PRIORITIZATION OF SOIL EROSION PRONE AREAS BASED ON MORPHOMETRIC AND LAND USE / COVER PARAMETERS IN RIVER THIRIRIKA WATERSHED, KIAMBU COUNTY KENYA

JULIET INYELE

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE (INTEGRATED WATERSHED MANAGEMENT) IN THE SCHOOL OF PURE AND APPLIED SCIENCES, KENYATTA UNIVERSITY

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DECLARATION

This thesis is my original work and has not been presented for award in any other institution of high learning.

Signature……………………………………………..Date…………………………...

Juliet Inyele

I56/25846/2018

Department of Geography

SUPERVISORS

The work reported in this thesis was carried out by the candidate under our supervision.

Signature **Date: 8th MAY 2024**

Dr. Shadrack Murimi

Department of Geography

Kenyatta University

Signature **Date: 8th MAY 2024**

Dr. Raphael Kweyu

Department of Geography

Kenyatta University

DEDICATION

This work is dedicated to my loving mother Alice Miriam Toto for always wanting me to have good education.

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ABREVIATIONS AND ACRONYMS

CP	Compound Priority
DEM	Digital Elevation Model
ESA	European Space Agency
GEE	Google Earth Engine
GIS	Geographic Information System
FAO	Food and Agriculture Organisation
LULC	Land use / Land cover
NDVI	Normalized Difference Vegetation Index
RF	Random Forest
RUSLE	Revised Universal Soil Loss Equation
RS	Remote Sensing
SRTM	Shuttle Radar Topography Mission
SW	Sub watersheds
SW1	Sub watershed 1
SW2	Sub watershed 2
SW3	Sub watershed 3
SW4	Sub watershed 4
SW5	Sub watershed 5
TWI	Topographic Wetness Index
USGS	United States Geological Survey

ABSTRACT

Morphometric studies and land use / land cover analysis play a key role in integrated watershed management. Sustainable resource utilization at a watershed level requires an in-depth understanding of the vegetation characteristics, land surface features, land use, drainage and hydrological patterns of the watershed. In developing countries, poverty have led to unsuitable land management practices (e.g. deforestation, continuous tillage), contributing to increased runoff causing land degradation and increased soil erosion in watersheds. This inhibits the achievement of the Sustainable Development Goals (SDGs) of zero hunger, access to clean water, and sanitation. To reduce soil erosion at the watershed level, watershed managers need to make informed decisions such as developing vegetative cover, agroforestry, and terracing. However, this is limited in Kenya due to lack of readily available data to guide the process. This study explored the potential use of basin and drainage network properties, land use / land cover characteristics with Geographic Information Systems (GIS) and Remote Sensing (RS) tools to identify sub watersheds susceptible to soil erosion in Thiririka watershed in Kenya. Five sub watersheds were delineated and assigned a code from SW1 to SW5 using the Shuttle Radar Topographic Mission (SRTM) 30 meter resolution Digital Elevation Model (DEM) with Arc Hydro tools in ArcGIS 10.8 software. These was followed by the analysis of morphometric parameters of linear, aerial, and relief characteristics of the watershed. Land use / land cover classes were generated from an annual median composite of Sentinel-2 image for the year 2020, collected using Google Earth Engine (GEE). The training polygons were systematically sampled from the field using handheld GPS. A supervised classification scheme was used to develop a random forest classifier to perform the classification. In addition, the Normalized Difference Vegetation Index (NDVI) extracted from a median composite of Sentinel-2 image for 2020 and the SRTM-DEM were incorporated to improve the classification accuracy. The overall accuracy was 0.88, and Kappa statistics of the classifications was 0.86. Further, to understand the spatial distribution of water in the catchment, the Topographic Wetness Index (TWI) values were extracted from the SRTM DEM. The effect of land use / land cover, vegetation cover and soil moisture to soil erosion tested using a two way ANOVA showed that all the parameters have a positive correlation with soil erosion. Finally, the effects of morphometric parameters, land use/ land cover, vegetation characteristics and soil moisture on soil erosion were assessed and assigned ranks 1 to 5. The ranks assigned for all the parameters were averaged to get the compound priority value (CP). Results showed that sub watershed 5 (SW5) and sub watershed 1 (SW1) are highly susceptible to soil erosion needing immediate management actions, while sub watershed 4 (SW4) and sub watershed 3 (SW3) show less susceptibility to soil erosion. This study provides information on sub watersheds exposed to soil erosion, which is important for all the stakeholders in watershed management such as agricultural officers, farmers, planners, and policymakers to focus the appropriate sustainable watershed management practices.

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Over the years, increased food demand has been a major problem particularly under the current global changes such as population growth, climate change and variability (EU, 2015). The increasing population results in more land being converted into agricultural production at the expense of forest (Ahmed and Ismail, 2008). In developing countries, the issue is escalated by the lack of financial and skilled human resources to support sustainable agricultural intensification. Consequently, inefficient land utilization has played a role in the escalation of land degradation.

Major drivers of land degradation identified by (FAO-UNESCO, 2018) include soil erosion (i.e. wind, water, and tillage), decline in soil organic matter, soil compaction, salinization, and landslides of soils and rock materials. Soil degradation due to water and wind erosion is estimated at 1100 million ha^{-1} and 550 million ha^{-1} respectively (Olang *et al.,* 2012). The impacts of these problems are more pronounced in developing countries where poor farm management have worsened the issue, leading to poverty-population-land degradation cycle.

In Kenya the annual cost of land degradation is estimated at 1.5 billion USD and has been associated with increased soil erosion (Egede and Donatus, 2013). This is particularly important in the hilly regions and floodplains areas where natural factors (e.g. high-intensity rainfall, steep slopes), often coupled with unsuitable land management practices (e.g. deforestation, continuous tillage), contribute to increased runoff and erosion.

The Athi River flows through regions characterized by extensive agricultural, industrial, commercial, and residential development. These human activities play a significant role in fostering soil erosion and the transportation of sediments. This phenomenon is particularly notable in the middle and lower sections of the river, where the soil is more delicate, and the tributaries exhibit seasonal patterns. In Thiririka sub-watershed tributary of Athi River, for instance, increasing demand for forest products and agricultural land due to high population pressure has led to increasing deforestation (Kiio and Achola, 2015). The population of Kiambu County stands at 2,418,000 people and is projected to be 3,899,000 people by 2028 (MoALFC. 2021)

Conservation of the limited resources, especially top fertile soils, should be given high priority at the watershed level through the assessment of drivers to soil erosion factors such as LULC, vegetation cover, rainfall and morphometric parameters (Tamma Rao *et al.,* 2012). Therefore, to establish soil erosion management plans at a watershed level, it is important to assess these parameters. Hence, it is essential to prioritize the sub watershed within the main watershed where potential soil erosion may rise. Mapping the soil erosion areas at the watershed level will help identify sub watersheds prone to soil erosion, provide management and conservation measures and ultimately reduce environmental degradation (e.g. erosion of agricultural land, pollution of water). More importantly, it would guide decision-makers to target responses (e.g. reforestation, awareness) and resources to areas of high erosion risk.

Many researchers have attempted to study soil erosion using models formulated to predict and provide rough estimates of soil erosion to guide control. The applicability or the performance of these models vary with location and the prevailing conditions such as soil types, climatic condition, topography, hydrological properties and LULC.

Examples of such models include: The Revised Universal Soil Loss Equation (RUSLE), Coordination of Information on the Environment (CORINE), Kinematic Runoff and Erosion Model (KINEROS), Water Erosion Prediction Project (WEPP) and Pan-European Soil Erosion Risk Assessment (PESERA) (Igwe *et al.,* 2017). The major limitation of these models is lack of data to fit or accurately study soil erosion in some areas. For example a widely used model of Revised Universal Soil Loss Equation (RUSLE) in predicting annual soil loss in watersheds (Renard *et al.,* 1997) is limited because initially it was designed to estimate soil losses due to agriculture. Again, some of the model input variables such as management cover crop and support practices might change within the year and between years hence, hindering the final annual output (Rahaman *et al.,* 2015). In addition, studying the chemical and physical structure of soil is an important factor to understand the exposure of the soil to agents of erosion. However, this is limited since it requires more resources to implement which in most cases is lacking in developing countries. Sediment yield monitoring using Sediment Yield Index (SYI) is another method to monitor soil erosion estimates; the unavailability of data across Kenya hinders adoptability.

Nevertheless, combining the LULC and morphometric parameters has proven to assess soil and hydrological patterns of the watershed. Morphometric analysis is a method developed by (Horton, 1945) to quantitatively study watersheds. The analysis uses the elevation model to generate drainage characteristics that help depict the behavior of the river. The morphometric parameter are derived from the Digital Elevation Models (DEMs) representing the topography of the earth surface without ground surface features such as buildings (Moore *et al.,* 1991). Studying the basin morphometry contemplates the hydrological response to understand the hydrological behavior.

Again, these morphometric parameters and LULC factors provide a guide for informed decisions in water resource allocation as well as understanding the drainage characteristics and ranking of the sub watersheds for efficient resource distribution (Malik *et al.*, 2019). The following study explores the potential use of DEM and multi-temporal satellite images use in analysis of the LULC and basin morphometric parameters to identify sub watersheds exposed to soil erosion within Thiririka watershed.

1.2 Statement of the problem

Soil erosion affects the Sustainable Development Goals (SDGs), attainment and the global food security. It poses a global challenge to food supply, human health, environmental ecosystems and economic development. Controlling soil erosion can help to combat desertification, prevent loss of biodiversity, and provide clean water and food for sustainability. Environmental degradation is rampant in Kiambu County with immense felling of trees, leading to high soil erosion and desertification risk (County Government of Kiambu, 2013). In the last three decades, Kiambu County has experienced rapid population growth causing land use change (Kiio and Achola, 2015).

The Thiririka watershed grapples with two significant geomorphological challenges: soil erosion and mass movement (Fabian Becker *et al.,* 2015). Land degradation is increasing due to changes in land use. Forested areas are being converted to farmlands and settlements, resulting in increased runoff. Rural livelihoods of the residence also depend on the forest for biomass energy. Continuous farming with no protective measures increase erosion and reduce land productivity due to loss in soil nutrients.

To reduce these problems there is a need to establish proper watershed management plans, by assessing the hydrological behaviour of a watershed. This is because in most cases there is less resources to implement management programme to the entire watershed hence the most critical sub watershed are selected to better focus suitable management measures. The following research identifies the sub watersheds that are susceptible to soil erosion within Thiririka watershed using basin morphometry, soil moisture and LULC parameters with the aim of focussing the scarce to the critical sub-watershed for management action.

1.3 Justification and Significance of the study

Thiririka watershed provides socio-economic and ecological functions; most rural livelihood depend on the catchment resources for agricultural activities, wood fuel, timber and water for domestic use. Land degradation from increased population and deforestation has negatively affected agricultural productivity threatening the rural livelihood of the community. Both rill and gully erosions are common in the area.

The results of the study shows the sub watershed susceptible to soil erosion that need attention for better soil management measures. Consequently, the results can help to avoid future erosion by informing the government policy on appropriate land management practices and specific areas to channel the limited resources. Farmers, watershed managers and agricultural extension officers can use the results for planning better soil management practices to achieve long-term agricultural productivity and sustainable farming decisions for future food security.

1.4 Objectives of the study

1.4.1 General Objective

The general objective of this study was to prioritize soil erosion prone areas in Thiririka watershed.

1.4.2 Specific Objectives

1. To assess the land use and land cover of Thiririka sub watersheds and their effects to soil erosion.
2. The assess the influence of River Thiririka drainage basin and channel network (morphometric characteristics) on the exposure of the sub watersheds to soil erosion.
3. The analyse the joint effect of varying vegetation cover and soil moisture on soil erosion in Thiririka sub watersheds.

1.5 Research Questions

The research questions addressed by the study are:

i. What are the land use / land cover classes in Thiririka sub watersheds?
ii. How does the behaviour of River Thiririka drainage basin and channel network influence the exposure of the sub watersheds to soil erosion?
iii. What is the joint effect of varying soil moisture and vegetation cover on soil erosion in Thiririka sub watersheds?

1.6 Definition of operational terms

Watershed prioritization: It is the assigning ranks to sub watersheds in the catchment for various interventions consideration.

Watershed characterization: It is the assessment of watershed features and the effects of their interaction to the natural environment, which is a guideline for policy makers for action plan.

Watershed morphometry: It is the measurement of geometry as well as the analysis of the shape of earth’s surface, and dimensions of its landforms based on mathematical analysis. In this context, watershed morphometry is used to describe the hydrological characteristics of the watershed.

Topographic Wetness Index: A tool used as an indicator for static soil moisture content of a watershed and flow accumulation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The section covers literature related to the theme(s) of the study in order to examine what has been covered in the past by various researchers. The chapter provides an overview of the research design in the study summarized through a conceptual/theoretical framework where the independent (cause) and dependent (effect) variables are linked through a flow diagram. It concludes by outlining the research gaps identified from various related studies, and explains how the current study attempts to fill them.

Contemporary soil erosion is the displacement of soil particles by agent of erosion such as water or wind (Ganasri and Ramesh, 2016). This natural process is accelerated by human activities changing land cover from permanent to lesser vegetation cover, leading to soil loss that exceeds the formation rate in a given area. Soil erosion as described by FAO (2015) is the removal of soil organic matter, particles and aggregates, and soil nutrients from the land surface through water, wind and tillage.

GIS and remote sensing are tools used in watershed to provide data and manage programs implementation (Rao and Yusuf, 2013). GIS approaches are useful in estimating terrain factors of a watershed, a parameter in identifying areas subjected to soil erosion. The study by Om Kashyap (2011) reveals that GIS and remote sensing can be used to assess the influence of morphometric parameters on landforms. GIS as a tool, supports the analysis of the morphometric parameters and the influence to the environment (Savita *et al*., 2017). The significance of employing GIS in identifying priority areas within watersheds is on the rise. Examples showcasing the integration of

GIS and RS for watershed prioritization encompass: (Binay and Uday, 2011, 2016; Javed *et al.,* 2011; Manjunath and Suresh, 2014). GIS and RS support LULC classification in space and time, allowing for the quantification of effects of each land use type to soil erosion over years.

