

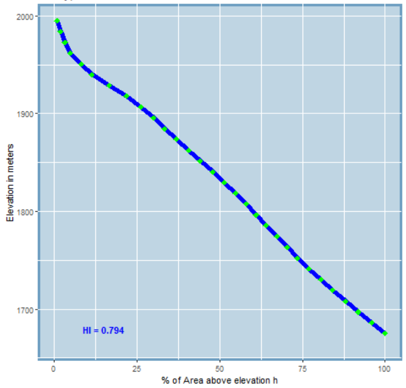

45. Hypsometric Curve of Catchment No 45
Elevation in meters
% of Area above elevation h
HI = 0.706


46. Hypsometric Curve of Catchment No 46
Elevation in meters
% of Area above elevation h
HI = 0.778

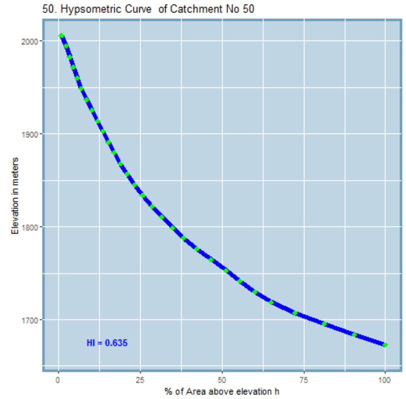

47. Hypsometric Curve of Catchment No 47
Elevation in meters
% of Area above elevation h
HI = 0.613


48. Hypsometric Curve of Catchment No 48
Elevation in meters
% of Area above elevation h
HI = 0.557

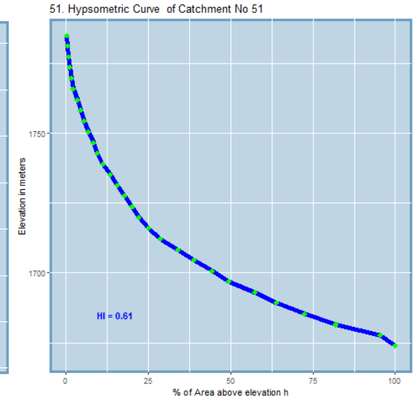
49. Hypsometric Curve of Catchment No 49



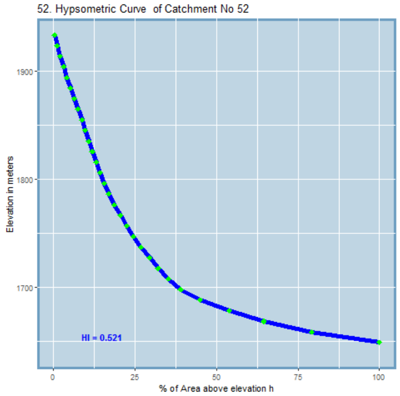
50. Hypsometric Curve of Catchment No 50



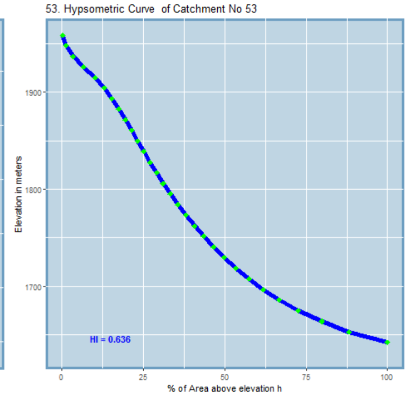
51. Hypsometric Curve of Catchment No 51



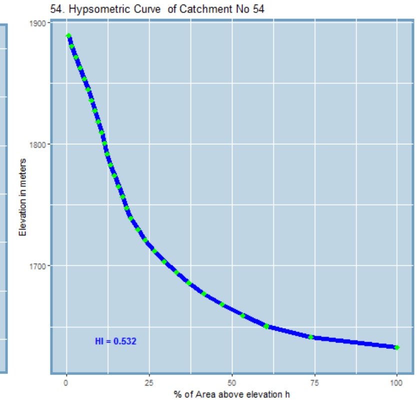
52. Hypsometric Curve of Catchment No 52