Watershed ranking criteria is based on morphometric factors, land use or land cover, drivers of socio-economic changes and other relevant factors. These processes results from different steps such as watershed delineation into sub watershed units and assigning ranks based on the order to be considered for treatment (Ikbal and Ali, 2017). The process provides detailed analysis of the terrain in the sub watersheds and quantifying the morphometric features of a catchment by utilizing remotely sensed Digital Elevation Model within the GIS environment, which are techniques, adopted in characterizing and prioritizing the sub watersheds.

2.2 Effects of land use / land cover on soil erosion within the catchment

Land use and land cover is a useful factor considered in watershed prioritization. Changes in environment is associated with the alteration in LULC, which accelerates soil erosion. According to Opeyemi (2006), human activities and anthropogenic trends have modified various land cover into agricultural lands, human settlement, and industrial centers. Land use refers to the activities or purpose of land, it can be social or economic, such as grazing, industries, play grounds and agricultural activities (Opeyemi, 2006). On the other hand, land cover defines the physical state of the earth’s surface, including water, soil and human structures (Imani et al., 2014).

Various researchers have studied the relationship between LULC and soil erosion. Quan et al., (2011) carried out a study in southern Ningxia, China where they observe that soil erosion increased with increase in farming and grazing on steep slopes. A study by Tadesse et al., (2017) carried in Ethiopia reported that NDVI values increase due to the implementation of integrated catchment development program. These results show that land use has the potential to reduce soil erosion through cover crops that reduce impact of raindrop and increase infiltration.

2.3 Influence of morphometric parameters on exposure of the catchment to soil erosion

Morphometric studies has been indirectly utilized in earth sciences and engineering studies as a tool to assess topography, ground water interactions, soil erosion and landslides mapping, LULC and climatic condition of the watershed (Sujatha *et al.*, 2015). Physiographic features of the watershed such as stream length, size and shape of the basin, topographical slope and the stream density have significant relationship with the hydrological characteristic of the drainage catchment. The morphometric characteristics account for the basin behavior and interaction processes describing the geologic and geomorphic evolution of the drainage basin. Therefore, combining hydrological and morphometric characteristics of the basin is a crucial step that helps in understanding the hydrological behavior of the basin (Puno and Puno, 2019). This is important in the process of soil and water management to identify sub watershed that needs more attention to channel resources.

Several researchers have utilized basin morphometry and LULC analysis for watershed prioritization, examples include (Ahirwar *et al.,* 2019; Ali *et al.*, 2018; Javed *et al.*, 2011; Manjunath and Suresh, 2014; Pawar *et al.,* 2013; Suji *et al.*, 2015). The catchment morphometric parameters such as form factor, circulatory ratio, stream frequency, stream density, elongation ratio and bifurcation ratio are referred to as the erosion risk assessment factors and are utilized in ranking watersheds (Puno and Puno, 2019).

Many researchers have carried out mapping of watershed susceptibility to soil erosion using GIS and remote sensing techniques. These studies are common in India for example Rahaman *et al.,* (2015), studied the prioritization of Kallar watershed, based on morphometric characteristics utilizing the Fuzzy Analytical Hierarchy Process and GIS, whereby they found 2 sub watershed being highly susceptible to erosion. Other studies that have used morphometric parameters analysis to prioritize sub watersheds in India include: (Biswas and Chakraborty, 2016; Choudhari *et al.,* 2018; Savita *et al.,* 2017; Suji *et al.,* 2015; Tolessa and Rao, 2013).

2.4 Effects of vegetation cover and soil moisture on soil erosion

NDVI indicates the abundance of green vegetation (Tucker, 1979). Therefore, the NDVI time series are widely used in studies related to agriculture, drought and watershed prioritization. Examples include: (Panagos *et al.,* 2015; Sarkar *et al.,* 2020; Woldemariam *et al.,* 2018). Topographic Wetness Index (TWI) has gained wide application in determining the spatial distribution of soil moisture, modelling rainfall run off and precision agriculture (Bisrat and Berhanu, 2018; Rózycka *et al.,* 2017; Vijith and Dodge-Wan, 2019). The index works on the basis that topography has control of water distribution and flow accumulation. The index within the runoff model, known as TOPMODEL, was formulated by Beven and Kirkby (1979). This model simulates the interaction between ground and surface water with the slope, effectively revealing areas of saturation. Calculating the TWI of the sub watershed helps in assessing the flow direction, flow accumulation, the catchment contributing area and terrain slope (Sharma, 2010).

2.5 Research Gap

In Africa, watershed prioritization studies are very limited. To mention a few: In Mali, Gumma et al.,(2016) conducted watersheds prioritization across the country using RS and GIS tools to map priority zones across Mali pointing out watersheds requiring quick interventions for increase agricultural productivity and policy implementation. A similar study has been carried out by Ikbal and Ali, (2017) to determine sites for soil conservation in Ethiopia where they established five sub-watersheds that need attention to reduce soil erosion and prevent rock fall in the mountain ranges. Most of this available studies conducting priority mapping based on LULC classification use images of low resolution (e.g. 30-meter resolution Landsat images) leading to low accuracy of the results, again most of the studies utilize a single date image in a year. However, this study utilized 10 meter resolution Sentinel-2 image data with a high resolution (ESA, 2013). The sentinel-2 images used comprised of 2020 median composite of all the available cloud free images hence minimizing errors and biasness brought in by seasonal changes in rainfall throughout the year. In addition to morphometric parameters analysis and LULC characteristics, the study integrates the Normalized Difference Vegetation Index (Tucker, 1979), and the Topographic Wetness Index values (A. Sharma, 2010) to assess watershed susceptibility to soil erosion.

2.6 Conceptual Framework

The study adopts and modifies the soil erosion assessment framework applied by Gobin *et al.,* (2003). The technical report was based on assessment and reporting on soil erosion, which outlines on the drivers, pressures, state, impacts and responses to soil erosion. The conceptual framework in (Figure 2.1) shows how the morphometric parameters, LULC, vegetation cover and soil moisture lead to soil erosion. Potentially, the mentioned parameters will have either direct or indirect impact, in some cases both on natural resources including soil services or functions, environmental health, and in the long run affect human wellbeing (Gobin *et al.*, 2003).

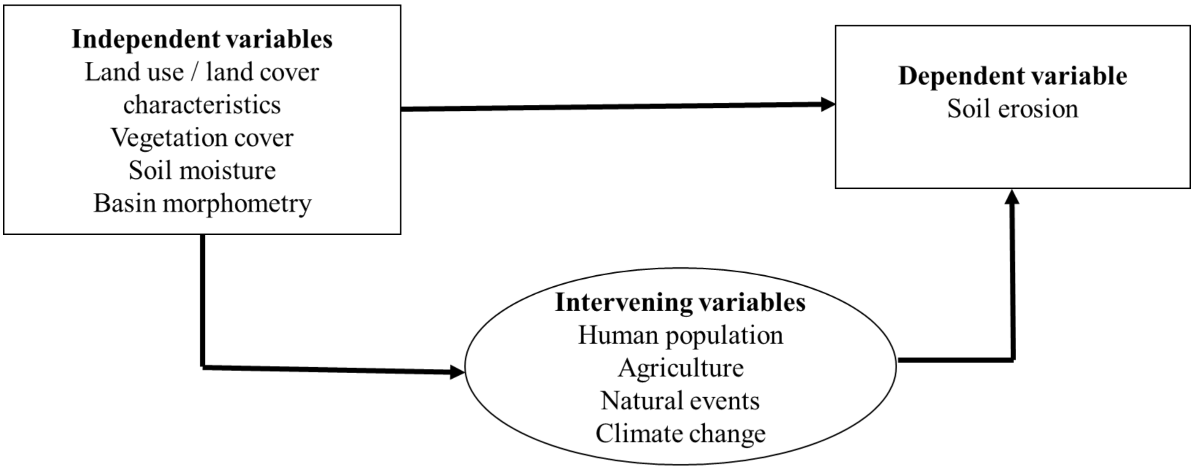

Figure 0.1: Conceptual framework modified

Gobin *et al*. (2003)

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

In this chapter, an in-depth exploration is presented concerning the data and methodologies utilized in the study. The section encompasses a comprehensive depiction of the study area, the various types of data employed, and the sources from which the data was obtained. Additionally, it elucidates the software and methodological procedures applied in the process of conducting data analysis to fulfill the specified objectives.

3.2 Study Area

Thiririka watershed is located in Kiambu County in Kenya. The watershed is located in Gatundu South District, within three (3) Sub-counties of Lari in the upstream, Gatundu South in the mid-stream and Juja sub country in the downstream section. Thiririka River originates from the southern slopes of the Aberdare Ranges in the Kikuyu Escarpment forest and drains to Ruiru River a tributary of the Athi River. The river is on the Eastern slopes of the Aberdare mountain and is approximately 120 km^2 (Figure 0.1).

In Thiririka watershed, rainfall exhibits a bimodal distribution in the catchment, with the wet season from mid-March to April and the short wet season from November to December. The annual rainfall is 1,200 millimetres. The watershed lies within the humid to semi-humid agro-climatic zones of Kenya (Fabian Becker *et al.*, 2015).

The upper part of the catchment is characterized by humic nitisols soils, while the lower part has Rhodic Nitosols (Albert *et al.,* 2015). The lower area of the catchment has dense population, while the upper part of the catchment is forested (the Kikuyu escarpment). The southern part of the study area is dominant of settlements. The residents in the mid-catchment area practice mixed farming and cash crop plantations. Cumulatively, subsistence and commercial farming are the main economic activities in the area.

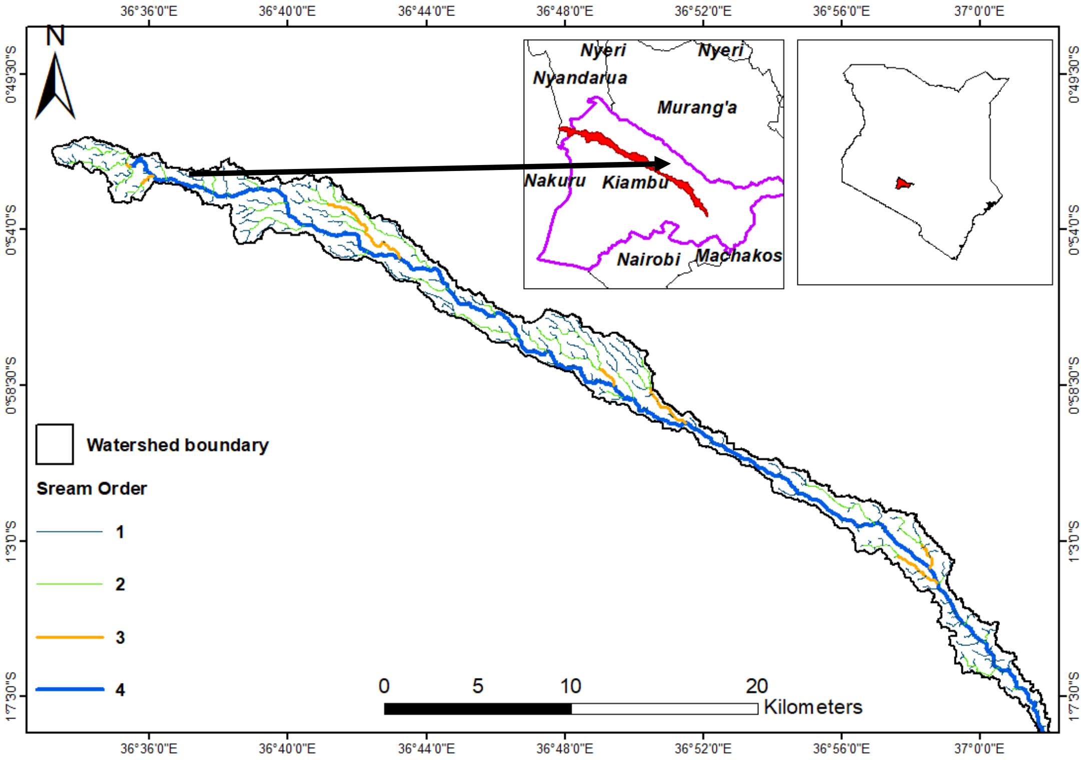

Figure 0.1: Map of Thiririka watershed and stream orders derived from 30 m Shuttle Radar Topographic Mission (SRTM-DEM)

3.3 Materials and data collection techniques

The secondary data in the study included a set of satellite images Sentinel-2 and SRTM-DEM. The Sentinel-2 image data was acquired from the Copernicus website: https://scihub.copernicus.eu/dhus/#/home used for LULC classification, as well as NDVI extraction. SRTM DEM obtained from the USGS website (https://earthexplorer.usgs.gov/) was used to delineate the sub watersheds, computing the morphometric parameters and the TWI of the watershed (Table 0.1). The primary data for this study was a set of ground-truthing polygons used for training and validating the model for LULC classification. These polygons were systematically collected across the existing land cover classes using handheld GPS from the field. The polygons collected were confirmed with the available literature and the images from Google Earth Pro high-resolution satellite data.

Watershed and sub watershed delineation was done using the ModelBuilder and Arc Hydro 10.8 tools in ArcGIS 10.8. The LULC classes were obtained by performing LULC classification in ArcGIS 10.8. The NDVI and TWI were computed using the raster calculator tool in ArcGIS. The results are presented using tables, graphs, and maps.

Table 0.1: Dataset types, description, sources and purpose adopted for the study

Dataset	**Description**	**Source**	**Purpose**
Sentinel-2 satellite image	10m, 20m and 60m spatial resolution for the year 2020, resampled to 10m in Google Earth Engine	https://scihub.copernicus.eu/dhus/#/home	• Classification of LULC • Extracting mean NDVI values
SRTM-DEM	30 meter spatial resolution	http://www.earthexplorer.usgs.gov/	• Delineating watershed and sub watershed boundaries • Computing morphometric parameters • Calculating the TWI
Ground thruthing data (polygons)	LULC polygons collected from the field of study	Field Survey using GPS	• Training the classification algorithm • Performing accuracy assessment

3.3.1 Land use / land cover classification and analysis

Sentinel-2 Image from the Copernicus was used in the study (Table 0.1). The Sentinel images have a high-resolution spectral bands used by Copernicus for monitoring land use changes, assessing the vegetation growth and health, monitoring the water quality and quantity (ESA, 2012). The Sentinel-2 image have a spatial resolution of 10m, 20m, and 60m for different bands. The bands with a 10-meter resolution include blue, green, red (B2, B3, B4), and near-infrared (B8), the bands with 20 meters spatial resolution are B5, B6, B7, and B8A, and short-wave infrared SWIR (B11 and B12). Aerosol (B1) band, SWIR (B9) and SWIR (B10) have 60 meters ground sampling distance (ESA, 2013). Most of the bands were used in the classification for improved accuracy since they have different spectral surface reflectance and wavelength to capture distinct ground features (Zhang *et al.,* 2017). In addition to the spectral bands, the Normalized Difference Vegetation Index (NDVI) band (Tucker, 1979) and the DEM band were incorporated to improve the classification accuracy.

The image used for classification was a cloudless median composite of all the Sentinel-2 images from 1 January 2020 to 31 December 2020. The annual composite is considered to capture LULC variation of different seasons all year round (Liu *et al.,* 2020). The Google Earth Engine (GEE) was used to process the multi temporal images. GEE is a cloud platform for processing large amount of data within a short time (e.g. satellite imagery) with several classification algorithm (LUO *et al.,* 2021).

Sentinel-2 image bands were considered for the following reasons: Aerosols band (B1) accounted for atmospheric factors such as dust; B2, B3, and B4 detected the natural chlorophyll content in vegetation. NIR band captured areas of high vegetation canopy whereas the SWIR-1 (B11), SWIR-2 (B12) were used to detect geological features in the watershed (Tadele *et al.*, 2017). NDVI band represented the density and intensity of green vegetation, and the SRTM-DEM was used to capture the slope / topography aspect in the classification. To get a cloudless image for the Thiririka watershed, Sentinel-2 cloud mask function was created and applied the Sentinel-2 cloud probability to clean the image. During image processing in Google Earth Engine, the images were filtered to include only images below 60% cloud cover with a cloud probability threshold of 50% per pixel. Furthermore, advanced processing of Sentinel-2 images developed by Justin (2020) was adopted, including a NIR dark threshold of 0.15 to identify the dark NIR pixels that are not water (potential cloud shadow pixels) and cloud projected distance of 1 (one). Subsequently, a buffer of 50, representing approximately the minimum probability frequency between cloud and non-cloud modes, was employed. This procedure effectively eliminated cloud shadows and pixels obscured by cloudiness.

Finally, the median composite of all the preprocessed images from 1 January 2020 to 30 December 2020 was obtained for LULC classification. The median was preferred because it is closer to the majority of values and is insensitive to extreme/noise values (Rumora *et al.*, 2020). The annual median composite was considered to cover for seasonal changes in rainfall (rainy and dry periods). All the image bands were then resampled to a 10 m spatial resolution using the nearest neighbor method (Liu *et al.*, 2020) and clipped using a bounding box of the watershed boundary.

During classification, seven (7) LULC classes were identified to exist in the watershed. The classes are water bodies, built up, closed forest, open forest, croplands, crop and vegetation mosaic, and shrublands (Table 0.2). Most of these LULC classes were defined based on the standard International Geosphere Biosphere Programme (IGBP) and FAO LULC classification scheme (FAO-FRA, 2000). Training and validation data were collected from the field using the handheld GPS for training and validation of the model. A minimum of 100 polygons were sampled from each land cover in which 70% was used for classification and 30% for validation and accuracy assessment.

A supervised classification was used with a random forest algorithm to perform LULC classification. This machine learning algorithm random forest classifier (RF) was considered because it gives better results capable of reducing the overfitting problems (Breiman, 2001). The pre-processed image and the selected training samples were used to generate LULC for the entire Thiririka watershed in ArcGIS 10.8. Later, the individual sub watersheds LULC classification were clipped and each LULC areal coverage data extracted from the clipped images.

Table 0.2: Categories of land use and land cover used for an image classification in Thiririka watershed

Land use and land cover	**Description**	**Name on the map**
Water bodies	Streams, dams, canals rivers, wetland and water pans.	Water
Built up/ developed areas	Residential areas, industrial, commercial and roads.	Built up
Croplands	Perennial and annual crops lands followed by harvest and a bare soil period.	Croplands
Crop and vegetation mosaic	Lands covered with crops, trees and grass, mostly perennial crops including coffee and tea plantations.	Mosaics
Dense forest	Land covered with tall strands of trees, purely evergreen with 70% land coverage.	Closed forest
Open forest	Land covered with trees below 60% and above 30%	Open forest
Shrublands	Extended lands with little grass, bare soil and bush areas.	Shrublands

3.3.3.1 Accuracy assessment of the land use and land cover classification

The identified classes of the sub watersheds were validated through accuracy assessment with ground truth data collected using handheld GPS from the field. About

100 polygons were collected for each LULC across the watershed. Furthermore, the sampled polygons were compared with the 2020 satellite images from Google Earth Pro to crosscheck the polygons. Out of the collected samples, 70% were used for training the model while 30% was used for validation. The training and validation was carried out using the Random Forest classifier (RF) with a maximum number of 30 trees.

3.3.2 Watershed delineation and morphometric analysis of Thiririka watershed

To obtain values of the morphometric parameters of the watershed and sub watershed boundaries, 30 meter spatial resolution Shuttle Radar Topography Mission (SRTM) DEM accessed from USGS-http://www.earthexplorer.usgs.gov/ was_utilized (Table 0.1). The procedure for delineating watershed and streams was systematically followed using the hydrology tools in ArcGIS 10.8 (Figure 0.4). Although several approaches are used to study the drainage of an area, the DEM elevation grids was preferred because of their wide availability (Seemuller, 1989).

From the DEM, the pit removal algorithm was applied to raise pixel values surrounded by high elevation values using the fill-DEM function of hydrology tools in ArcGIS environment. This procedure allows for adequate flow routing during the computation (Moore *et al.,* 1991). Filling sinks is an iteration process that occurs in every grid cell by comparing the cell value to the neighboring cells of the DEM (Gumma *et al.,* 2016).

Depression less DEM layer was used to generate the flow direction per grid cell, showing the direction of the steepest descent from the cell. D8 algorithm was used to extract the flow direction, a method proposed by (Tarboton, 1997). In any grid cell, water flows to any of the eight (8) surrounding directions whereby it is assigned a value corresponding to the orientation of one of the eight cells surrounding the cell as described by (Jenson and Domingue, 1998). These cell numbers correspond to a binary and each flow direction value is encoded with a unique color (Figure 0.2 and Figure 0.3).

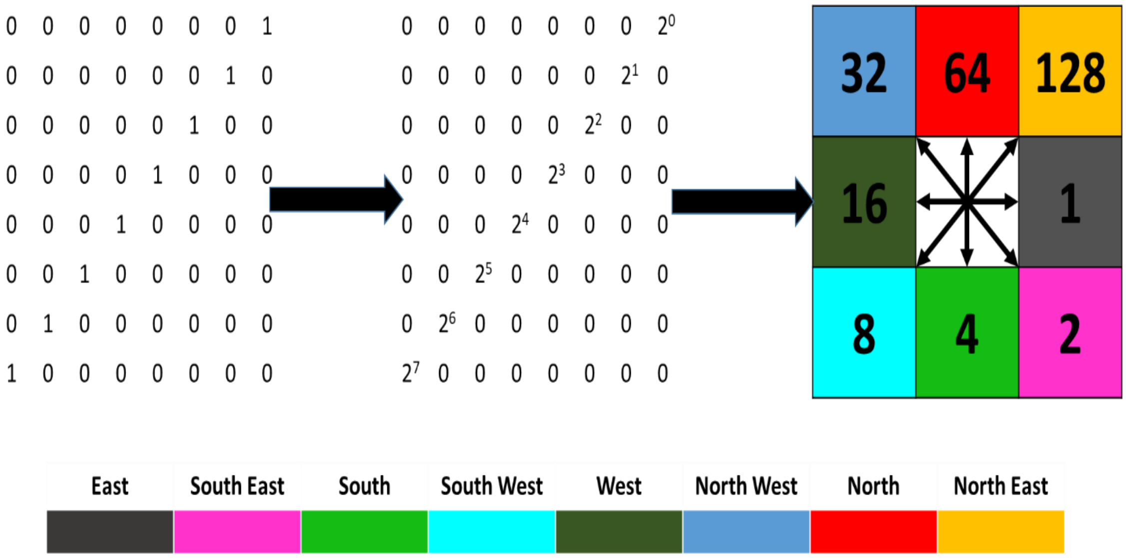

Figure 0.2: Pour point flow direction model

(adopted and modified from Arge *et al.*, 2003)

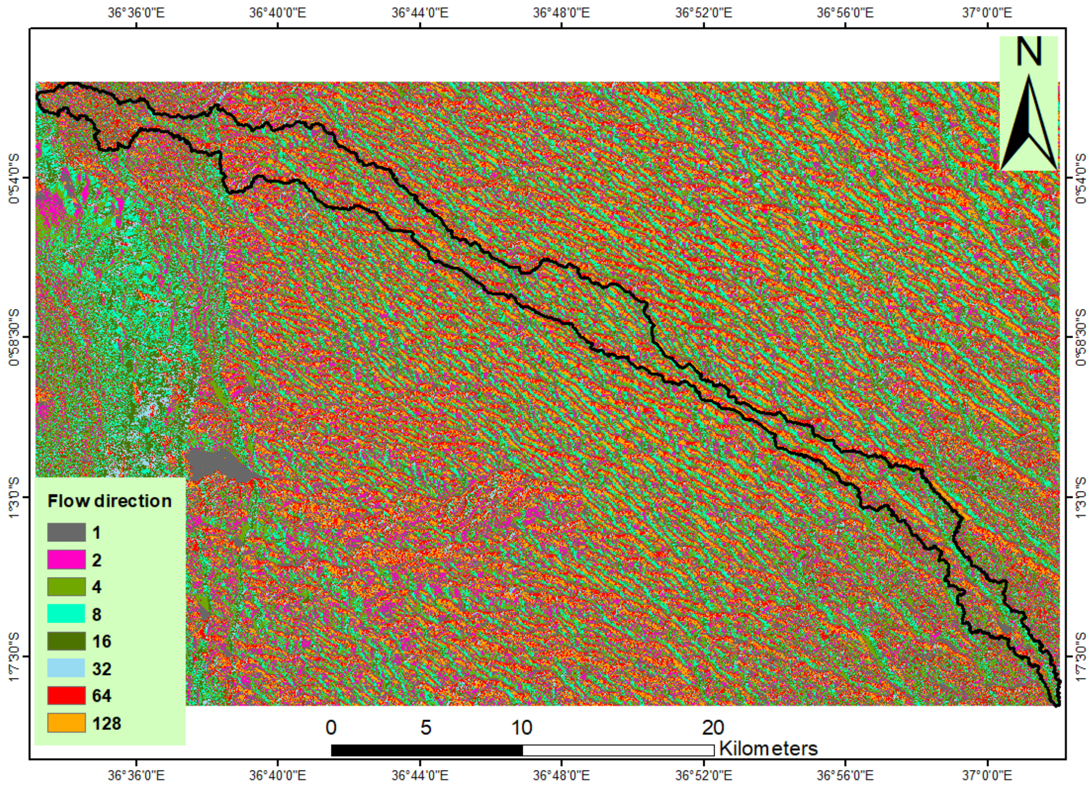

Figure 0.3: A bounding box of Thiririka watershed flow direction map, derived from a 30 m depression less Shuttle Radar Topographic Mission-DEM

The third step is generating the flow accumulation layer defining the grid cells containing the accumulated water from the upstream cells. The flow accumulation is calculated by combining the flow direction and counting the number of cells flowing downslope to a particular cell (Gumma et al., 2016). This step is necessary to define the drainage channels. The higher the values of the cells, the lower the drainage network whereby, grid cells with zero values represent ridges.

Upon finishing DEM reconditioning (obtaining depression less DEM, flow direction, and flow accumulation) steps (Figure 0.4), the watershed and sub watersheds boundaries were delineated by defining an outlet point from the drainage network (digitized the pour point). The flow accumulation layer was used to generate the stream network with a threshold value of 200 pixels (Arge *et al.*, 2003) all the cells within or above 200 in the flow accumulation grid generated stream network raster (Figure 3.4). The raster layer of the stream network were vectorized to create streams shapefile lines for analysis. Stream orders were derived using stream ordering method (Strahler, 1957).

Five (5) sub watersheds were derived from the main watershed using watershed tool in Arcmap, and coded as follows: SW1, SW2, SW3, SW4, and SW5 (Figure 0.6). After the delineation process of sub watersheds summarized using model builder in (Figure 3.4), each sub watersheds morphometric parameters were computed using the standard formula in (Table 0.3). These parameters were categorized to three (3) namely, linear, areal, and relief parameters.