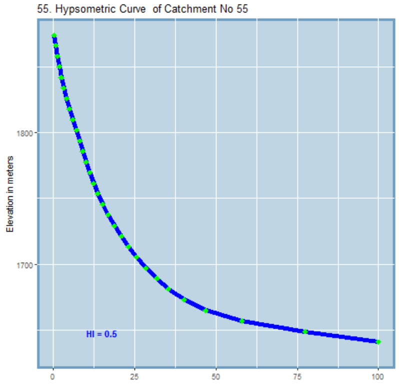
53. Hypsometric Curve of Catchment No 53



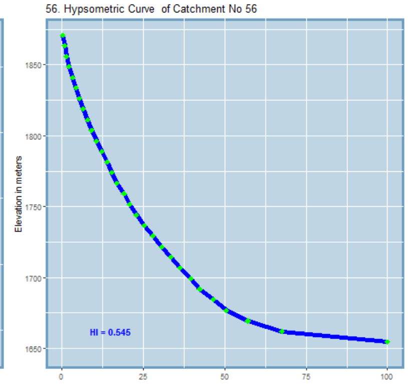
54. Hypsometric Curve of Catchment No 54



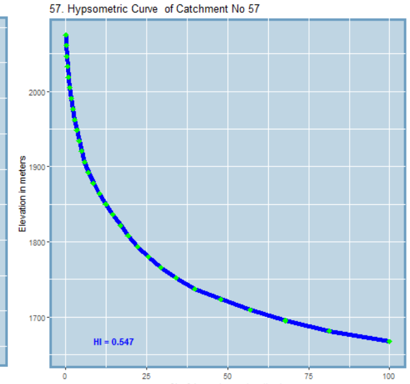
55. Hypsometric Curve of Catchment No 55



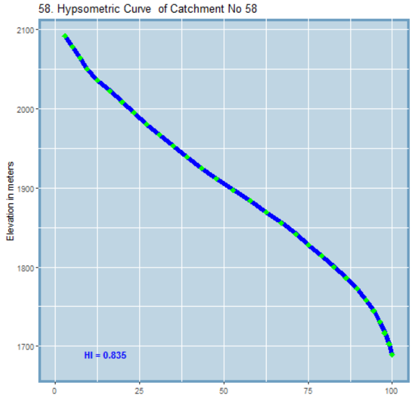
56. Hypsometric Curve of Catchment No 56



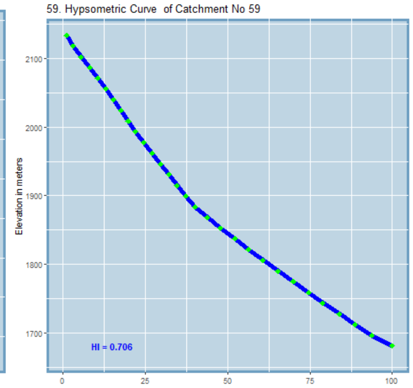
57. Hypsometric Curve of Catchment No 57



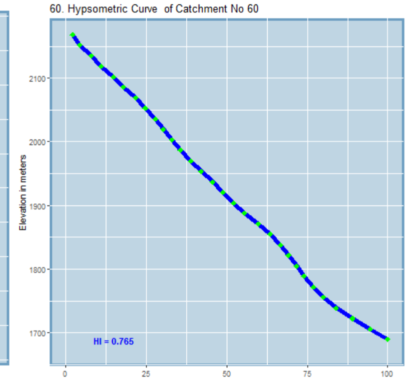
58. Hypsometric Curve of Catchment No 58

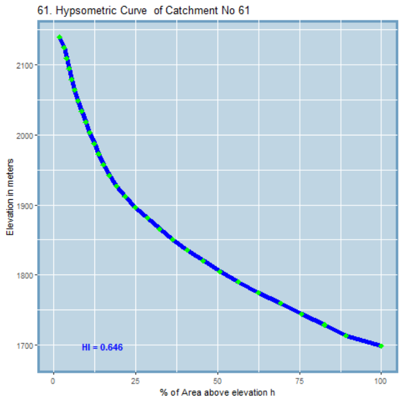


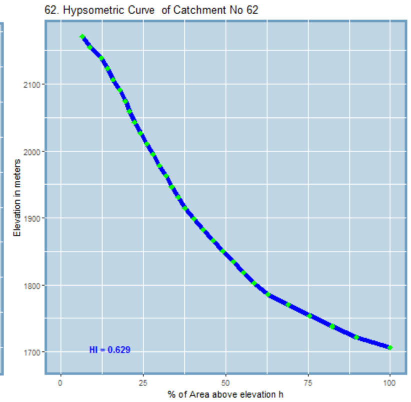
59. Hypsometric Curve of Catchment No 59