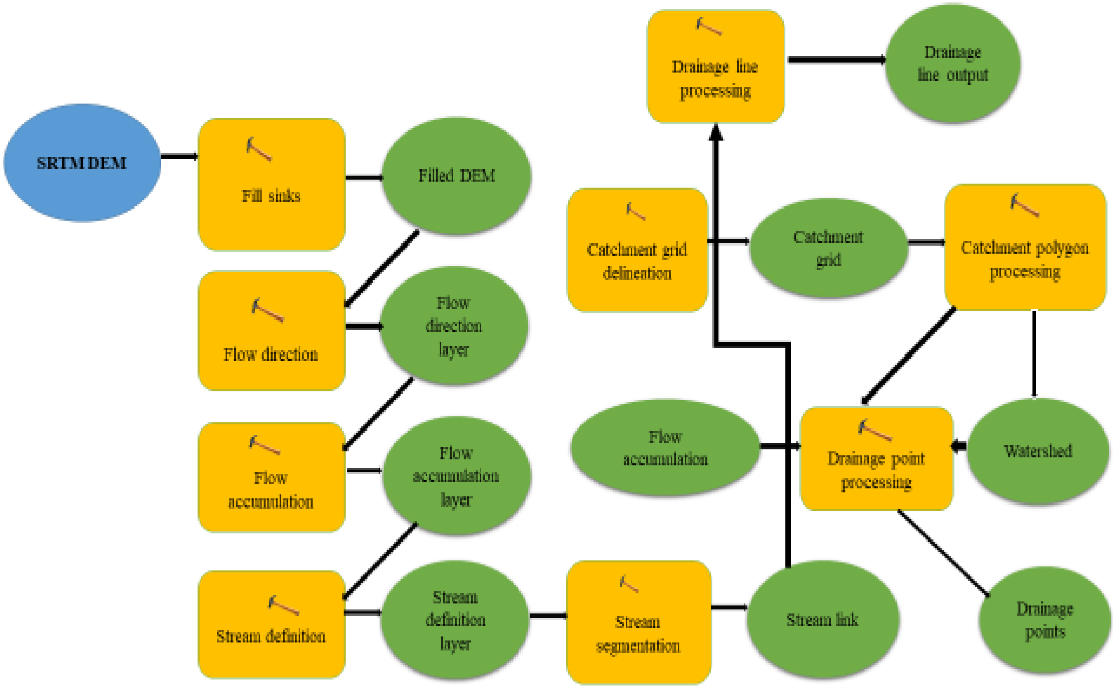

Figure 0.4: Watershed delineation using model builder in ArcGIS 10.8 software

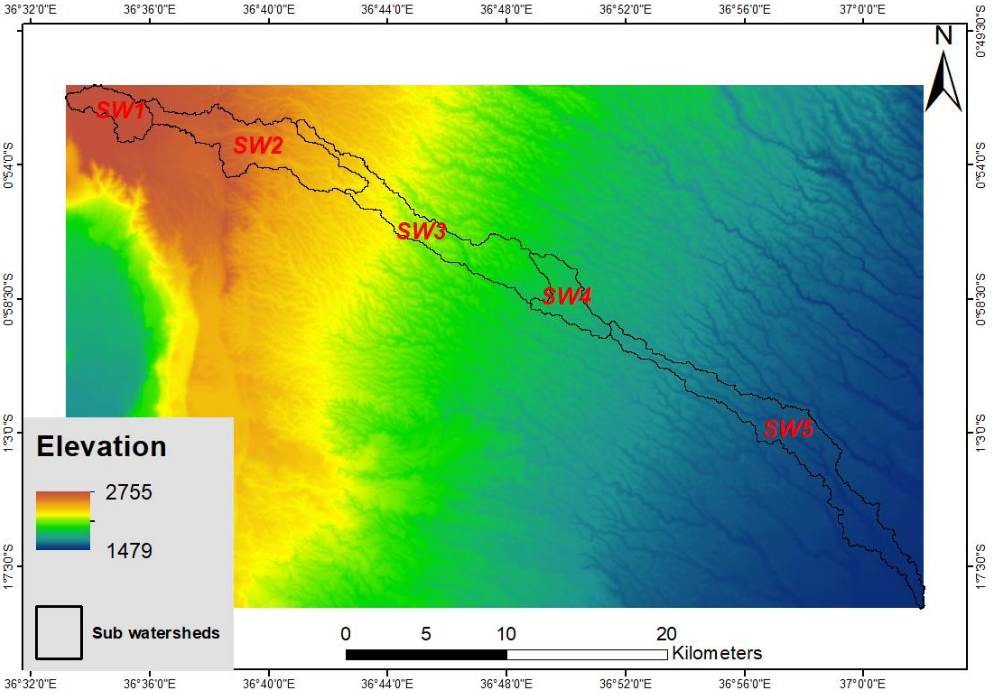

Figure 0.5: Thiririka watershed elevation map, the values are represented in meters

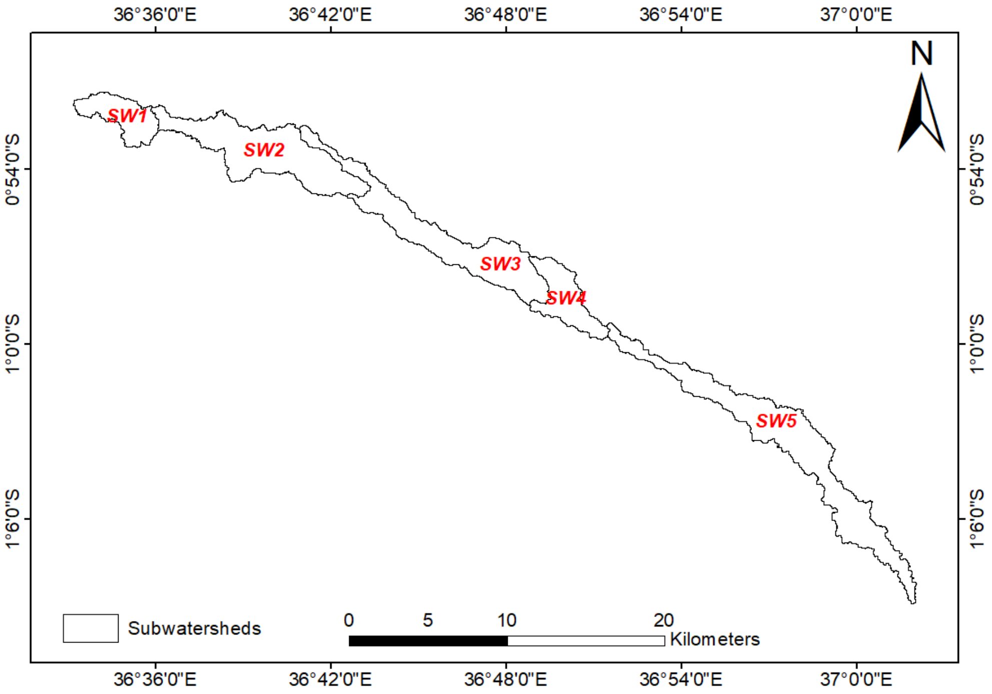

Figure 0.6: Thiririka sub watersheds map. The sub watersheds were delineated automatically using watershed tool in ArcGIS 10.8 software

Table 0.3: Morphometric parameters standard methods and formula adopted in the study

Morphometric parameter	Formula	References
Stream order	Ordering of stream segment based on the hierarchy	(Sarkar *et al.*, 2020)
Stream length (Lu)	Length of the streams (km)	Ibrahim Batis and Ahmed, (2014)
Basin area (A)	Area of watershed (km^2)	
Basin perimeter	Perimeter of watershed (km)	
Stream number	The number of stream segments of various orders in a sub watershed	(Sarkar *et al.*, 2020)
Basin length (L_b)	The line along the flow path of the longest stream from the basin inlet to the outlet point	(Oruonye *et al.*, 2016)
Drainage density (D_d)	$\boldsymbol{Dd = \frac{Lu}{A}}$ Where, D_d = Drainage density L_u = total stream length of all orders (km) A =area of the basin (km^2)	Thapliyal *et al.*, (2017)
Stream frequency (F_s)	$\mathbf{Fs = Nu/A}$ Where, F_s =Stream frequency N_u =Total number of streams of all orders A =Area of the basin (km^2)	Chandniha and Kansal (2017)
Length of overland flow (L_g)	$\boldsymbol{Lg = 1/2Dd}$ Where, L_g =Length of overland flow (km) D_d =Drainage density	Chandniha and Kansal (2017)
Elongation Ratio (R_e)	$\boldsymbol{Re = \left(\frac{2}{Lb}\right) \times (\sqrt{A}/\pi)\text{\^{}}0.5}$ Where, R_e =Elongation ratio A =Area of the basin $L_{b.}$=Length of the basin while π =3.14	Thapliyal *et al.*, (2017)
Form factor (R_f)	$\boldsymbol{Rf = \frac{A}{Lb2}}$ Where, R_f =Form factor A =Area of the basin (km^2) L_b =Length of the basin (km)	Thapliyal *et al.*, (2017)
Circulatory ratio (R_c)	$\mathbf{Rc = 4\pi A/P^2}$ Where, R_c =Circularity ratio A =Area of the basin P =Perimeter	(Manjunath and Suresh, 2014)

Bifurcation ratio (R_b)	**$R_b=N_u/N_u+1$** Where, N_u =Total number. of stream segment of order 'u' N_u+1 =Number of segment of the next higher order	Thapliyal *et al.,* (2017)
Watershed Relief	Vertical difference between the highest and the lowest point	Sarkar *et al.,* (2020)
Relief ratio (R_h)	$$\boldsymbol{Rh=\frac{H}{Lb}}$$ Where, R_h =Relief ratio H =Watershed relief (km) L_b =Basin length	(Manjunath and Suresh, 2014)
Ruggedness number (R_n)	$$\boldsymbol{Rn=H\times Dd}$$ Where, R_n =Ruggedness number H =Watershed relief (km) D_d =Drainage density (km/km^2)	(Manjunath and Suresh, 2014)

3.3.3 Extracting vegetation cover characteristics using Normalized Different Vegetation Index (NDVI) in Thiririka sub watersheds

To identify soil erosion-prone areas, some important variables to consider are the vegetation cover and land features characteristics. Hence, to determine the nature of the vegetation cover several indices in remote sensing such as NDVI are used as an indicator of more or less vegetation (Ayalew *et al.*, 2020). NDVI values range between (-1 to +1) with values close to +1 (positive) representing a possibility of healthy vegetation, values close to 0 (zero) showing bare soil, rocks, and urbanized land while, – (negative) values represent water features (Tucker, 1979). In this case, mean NDVI values of the sub watersheds were extracted to assess vegetation characteristics.

The NDVI values for the study were extracted from a median band composite of the Sentinel-2 satellite image of 2020 and a raster calculator in ArcGIS 10.8. As described by Tucker, (1979), NDVI values are calculated using the NIR and the RED bands (Equation 3.1). The sub watersheds NDVI were clipped using the clip raster function in

ArcGIS 10.8. The mean NDVI values were generated from a summary histogram showing: minimum, maximum, mean, median, and standard deviation in ArcGIS 10.8

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})} \qquad \text{Equation 3.1}$$

Where,

NDVI is the Normalized Difference Vegetation Index

NIR is the near infrared channel (band 8) of Sentinel-2

RED is the red channel (band 4) of Sentinel-2

3.3.4 Extracting soil moisture using the Topographic Wetness Index (TWI) in Thiririka sub watersheds

TWI is a function of the upstream contributing area and slope used as an indicator for static soil moisture content of a watershed (Rózycka *et al.*, 2017). It accounts for the terrain aspect and the catchment area of a watershed and used to assess the soil hydrological conditions (spatial distribution of water from upstream to downstream) (Moore *et al.,* 1991). Several studies have adopted the TWI to assess soil moisture distribution in watershed studies (Bisrat and Berhanu, 2018; Ma *et al*., 2010; Sørensen *et al*., 2006, Sharma, 2010). TWI is defined as the function of slope and the upstream contributing area whereby the watershed catchment area / flow accumulation determines the upstream contributing area and identifies the overland flow of the watershed. The slope variable shows how water interacts with the slope of the watershed (Bisrat and Berhanu, 2018).

Similar to watershed delineation, a 30 m spatial resolution SRTM DEM used to derive morphometric parameters was used to calculate TWI estimates (Table 0.1). The filled / depression less DEM was used to derive the TWI inputs variables such as the flow direction, flow accumulation, and slope. This step was conducted using the hydrology and surface analysis tool in ArcGIS 10.8 environment. The upslope contributing area layer (areas most likely to contribute to runoff) was derived by multiplying the flow accumulation with 30-meter grid cell size. The slope gradient was generated in degrees and later then converted to radiance (Equation 3.2).

Slope plays an important role in determining the areas where water will flow in a catchment. For example, a lower slope degree (flat area) will tend to slow down water and accumulate it in the area, whereas in areas with high slope degrees (steep areas) water flows constantly forming channels on the surface (Ballerine, 2017).

$$\text{TWI} = \ln\left(\frac{\alpha}{\tan\beta}\right) \qquad \text{Equation 3.2}$$

Where,

TWI is the Topographic Wetness Index

α is the local upslope area draining through a certain point per unit contour length (m)

Tanβ is the local slope gradient

(It is important to note that the equations assumes a uniform soil conditions across the entire watershed)

3.3.5 Prioritization of sub watersheds exposed to soil erosion based on land use and land cover, morphometric parameters, soil moisture and vegetation cover characteristics

3.3.5.1 Sub watershed prioritization based on land use and land cover parameters

Ranking of the sub watershed susceptible to soil erosion was carried out by looking at the LULC class abundance and their effects on soil erosion in the sub watersheds (Tamene *et al.,* 2017). The LULC classes used are namely; cropland, dense forest, open forest, crop and vegetation mosaics, shrublands and water bodies. High priority (1) was assigned to the sub watersheds with less vegetation cover, large cropland, large water coverage and more built up areas (Gumma *et al.*, 2016). Whereas, sub watersheds with less cropland, more forest cover, more shrubland and more mosaics were given low ranking (5). The LULC ranks in each sub watershed were averaged to get the compound priority (CP) of each sub watershed

3.3.5.2 Sub watershed prioritization based on analysis of morphometric parameters

The parameters (length of the overland flow, form factor, stream frequency, circulatory ratio and drainage density are referred to the erosion risk assessment parameters (Avinash *et al.*, 2011). Linear parameters (e.g. bifurcation ratio) have a direct effect on soil erodibility therefore high values of linear parameters show more risk of erodibility. The length of overland flow is a unique linear factor that has an inverse relationship to soil erosion (Puno and Puno, 2019). Aerial parameters such as circulatory ratio, form factor and elongation ratio have an inverse relationship to soil erosion hence lower values of this parameter indicate a high susceptibility of watershed to soil erosion. Other aerial parameters such as stream frequency and drainage density have a direct relationship with soil erosion (Ali *et al.,* 2018). Relief parameters such as basin relief, relief ratio and ruggedness number have a direct influence on soil erodibility (Tolessa and Rao, 2013). Therefore, sub watersheds with higher values of relief parameters were given value rank of 1, while the lowest value were assigned a value of 5. Later the morphometric parameter ranks for each SW were averaged to get compound priority (CP).

3.3.5.3 Sub watershed prioritization based on vegetation cover and soil moisture

During prioritization, the sub watersheds with high NDVI value were given lower rank (5) because high NDVI represents abundance of healthy vegetative cover hence the soil is less exposed to agents of erosion (Tadesse *et al.*, 2017). Whereas, sub watersheds with lower NDVI were assigned high rank (1). Because water is considered an agent of soil erosion through seepage erosion and surface saturation contributing to surface runoff a factor that can lead to occurrence of soil erosion.

To find out the sub watershed that is more susceptible to erosion, priority ranking was done based on the compound value of the parameter affecting soil erodibility. Values of morphometric parameters, LULC classes, mean NDVI, mean TWI were assigned ranks based on their contribution to soil erosion. Parameters that show higher positive correlation were assigned a higher rank. Assigning priority rank to sub watersheds was carried based on compound parameter value (i.e., the mean of preliminary priority ranks). For the final prioritization of sub watersheds, the values 1 to 5 were assigned to the mean rank (one means that the watershed is highly susceptible to soil erosion while five represents sub watersheds that are not exposed to soil erosion. If it happens that two sub watersheds are having same values of the parameter, the two sub watersheds were given equal ranks (Chandniha and Kansal, 2017).