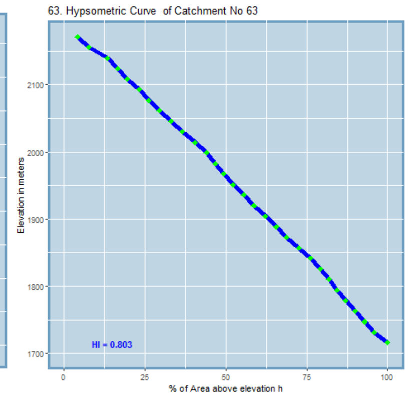


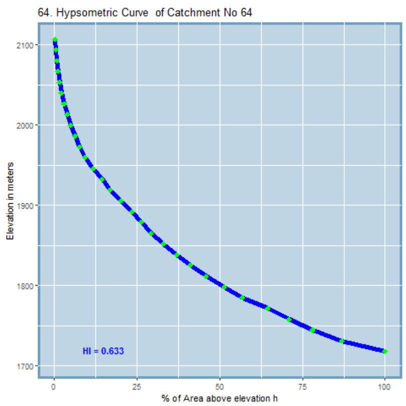
60. Hypsometric Curve of Catchment No 60

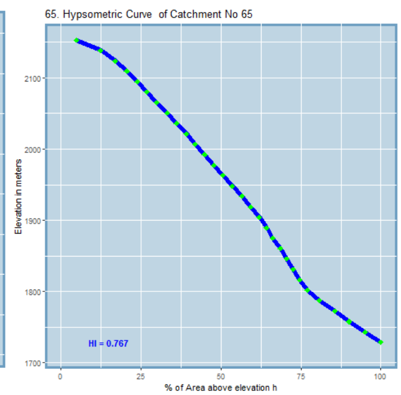


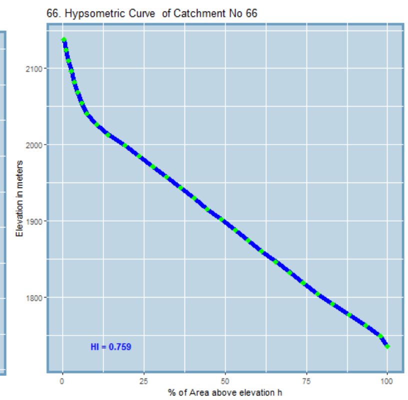

61. Hypsometric Curve of Catchment No 61
Elevation in meters
% of Area above elevation h
HI = 0.646

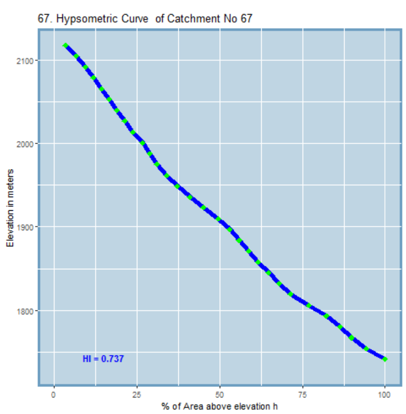

62. Hypsometric Curve of Catchment No 62
Elevation in meters
% of Area above elevation h
HI = 0.629

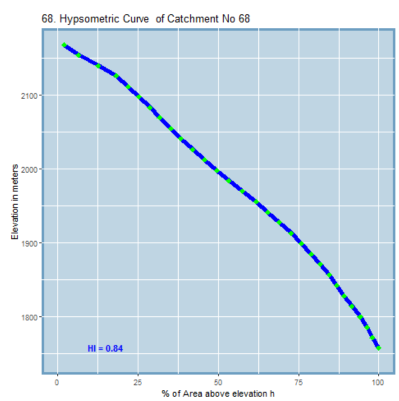

63. Hypsometric Curve of Catchment No 63
Elevation in meters
% of Area above elevation h
HI = 0.803

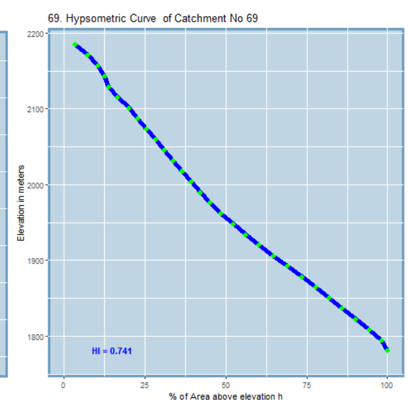

64. Hypsometric Curve of Catchment No 64
Elevation in meters
% of Area above elevation h
HI = 0.633

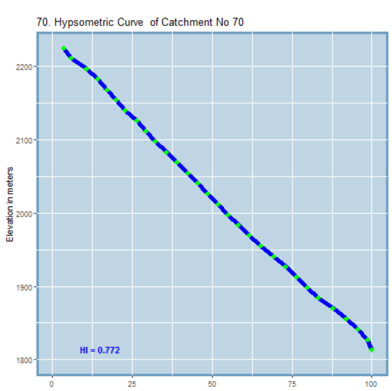