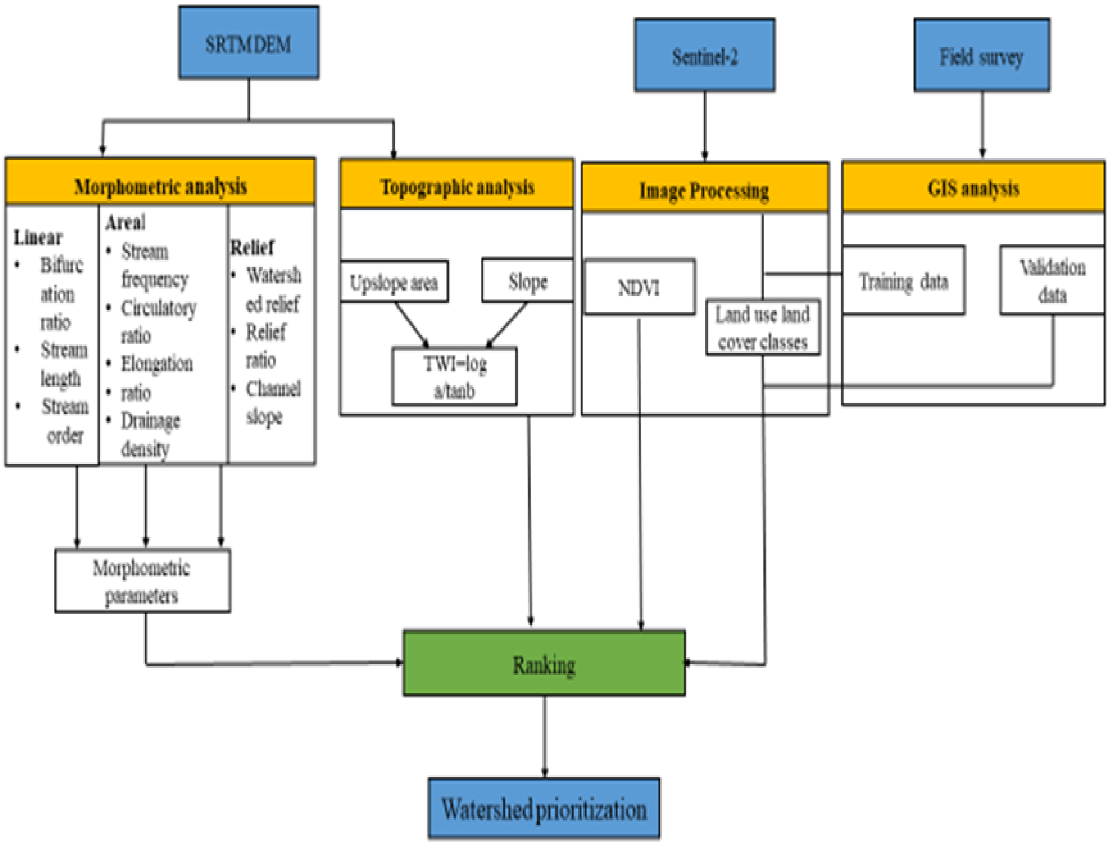

Figure 0.7: Methodology Framework

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter consist of the outputs of the research questions and hypothesis of the study and an in-depth discussion of the results. It contains the results of the hypothesis tested, accuracy assessment of the LULC, the parameter maps and statistical output in form of tables and figures of the variables of the study.

4.2 Assessing the land use and land cover characteristics of Thiririka sub watersheds

4.2.1 Accuracy assessment

The results of the classification accuracy show that the Kappa and the overall accuracy are close making the classification reliable. The overall accuracy for the classification was 0.88, with the overall kappa statistics of 0.86. Producer accuracy for the classes range from 0.74 to 1, while consumer accuracy value range from 0.78 to 1. The highest individual class accuracies were established, in which water bodies recorded the best model performance with consumer accuracy of 1 and the producer accuracy of 0.93 followed by the mosaics with consumer accuracy of 0.97 and producer accuracy of 0.86 (Table 4.1).

Table 0.1: Statistical accuracy assessment for land use / land cover classifications of Thiririka watershed

Class	Producer accuracy	Consumers accuracy
Closed forest	1.00	0.92
Built up areas	0.89	0.85
Water bodies	0.93	1.00
Shrublands	0.93	0.93
Croplands	0.74	0.78
Open forest	0.90	0.79
Mosaics	0.86	0.97
Overall Accuracy	**0.88**	
Overall Kappa Statistics	**0.86**	

4.2.2 Thiririka sub watersheds land use and land cover classification results

The maps produced represent major LULC classes of Thiririka sub watersheds for 2020. Overall, the land use and land cover in the Thiririka watershed exhibit distinct patterns. Upstream, the predominant features include agricultural activities and dense forest cover. Moving towards the midstream, the landscape is characterized by a mosaic of cropland with interspersed patches of cropland. Downstream, the predominant land over is mainly composed of built-up areas (Figure 4.1).

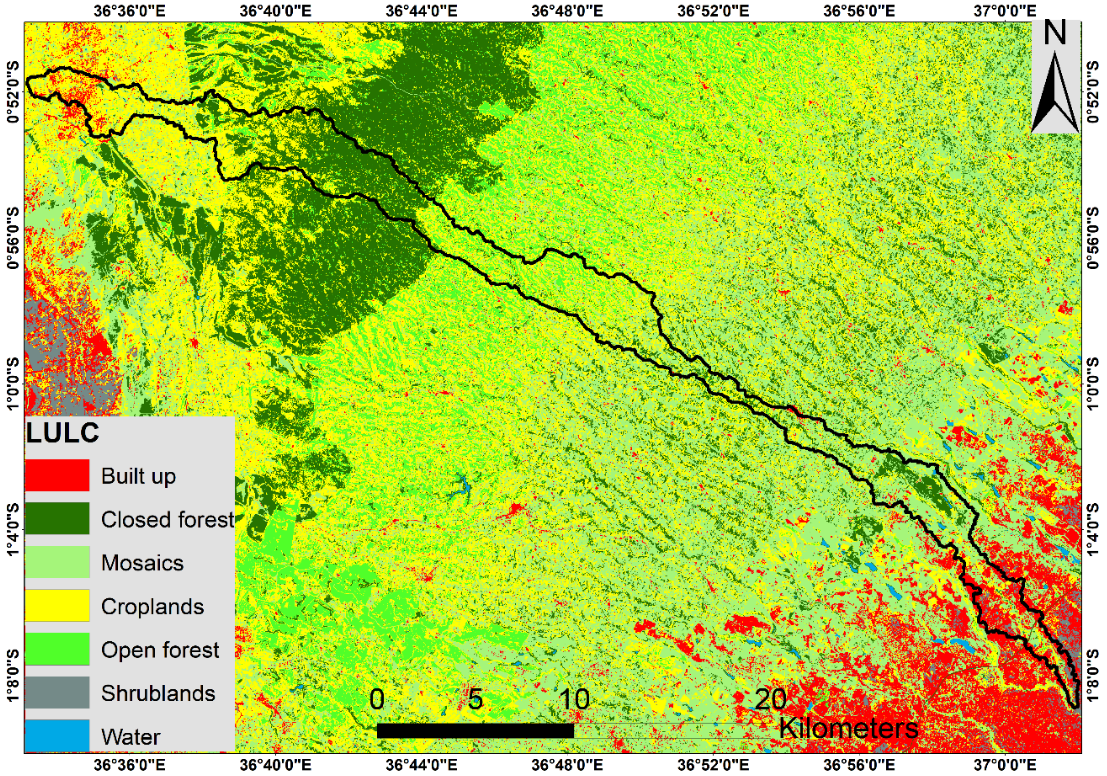

Figure 0.1: A bounding box of Thiririka watershed land use and land cover map

By visual interpretation, all the sub watersheds have a unique class that is dominant As observed in SW1 of Thiririka watershed (Figure 0.2), the sub watershed is dominant of croplands and built up areas. Built up areas are concentrated in middle part of the sub watershed around Magumu area. Little patches of water bodies (Thiririka dam) located in latitude -0.870849° and longitude 36.598026° and open forest are observed in the sub watershed. Results show that (

Table 0.), croplands cover about 66.32% of the sub watershed area, built up areas cover 18.33% of the sub watershed. Only 0.21% of waterbodies exist in the sub watershed while open forest are estimated to cover 0.62 % of the sub watershed.

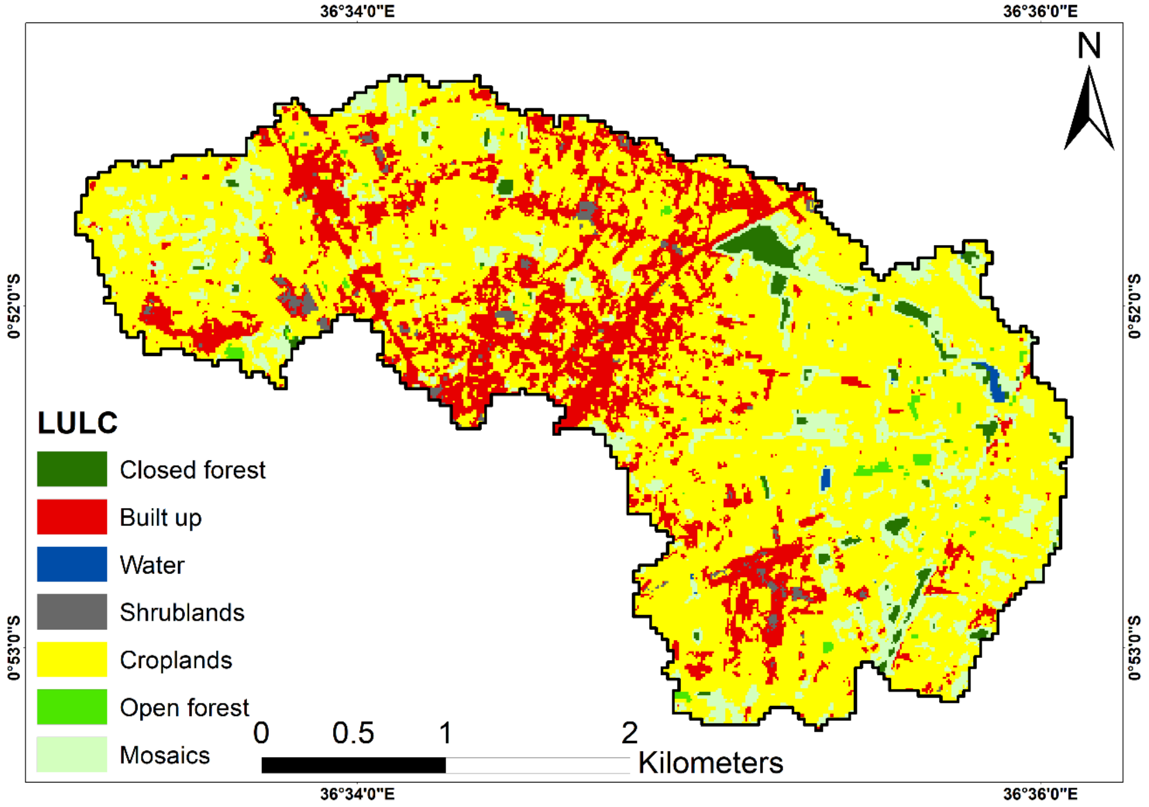

Figure 0.2: Thiririka watershed SW1 land use and land cover classes map

In SW2, it is observed that closed forest are dominantly present in the southeast with Thiririka river flowing through the dense forest while cropland cover most part of the North west side of the sub watershed. A few spots of open forest, crop and vegetation mosaics are in the mid-section of the sub watershed whereas very few built up area is seen in the Northeast region (Figure 0.3). The forested area within the sub watershed seems to be experiencing agricultural encroachment at latitude -0.894353° and longitude 36.645547° in Gatamaiyo forest. In (Table 4.3) closed forest cover 47.12%, cropland cover 41.39% while open forest and shrub lands cover 0.03 and 0.07% respectively.

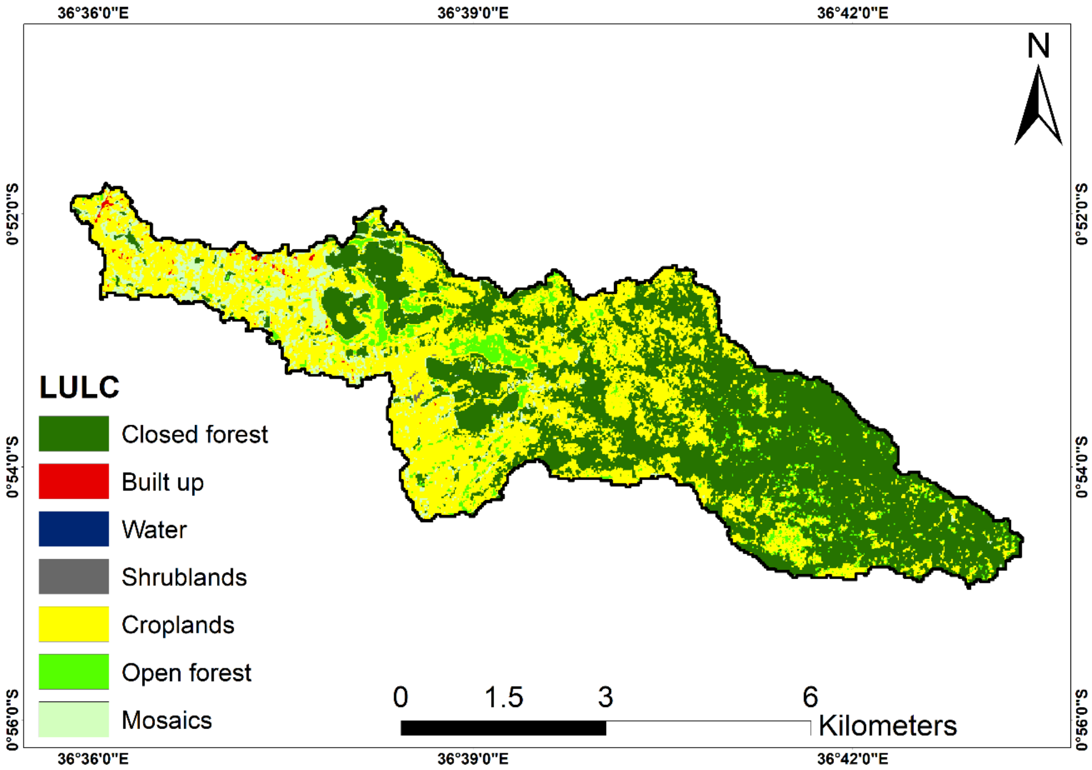

Figure 0.3: Thiririka watershed SW2 land use and land cover classes map

In SW3 (Figure 0.4), open forest and croplands cover most part of the sub watershed. Closed forest is dominant in the upper section of the sub watershed. The sub watershed exhibits an area of active agricultural activities as seen by existence of croplands, evident by presence of many farms namely Mutoro farm and Githunguri tea buying centre. The sub watershed is characterised by linear settlement with significant number of shopping centres namely: Karangi shoping center, Mundoro shopping centre, Ituramiro shopping centre, Roi shoping centre etc. Cropland cover 39.27% of land area and open forest cover 23.97% (Table 4.3).

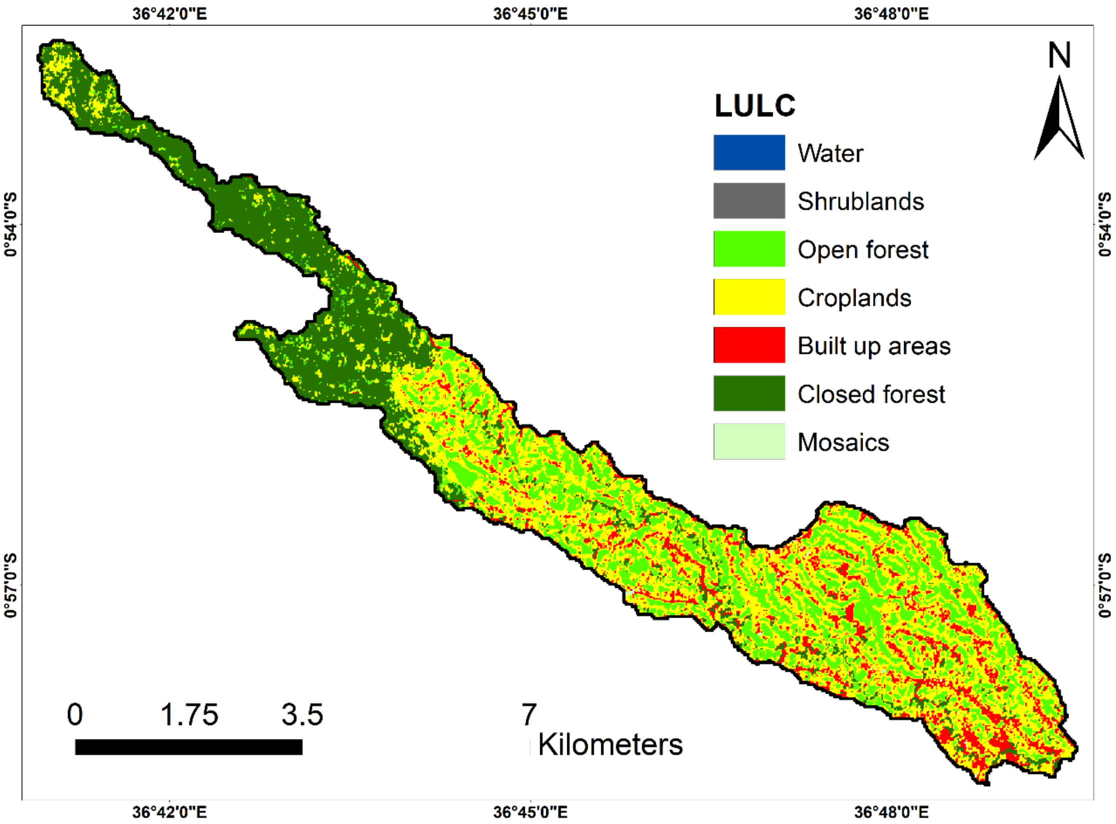

Figure 0.4: Thiririka watershed SW3 land use and land cover classes map

SW4 has more cropland and crop and vegetation mosaic spread across the sub watershed. There is noticeable patches of closed forest and open forest in some parts of the sub watershed (Figure 0.5). In (Table 0.), 42.37% of SW4 land is covered by cropland, crops and vegetation mosaics cover around 38.33% while closed forest cover 11.76% of the area in the sub watershed.

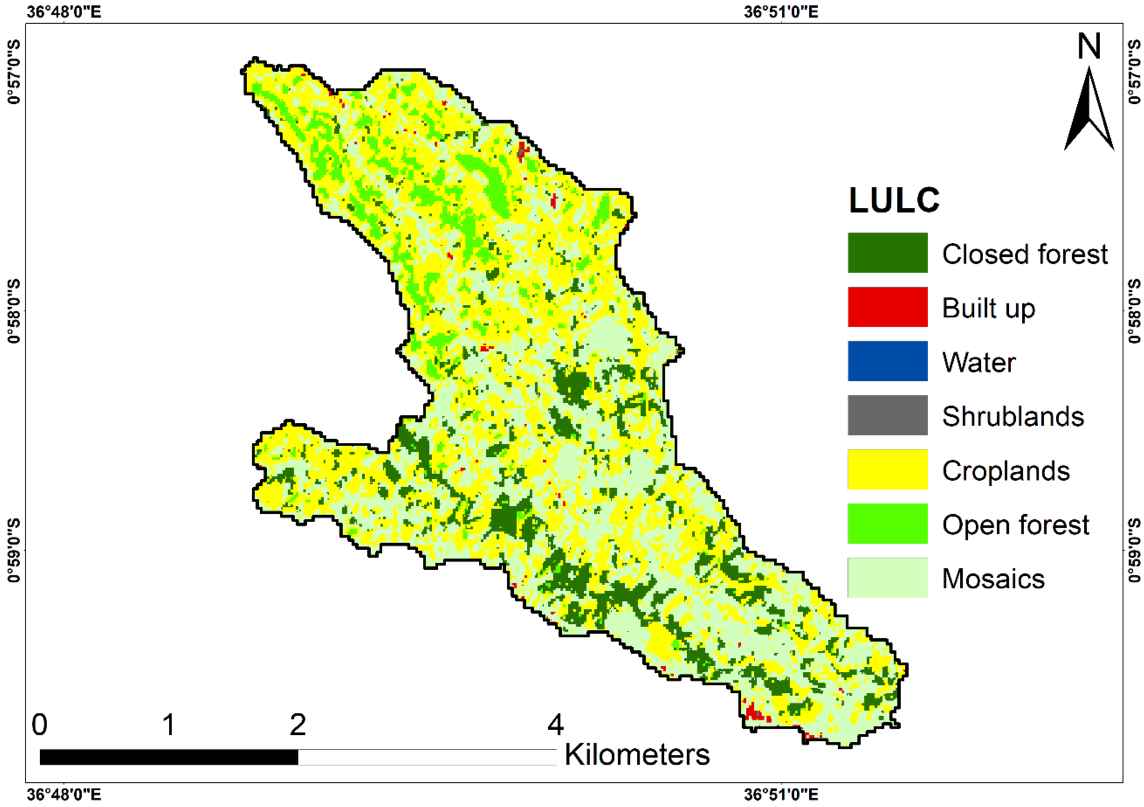

Figure 0.5: Thiririka watershed SW4 land use and land cover classes map

Crop and vegetation mosaics cover the upper and mid-section of SW5. Crop and vegetation mosaic include, coffee and tea plantations as seen by the presents of Handege coffee factory as observed from the field, Theta tea factory, vegetable and flower farms (Syngenta pollen ltd). A number of dams can be seen in the sub watershed (Murera dam, Kiahuria dam and Tatu dam). Downstream is covered with buildings around Juja town that is experiencing urban sprawl. Spots of shrublands are seen in this sub watershed (Figure 0.). As recorded in (Table 0.), crop and vegetation mosaic cover about 44.56%, built up area 19.37% and cropland cover 14.34%. The least occurring LULC is open forest with 0.81% of the sub watershed.

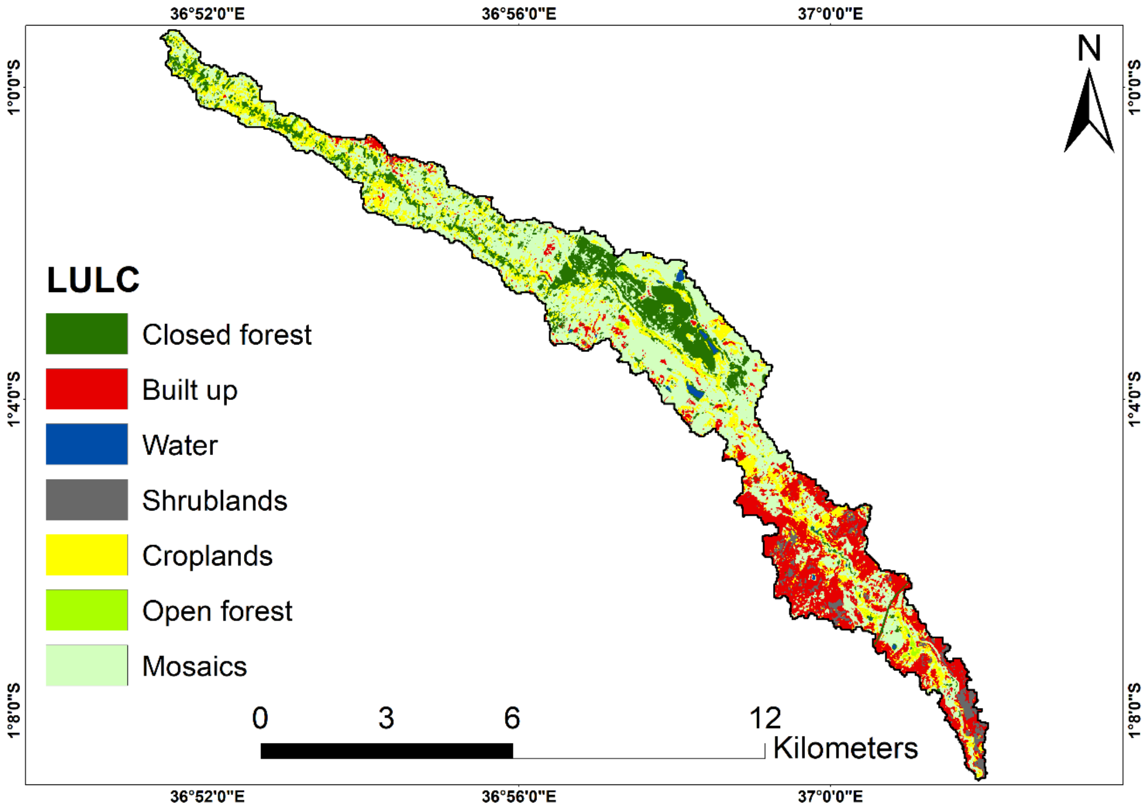

Figure 0.6: Thiririka watershed SW5 land use and land cover classes map

Table 0.2: Quantitative estimates of major land use and land cover in SW1, SW2 and SW3 of Thiririka watershed for the year 2020 reported in km^2 and percent cover

SW1 LULC

Land use / land cover class	Area	Percent cover (%)
Croplands	6.44	66.32
Built up areas	1.78	18.33
Mosaics	1.12	11.53
Closed forest	0.18	1.85
Shrublands	0.1	1.03
Open forest	0.06	0.62
Water bodies	0.02	0.21
Total	**9.71**	**100**

SW2 LULC

Land use / land cover class	Area	Percent cover (%)
Croplands	4.72	42.37
Mosaics	4.27	38.33
Closed forest	1.31	11.76
Open forest	0.77	6.91
Built up areas	0.07	0.63
Water bodies	0	0
Shrublands	0	0
Total	**11.14**	**100**

SW3 LULC

Land use / land cover class	Area	Percent cover (%)
Croplands	11.68	39.27
Closed forest	7.53	25.32
Open forest	7.13	23.97
Built up areas	3.29	11.06
Mosaics	0.1	0.34
Water bodies	0	0
Shrublands	0	0
Total	**29.74**	**100**

Table 0.3: Quantitative estimates of major land use and land cover of SW4, SW5 and Thiririka watershed for the year 2020, the values are reported in km^2 and percent cover

Area (km^2)

SW4 LULC

Land use / land cover class	**Area**	**Percent cover (%)**
Croplands	4.72	42.37
Mosaics	4.27	38.33
Closed forest	1.31	11.76
Open forest	0.77	6.91
Built up areas	0.07	0.63
Water bodies	0	0
Shrublands	0	0
Total	11.14	100

SW5 LULC

Land use / land cover class	**Area**	**Percent cover (%)**
Mosaics	17.65	44.56
Built up areas	7.68	19.39
Croplands	6.95	17.55
Closed forest	5.68	14.34
Shrublands	1.1	2.78
Open forest	0.32	0.81
Water bodies	0.22	0.56
Total	**39.61**	**100**

Thiririka watershed LULC

Land use / land cover class	**Area**	**Percent cover (%)**
Closed forest	29.06	24.09
Built up areas	12.9	10.69
Water bodies	0.25	0.21
Shrublands	1.23	1.02
Croplands	42.40	35.14
Open forest	9.78	8.11
Mosaics	25.07	20.78
Total	**120.65**	**100**

In Thiririka watershed, water bodies include rivers, streams, dams, and ponds covered fully or partially with water throughout the year. Most water bodies in the Thiririka watershed are mainly for irrigation and commercial farming (tea and coffee). SW5 had the highest waterbodies area of 0.23 km^2 (Figure 0.6 and

Table 0.). During prioritization the sub watersheds with more water were given high priority, whereas, sub watersheds with less water were given little priority because water is considered an agent of soil erosion and runoff through seepage erosion (Rózycka *et al.*, 2017; Vijith and Dodge-Wan, 2019). Built up areas within the watershed were mostly buildings, industries, and roads concentrated in SW5 with an estimated area extent of 7.68 km^2. Fewer developments were recorded in SW2 (0.08 km^2) (Figure 0.6). High built up areas are given high priority and vice versa because built-up areas have a high population exerting pressure on land resources causing land degradation like soil erosion. This happens especially in communities with underdeveloped social and economic domains *(*Rumora *et al.*, 2020), though not the case with sustained and developed communities whereby increased populations leads to increased technological innovations leading to efficient land resource utilization (Boserup, 2013).