65. Hypsometric Curve of Catchment No 65
Elevation in meters
% of Area above elevation h
HI = 0.767

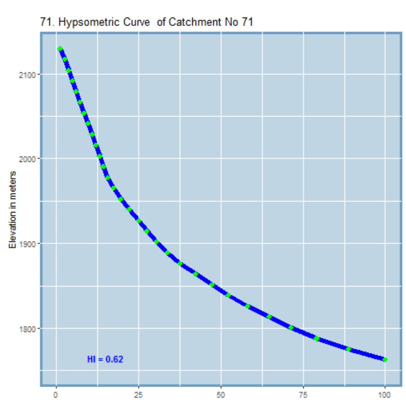

66. Hypsometric Curve of Catchment No 66
Elevation in meters
% of Area above elevation h
HI = 0.759

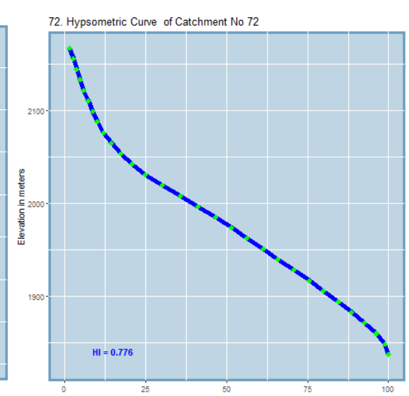

67. Hypsometric Curve of Catchment No 67
Elevation in meters
% of Area above elevation h
HI = 0.737


68. Hypsometric Curve of Catchment No 68
Elevation in meters
% of Area above elevation h
HI = 0.84

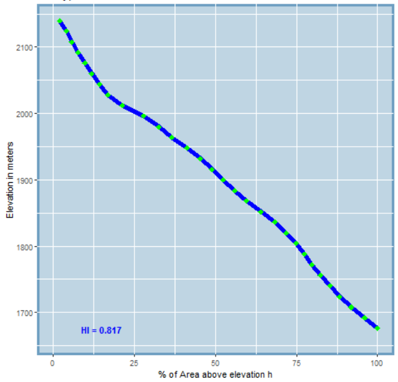

69. Hypsometric Curve of Catchment No 69
Elevation in meters
% of Area above elevation h
HI = 0.741


70. Hypsometric Curve of Catchment No 70
Elevation in meters
% of Area above elevation h
HI = 0.772

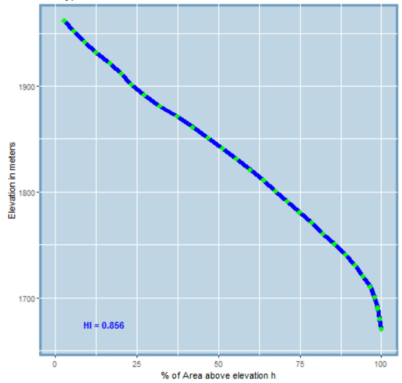