Dense evergreen trees covering 70% and above of the area are characterized as closed forests in the sub watersheds. Closed forests were highest in SW2 (14.39 km^2) and lowest in SW4 (1.31 km^2). The sub watersheds with less closed forests were given high ranks and vice versa. In general, vegetation tends to slow water movement hence reducing soil erosion, while fewer trees cover exposes the soil to agents of erosion (Tadele *et al.,* 2017). In addition, tree canopies enhance infiltration as well as reduce surface runoff in watersheds (Yustika *et al.*, 2019). A 3 year experimental study conducted by Song *et al.,* (2019), shows that soil erosion tend to reduce with increase in tree species cover due to increase in leaf area index of trees over the years. Furthermore, trees canopy intercept rainfall intensity. Open forests in the watershed are tree strands that are not continuous and cover between 10% and 40% of the land as described by (Davis and Holmgren, 2000). Higher open forest cover was recorded in SW3 (7.13 km^2) while less open forest cover was recorded in SW5 (0.32 km^2). For prioritization, areas with less open forest cover were assigned a high priority due to an increase in rainfall erosivity as compared to areas with less open forest cover (Panagos *et al.*, 2015).

In Thiririka watershed, shrublands are fields comprising of woody vegetation between 10 cm and 2m in height with many different species. It is less vegetated lands with stunted growth trees, grass, bushes, and shrubs. Shrublands also included degraded land that is not in use and rocky areas. In the study area, the total area covered with shrubs is approximately 1.2 km^2, concentrated in SW5 with an area of 1.1 km^2. SW3 and SW4 did not contain shrublands (Table 4.3 and 4.4). When giving priority, low priority was given to sub watersheds with less shrublands while, high priority was assigned to sub watersheds with more shrublands.

In the present study, croplands are taken as lands with perennial and annual crops having harvest seasons and bare soil periods. In Thiririka watershed, SW2 (12.64 km^2) and SW3 (11.68 km^2) have the largest area of croplands. SW4 recorded the lowest area of 4.72 km^2 of croplands. The sub watersheds with more cultivated land was given a higher priority, as compared to sub watersheds with less cultivated area. Generally, continuous and intensive tillage practices tend to affect the soil structure hence increasing surface runoff and sediments delivery (Seitz *et al.*, 2019). Moreover, areas with loose surface soil tend to slow the infiltration rate becoming more susceptible to erosion. Crops such as maize cover most sub watersheds; these annual crops do not reduce the impacts of raindrops as with forested land.

Mosaics are comprised of fields with a combination of croplands, trees, shrubland, and grasslands where no any of the component exceeds 60% of the land. From field observation, most occurring mosaics include coffee, avocado, maize, bananas, Napier grass, beans and potatoes (Plate 0.1:). In Thiririka sub watersheds, SW5 was highly dominant of mosaics (17.65 km^2) while SW1 had fewer mosaics (1.12 km^2). Sub watershed with less coverage of mosaics was given high priority because the soil is exposed to agents of erosion as compared to lands with more crops and vegetation mosaic. Besides, trees and grass in cropland fields may imply soil conservation and management practices are in place.

Plate 0.1: Crops and vegetation mosaics observed at GPS -101399; 36.91638 (Image taken on January 8, 2022 at SW5)

4.3 Influence of morphometric characteristics on soil erosion in Thiririrka drainage basin

The aerial, linear, and relief parameters of River Thiririka watershed were extracted . This is useful to describe the catchment geometry and hydrological behavior of River Thiririka in relation to soil erosion. Results of the morphometric analysis of Thiririka sub watershed. The parameters were calculated using the standard formulas (Table 0.3). In addition, basin properties of perimeter (P), basin area (A) and basin length (L_b) were extracted to guide the analysis. The results are presented in (

Table 0.) below and discussed in the subsequent sections.

Table 0.4: Thiririka watershed morphometric parameters values

Linear Parameters

SW	Basin Length (L_b) Km	Total No. of Streams (N_u)	Total Stream Length (L_u)	Mean Stream Length (L_{sm})	Mean bifurcation ratio (R_b)	Length of Overland Flow (L_g)
SW1	4.75	38	16.4	0.43	3.2	0.29
SW2	8.98	65	44.97	0.69	4.09	0.34
SW3	9.11	61	41.89	0.69	4.26	0.35
SW4	5.14	25	18.99	0.76	3.25	0.29
SW5	10.56	95	43.8	0.46	4.65	0.45

Aerial Parameters

SW	Perimeter (P) Km	Area (A) Km^2	Drainage density (D_d) (Km/Km^2)	Stream frequency (F_s)	Form factor (R_f)	Circulatory ratio (R_c)	Elongation ratio (R_e)
SW1	23.01	9.64	1.70	3.94	0.43	0.23	0.74
SW2	52.19	30.33	1.48	2.14	0.37	0.14	0.68
SW3	65.2	29.53	1.42	2.07	0.37	0.09	0.68
SW4	26.76	11.05	1.72	2.26	0.42	0.19	0.73
SW5	91.13	39.34	1.11	2.41	0.35	0.06	0.67

Relief Parameters

SW	Maximum elevation(m)	Minimum elevation(m)	Basin relief(B_h)(km)	Relief ratio(R_h)	Ruggedness number(R_n)
SW1	2755	2659	0.1	0.02	8.08
SW2	2683	2210	0.47	0.05	13.49
SW3	2515	1843	0.67	0.07	12.74
SW4	1981	1753	0.23	0.04	8.83
SW5	1814	1482	0.33	0.03	11.73

4.3.1 Linear Aspects

4.3.1.1 Stream order

According to Strahler, (1957), stream order is the ranking of the streams of the basin following the hierarchical position of the rivers tributaries. The smallest stream segment without tributaries is the first-order stream. Second-order streams is formed after two streams of the first order join. The third-order streams are formed when second-order tributaries join, and so forth. The main stream with all the discharge is the highest order stream. Singh *et al.,* (2016) reported that stream order determines the stream size, stream flow, and catchment area. Watersheds with a higher stream order, have more water accumulating into the river mouth making it susceptible to flooding (Ali *et al.,* 2018). In (Table 0.) it is revealed that the entire Thiririka watershed is a 4th order type with 284 streams. In addition, (Table 0.) shows that 1st order stream segments recorded the highest number across all sub watersheds. SW5 has the highest 1st order stream number of 80 streams and SW4 has the lowest 1st order stream segment of 19 streams. The watershed streams reveal a parallel drainage pattern indicating that the watershed is located in steep slopes (Figure 0.).

Table 0.5: Thiririka sub watersheds stream order numbers

Stream order	SW1	SW2	SW3	SW4	SW5
1st	28	49	51	19	80
2nd	6	13	7	4	11
3rd	3	2	2	1	3
4th	1	1	1	1	1
Total streams	**38**	**65**	**61**	**25**	**95**

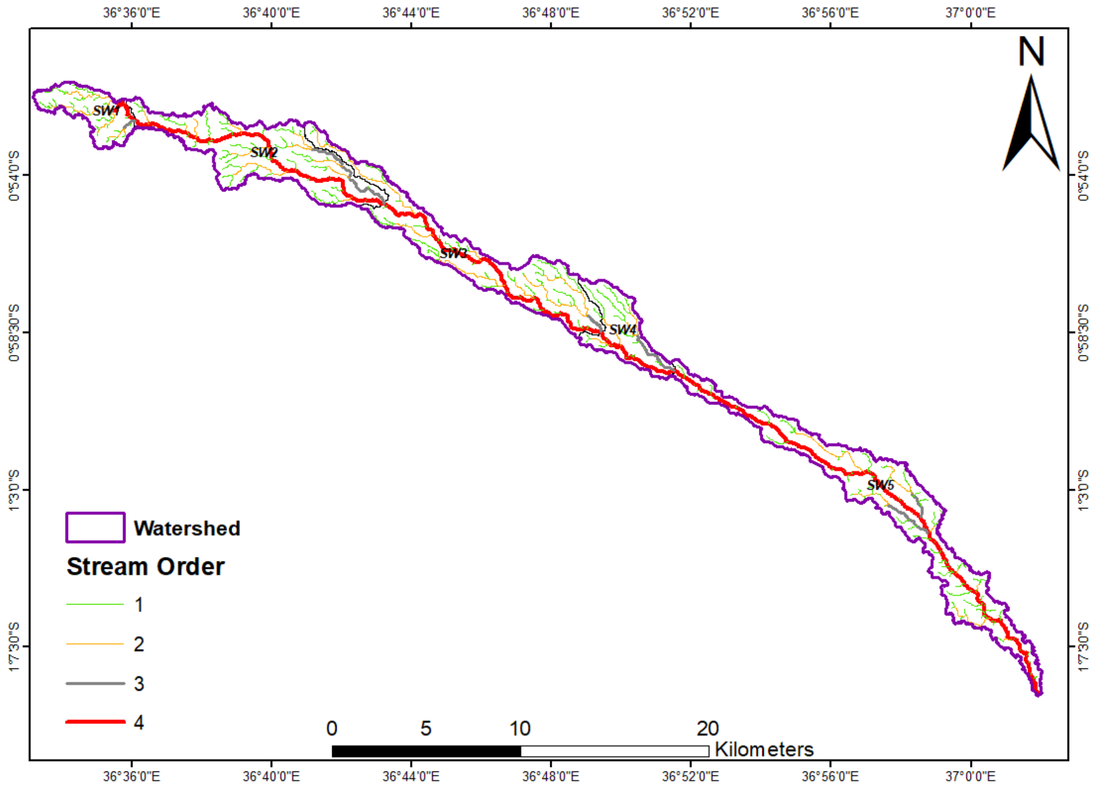

Figure 0.7: Stream order map of Thiririka watershed

4.3.1.2 Stream Number (N_u)

N_u is the joint count of each stream segment within the watershed. As suggested by Golekar *et al.*,(2013), the stream number of a given order in a watershed is indirectly proportional to the number of the stream order in that given watershed. The stream numbers in (Figure 0.), decrease with an increase in stream order in Thiririka sub watersheds.

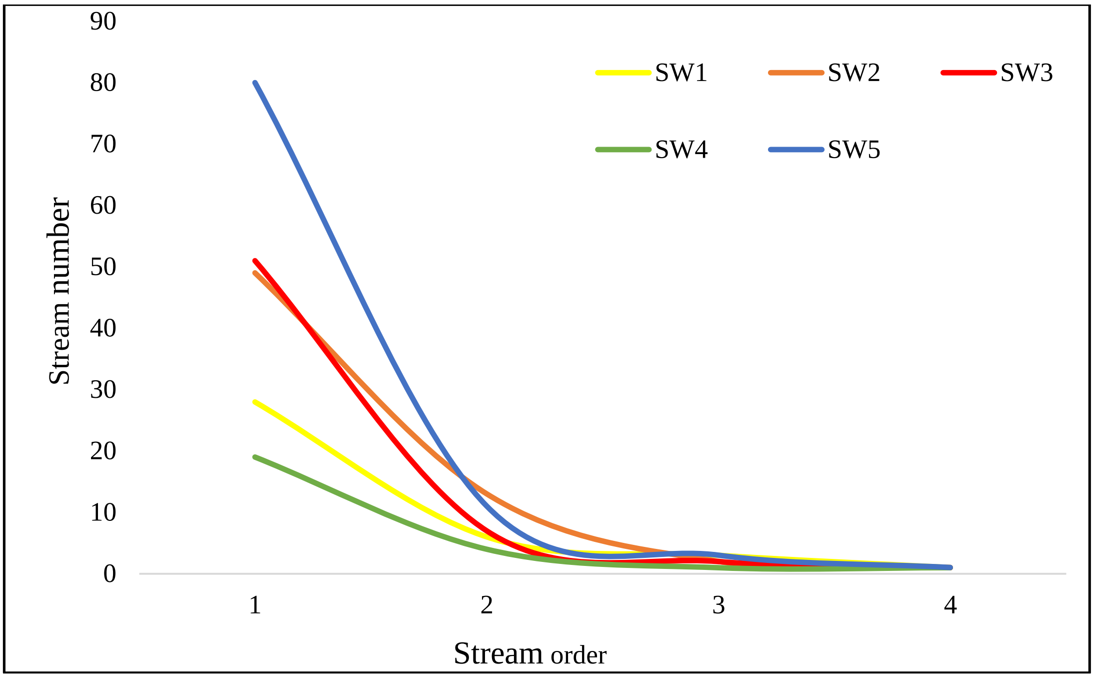

Figure 0.8: Regression plot showing the relationship between the stream order and Stream number of Thiririka sub watersheds

Stream length (L_u)

Horton (1945), defined L_u as the length of individual stream segment in the watershed. L_u is obtained by counting the number of streams in each order and measuring their length. L_u is an important parameter in studying the hydrology of the watershed indicating the amount of surface runoff. A high value of L_u shows that the watershed is characterized by gentle slopes while shorter stream lengths shows steep slopes with high amount of runoff (Tamma Rao *et al.*, 2012). In Thiririka watershed (Table 0.), SW2 recorded the highest value of stream length 44.97 km representing gentle slopes with reduced runoff, while SW1 had a shorter L_u value of 16.4 km indicating steep slopes with more surface runoff. Tamma Rao *et al*., (2012), noted that the total length of stream segments is higher in first order streams and decreases as the order of the streams increases which is observed in (Table 0.)

Table 0.6: Thiririka sub watersheds stream length value for each stream order and the total length values in km

Stream order	SW1	SW2	SW3	SW4	SW5
1st	12.65	32.35	29.68	13.65	35.59
2nd	2.56	10.62	8.18	3.65	5.51
3rd	0.76	1.74	2.69	0.87	2.42
4th	0.43	0.26	1.33	0.81	0.28
Total stream length	**16.4**	**44.97**	**41.88**	**18.98**	**43.8**

4.3.1.3 Mean Stream Length (L_{sm})

Mean stream length is the total length of the streams of a specific order to the number of streams in the same order (Chandniha and Kansal, 2017). According to Ahirwar *et al.*,(2019), L_{sm} is linked to the catchment surface and the drainage pattern. Whereby, the L_{sm} values of any catchment is higher in the lower order and reduces with the increase in stream order this is caused by variation in the terrain Figure 0.. L_{sm} value were higher in SW4 (0.76) SW2 and SW3 (0.69) and lower in SW1 (0.43).