71. Hypsometric Curve of Catchment No 71
Elevation in meters
% of Area above elevation h
HI = 0.62


72. Hypsometric Curve of Catchment No 72
Elevation in meters
% of Area above elevation h
HI = 0.776

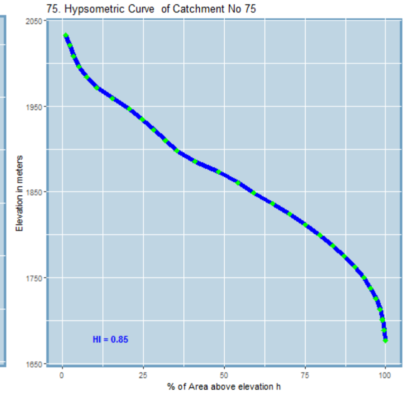
73. Hypsometric Curve of Catchment No 73



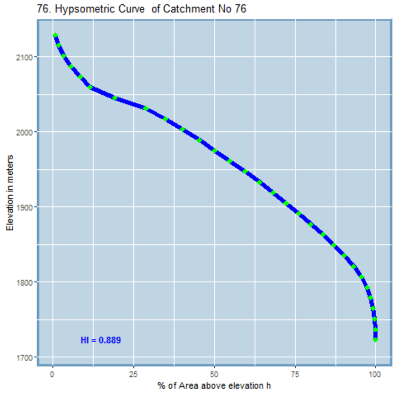
74. Hypsometric Curve of Catchment No 74



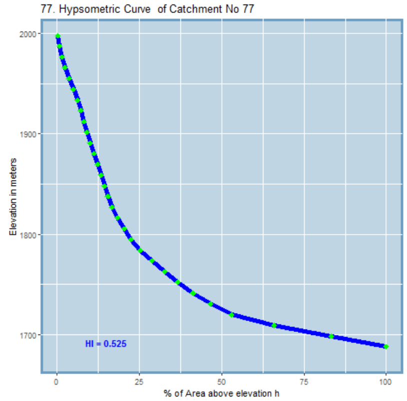
75. Hypsometric Curve of Catchment No 75



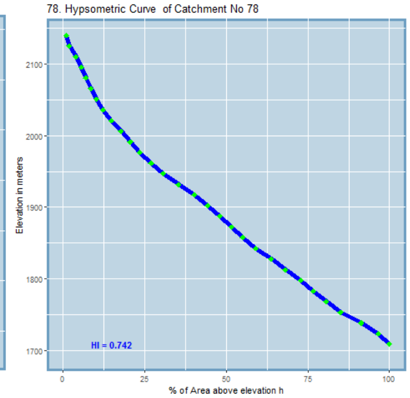
76. Hypsometric Curve of Catchment No 76



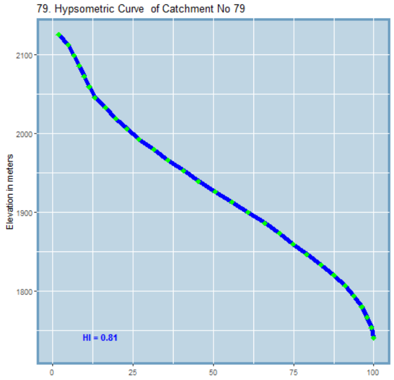
77. Hypsometric Curve of Catchment No 77



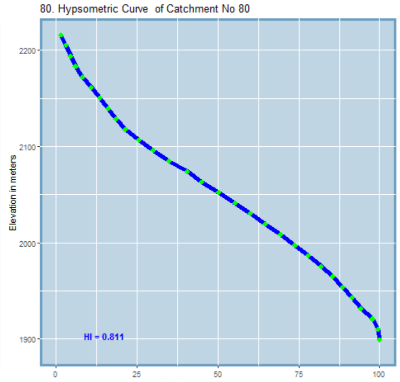
78. Hypsometric Curve of Catchment No 78



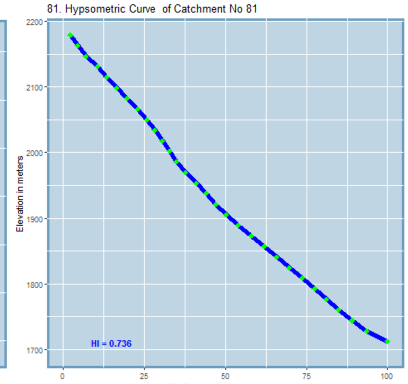
79. Hypsometric Curve of Catchment No 79



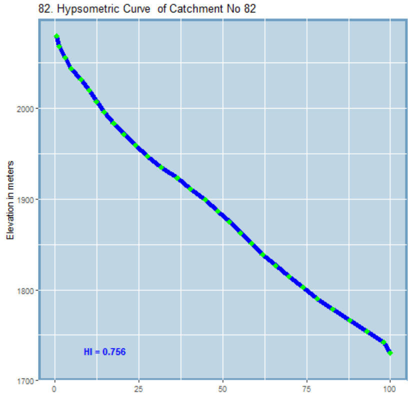
80. Hypsometric Curve of Catchment No 80



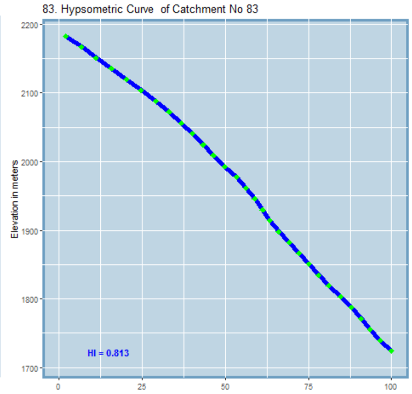
81. Hypsometric Curve of Catchment No 81



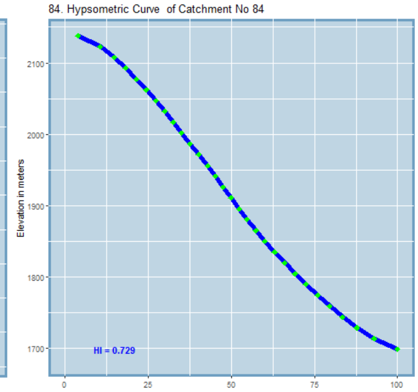
82. Hypsometric Curve of Catchment No 82

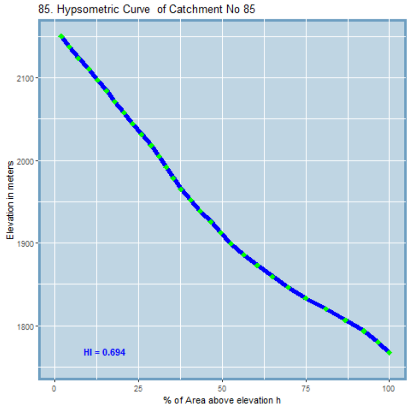


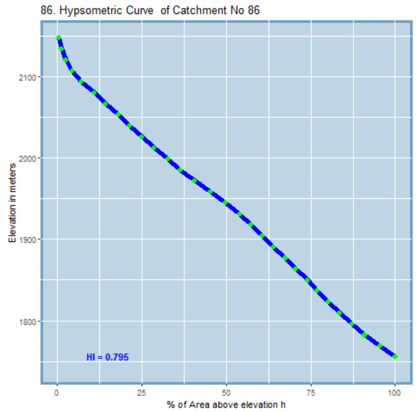
83. Hypsometric Curve of Catchment No 83

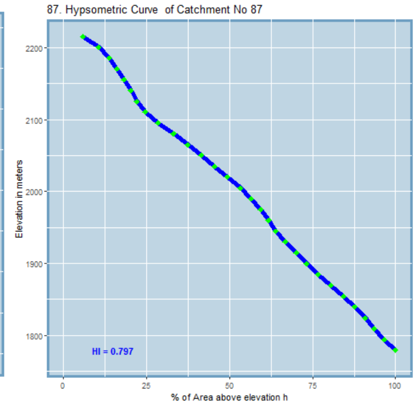


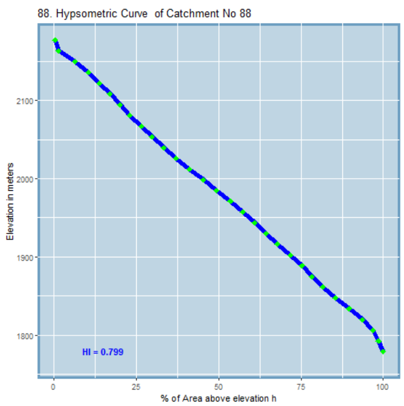
84. Hypsometric Curve of Catchment No 84

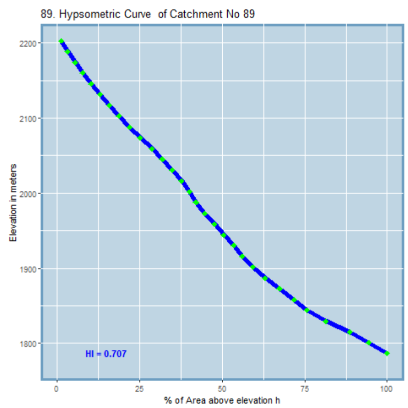


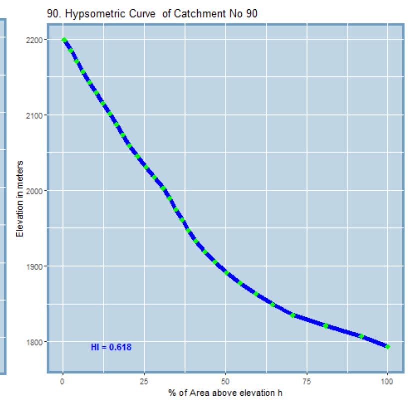

85. Hypsometric Curve of Catchment No 85
Elevation in meters
% of Area above elevation h
HI = 0.694

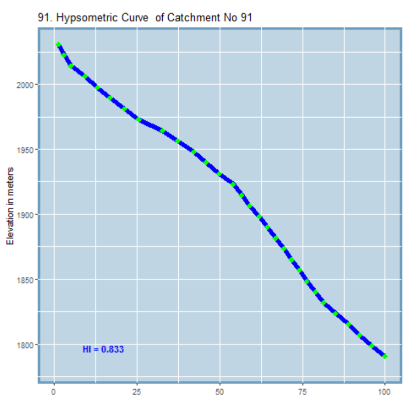

86. Hypsometric Curve of Catchment No 86
Elevation in meters
% of Area above elevation h
HI = 0.795

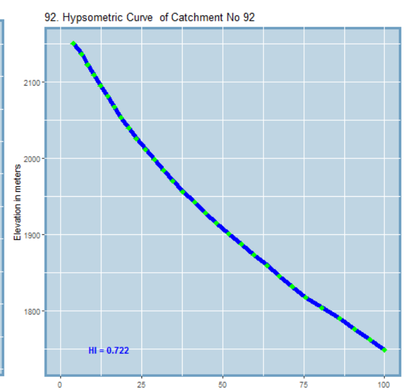

87. Hypsometric Curve of Catchment No 87
Elevation in meters
% of Area above elevation h
HI = 0.797

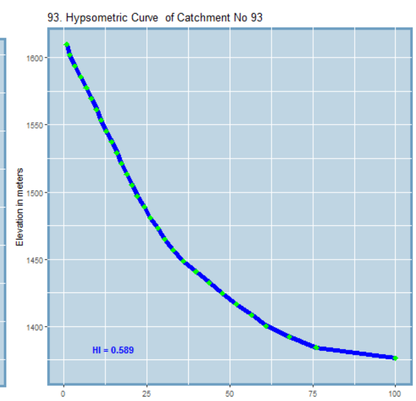

88. Hypsometric Curve of Catchment No 88
Elevation in meters
% of Area above elevation h
HI = 0.799


89. Hypsometric Curve of Catchment No 89
Elevation in meters
% of Area above elevation h
HI = 0.707


90. Hypsometric Curve of Catchment No 90
Elevation in meters
% of Area above elevation h
HI = 0.618


91. Hypsometric Curve of Catchment No 91
Elevation in meters
% of Area above elevation h
HI = 0.833


92. Hypsometric Curve of Catchment No 92
Elevation in meters
% of Area above elevation h
HI = 0.722


93. Hypsometric Curve of Catchment No 93
Elevation in meters
% of Area above elevation h
HI = 0.589