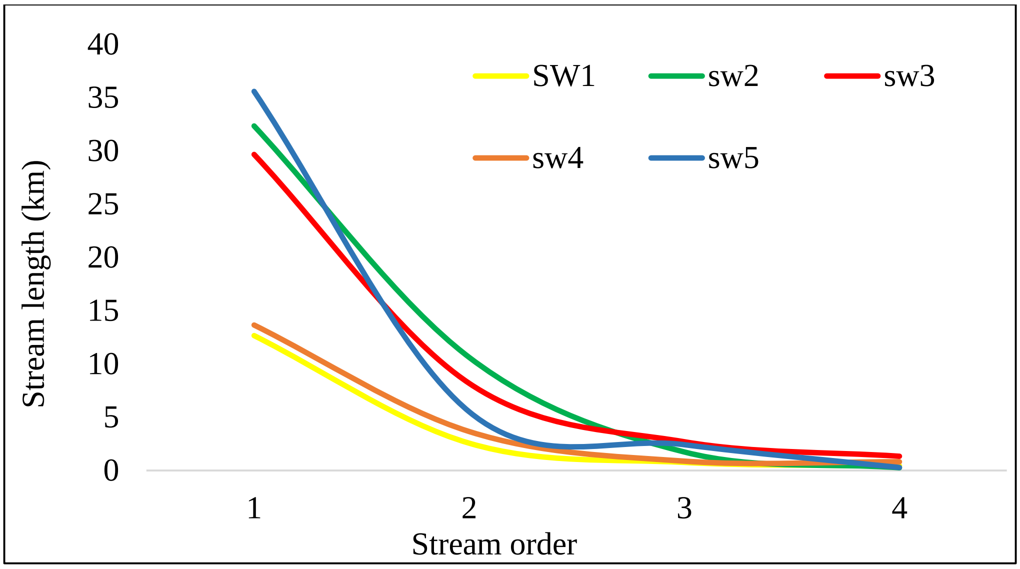

Figure 0.9: Relationship between the Stream order and Stream length of Thiririka sub watersheds

4.3.1.4 Bifurcation ratio (R_b)

It is the branching pattern of the drainage network. According to Avinash *et al.*,(2011), R_b is the ratio between the total numbers of stream channels of one order to that of the next higher order in a catchment. Choudhari *et al.*, (2018) reported that R_b ratios of between 3.0 – 3.6 show that the structure of the geology have less influenced the drainage pattern. Strahler (1957) suggested that lower R_b values represent more first and second order streams segments with plain terrain, lowlands, and permeable sub surface watersheds. Higher R_b is associated with mountainous region with high runoff (Avinash *et al.*, 2011). In addition, Ayanda (2015), noted that high R_b is associated to flash floods. As indicated in (

Table 0.), R_b of the study area ranges from 3.2 in SW1 to 4.65 in SW5. The watersheds mean bifurcation values recorded were lower indicating the watershed has not been influence by the geological structures (Choudhari *et al.*, 2018). These Lower R_b values can also be attributed to the abundance of first and second order streams in the sub watersheds recorded in (Table 0.) as noted by (Avinash *et al.*, 2011).

4.3.1.5 Length of overland flow (L_g)

According to Suji *et al*., (2015), L_g is described as the length of water flowing in the surface before reaching to the main streams. L_g is known to affect the physiographic properties of the watershed (Horton, 1945). During rain, water seeps into the ground while the excess water flows to the streams and rivers. The computed L_g values for Thiririka sub watersheds ranges from 0.29 for SW1 and SW4 to 0.45 in SW5 (

Table 0.). Length of overland flow as it is described to affect the physiography of the watershed whereby shorter values of L_g indicate that the basin is highly exposed to soil erosion from surface runoff especially the ridge formed after rain. The shorter values of L_g recorded in SW1 and SW4 indicate that the two sub watersheds experience high surface runoff hence highly susceptible to soil erosion as compared to other sub watersheds. The higher value of 0.45 recorded by the SW5 (

Table 0.) suggests a high water infiltration rates in the watershed.

4.3.2 Areal Aspects

4.3.2.1 Watershed perimeter (P), Watershed area (A) and watershed length (L_b)

Watershed perimeter is the boundary of the catchment indicating the size. The basin area (A), is the entire boundary of the watershed where all streams within that boundary drain into one outlet, separated by the drainage divide of streams flowing in the opposite direction, while the basin length (L_b) is the line along the flow path of the longest stream from the basin inlet to the outlet point. Basin length values were extracted using basin length function in Arc Hydro tools. SW5 is the largest with a perimeter of 91.13 km followed by SW3 with a perimeter of 65.2 km. The smallest sub basin is SW1 with 23.01 km. The drainage area of the Thiririka watershed is approximately 119.8 km^2. SW1 covers a smaller area of 9.64 km^2 while SW5 has a large area coverage of 39.34 km$^{2.}$ SW1 with the L_b of 4.75 km was the lowest while SW5 recorded the highest L_b of 10.56 km, indicating that the basin is elongated in shape (

Table 0.). Watershed area determines the amount of surface runoff whereby large watershed intercept more rainfall and high peak discharge, while small watersheds intercept less rainfall and low peak discharge (Oruonye *et al.*, 2016). Following this, in Thiririka watershed SW5 is more likely to intercept more rainfall. When the basin length is long, chances of flooding are reduced hence low erosion (Oruonye *et al.*, 2016). This shows that based on the basin length values SW1 is highly erodible while SW5 is less exposed to erosion.

4.3.2.2 Elongation ratio (R_e)

Elongation ratio is the ratio between the diameters of a circle having a similar area as that of the basin to the maximum length of the basin, used to show the shape of the catchment (Avinash *et al.*, 2011). R_e values of any given watershed tend to vary from 0.6 to 1.0 depending on the climate and geology of the area (Ket-ord *et al.*, 2013). In Thiririka sub watershed, R_e of SW1 is 0.74, which is the highest while SW5 recorded the lowest R_e of 0.63 (

Table 0.). Basins that are elongated in shape tend to increase runoff from precipitation hence causing soil erosion (Puno and Puno, 2019). The elongated shape of Thiririka watershed in (Figure 0.1) indicates that more water is generated by rainfall. The high R_e values of SW1 show that it is an area of active denudation with low elevation and high infiltration rates (Avinash *et al.*, 2011), this is evident also by the lower basin relief value of SW1 reported in the sub watershed (

Table 0.). Lower R_e values recorded in SW5 indicate that it is highly elongated and highly susceptible to erosion, these sub watershed facilitate high surface runoff with less infiltration and steep slopes hence more exposure of the sub watershed to erosion (Puno and Puno, 2019).

4.3.2.3 Circulatory ratio (R_c)

As defined by Choudhari *et al.*,(2018), circulatory ratio is the ratio of the area of a watershed to the area of a circle with similar diameter as the perimeter of the catchment. It describes the degree of roundness of the watershed. According to Ali *et al.*, (2018), R_c of a given basin is important in assessing the vulnerability of the watershed to flooding. In Thiririka sub watersheds, R_c values range from 0.06 for SW5 to 0.23 in SW1 (

Table 0.). The low values of R_c in SW5 indicate that the sub watershed is at a young stage while SW1 show that the watershed is at a geomorphic stage (Aybar *et al.*, 2020). Very high value of R_c above 0.5 indicate the catchment is at maturity stage (Paghadal *et al.,* 2013). R_c values are influenced by the basin length, LULC, slope geology, basin relief and climatic conditions (Suji *et al.*, 2015).

4.3.2.4 Form Factor (R_f)

The form factor 'R_f' describes the outlined form of a drainage basin affecting the stream discharge. According to Horton (1945), R_f is defined as the ratio of catchment area to square of the maximum catchment length which ranges from zero to one (1) (Aybar *et al.,* 2020). In (Table 0.), Watersheds with higher form factor are normally circular with high peak flows for shorter duration, whereas watersheds with lower values of form factor are elongated with low peak flowing for longer duration (Ahirwar *et al.,* 2019 and Tamene *et al.,* 2017). In Thiririka sub watersheds, the R_f values range from 0.35 for SW5 to 0.43 for SW1 (

Table 0.) indicating that they are highly elongated with flat peak flows for longer duration (Strahler, 1957). SW5 is highly elongated in shape showing that it has low peak flow for a longer duration, which tends to reduce soil erosion. On the other hand, SW1 with an R_f value of 0.43 is close to 0.5 elongation value resulting to high erodibility.

Table 0.7: Form factor classification values

Form factor (R_f) value	Watershed shape
<0.5	Highly elongated
0.5–0.7	Elongated
0.7–0.8	Less elongated
0.8–0.9	Oval
0.9–1.0	Circular

4.3.2.5 Drainage density (D_d)

Drainage density (D_d) as described by Horton (1945), is the total length of all the stream channels of all orders within the watershed per basin area. According to Sarkar *et al.,*(2020), D_d is used as an indicator of terrain dissection, infiltration capacity of the catchment, climatic characteristics as well as the vegetation cover of the watershed. Watersheds with high D_d experience high surface runoff because they are less permeable, have less vegetation cover and steep slopes, areas of low D_d are more permeable allowing for high infiltration with reduced runoff, characterized by dense vegetation cover with gentle slopes (Ikbal and Ali, 2017, Pawar *et al.*, 2013). According to Pandey *et al.*,(2011) higher D_d is associated with high sediment yield. The D_d of the sub watersheds in Thiririka (

Table 0.) recorded were lowest in SW5 with 1.11km/km^2 and higher in SW4 with 1.72 km/km^2 suggesting that the sub watershed are vegetated with little runoff and high infiltration rates. According to (Avinash *et al.*, 2011), high D_d is due to weak sub surface and less vegetation cover while lower D_d is related to dense vegetation cover, permeable subsoil material and low relief. These is similar to the LULC classification results whereby large closed forest cover are found in SW5 as compared to SW4. Although not the case when compared to with SW2 and SW3 with large closed forest, the variation can be attributed to continues LULC changes over the years.

4.3.2.6 Stream frequency (F_s)

The stream frequency of a watershed is the ratio between the total number of stream channels within the basin to the catchment unit area (Horton, 1945). In Thiririka sub watersheds, SW1 recorded the highest F_s value of 3.94, while SW3 had the lowest F_s value of 2.07 (

Table 0.). F_s determines the surface runoff and the rate of infiltration of the drainage area i.e., higher F_s values indicate that the watersheds have lower infiltration rates and reduced runoff (Ikbal and Ali, 2017). As reported by Pandey *et al.*, (2011) low F_s shows that the sub watershed is forested while high F_s shows that the sub watershed is mostly covered by cropland. With the F_s having a direct relationship with the soil erosion, in Thiririka watershed, the higher value recorded by SW1 suggests that the sub watershed is highly susceptible to erosion and has high relief with low surface permeability hence high runoff. In addition, SW1 recorded 66% of cropland and 18.33% of built up area (Table 0.), these LULC parameters are known to increase soil erosion. On the other hand, SW3 has the lowest F_s value suggesting a reduced amount of runoff from high permeability.

4.3.3 Relief Aspects

4.3.3.1 Basin Relief (B_h)

The basin relief shows the elevation of the watershed i.e., the difference between the peak of the basin and the mouth of the basin (Choudhari *et al.*, 2018). The B_h value of Thiririka sub watersheds range between 96 m in SW1 to 332 m in SW5 (

Table 0.). Basin relief parameter influences the amount of basin denudation, surface runoff and sediments yield. The high basin relief in SW5 shows that the watershed experiences high amount of runoff as suggested by (Vaibhav E. Gosavi, Pawan Kumar Thakur, 2018).

4.3.3.2 Relief ratio (R_h)

Relief ratio is the ratio of maximum relief to horizontal distance along the longest dimension of the basin parallel to the principal drainage line (Tamene *et al.*, 2017). In the present study, the relief ratio varies from 0.07 in SW3 to 0.02 in SW2 (

Table 0.). The relief ratio of the sub watershed was high in SW3 and lower in SW2. It shows that SW3 has steep slopes indicating high intensity of soil erosion as describes by (Tamene *et al.*, 2017). High relief ratio indicates steep slopes hence more erosion while low values depict less erosion.

4.3.3.3 Ruggedness number (R_n)

Ruggedness number (R_n) is the value derived by assessing the drainage density and the relief of the basin (Strahler, 1952). From the analysis, the R_n value of the present study varies from a maximum of 13.49 in SW3 to a minimum value of 8.08 in SW1 (

Table 0.). When R_n value is low, it indicates that the particular watershed is not susceptible to erosion. Ruggedness number assessment is useful to determine the steepness of the drainage network. Lower values of ruggedness number indicate that the basin is more resistant to erosion (Puno and Puno, 2019). Lower values of R_n in SW1 indicates that the watershed is not susceptible to erosion.

4.4 Assessing the joint effect of varying soil moisture and vegetation cover on soil erosion in Thiririka sub watersheds

4.4.1 Normalized Different Vegetation Index (NDVI) analysis in Thiririka sub watersheds

The entire Thiririka watershed has a mean NDVI value of 0.67 with a minimum of -0.47 and a maximum value of 0.9. SW2 recorded mean NDVI value of 0.77 showing a probability of having high vegetative cover while SW1 has less vegetative density cover with a mean NDVI value of 0.53 (Table 0.). Ouyang *et al.,*(2010), conducted a research project aiming to elucidate the connection between soil erosion, sediment yield, and NDVI. The findings revealed an inverse relationship between NDVI and soil erosion, indicating that areas with low vegetation cover are more prone to erosion, and conversely, areas with higher vegetation cover experience reduced erosion. SW1 and SW5 have very low minimum NDVI of –0.02 and -0.47 respectively. Suggesting that some parts of the sub watershed are covered by either water or bare soil. On the other hand, SW3 recorded the highest maximum NDVI values of 0.90 indicating the sub watershed is more vegetated (Table 4.8 and Figure 4.11).

Table 0.8: Thiririka sub watersheds Normalized Difference Vegetation Index minimum, maximum, mean and standard deviation values derived from the Sentinel-2 image composite for the year 2020

Sub watershed	Minimum	Maximum	Mean	Standard deviation
SW1	-0.02	0.86	0.53	0.11
SW2	0.15	0.89	0.77	0.09
SW3	0.09	0.90	0.76	0.11
SW4	0.09	0.89	0.68	0.11
SW5	-0.47	0.89	0.56	0.18

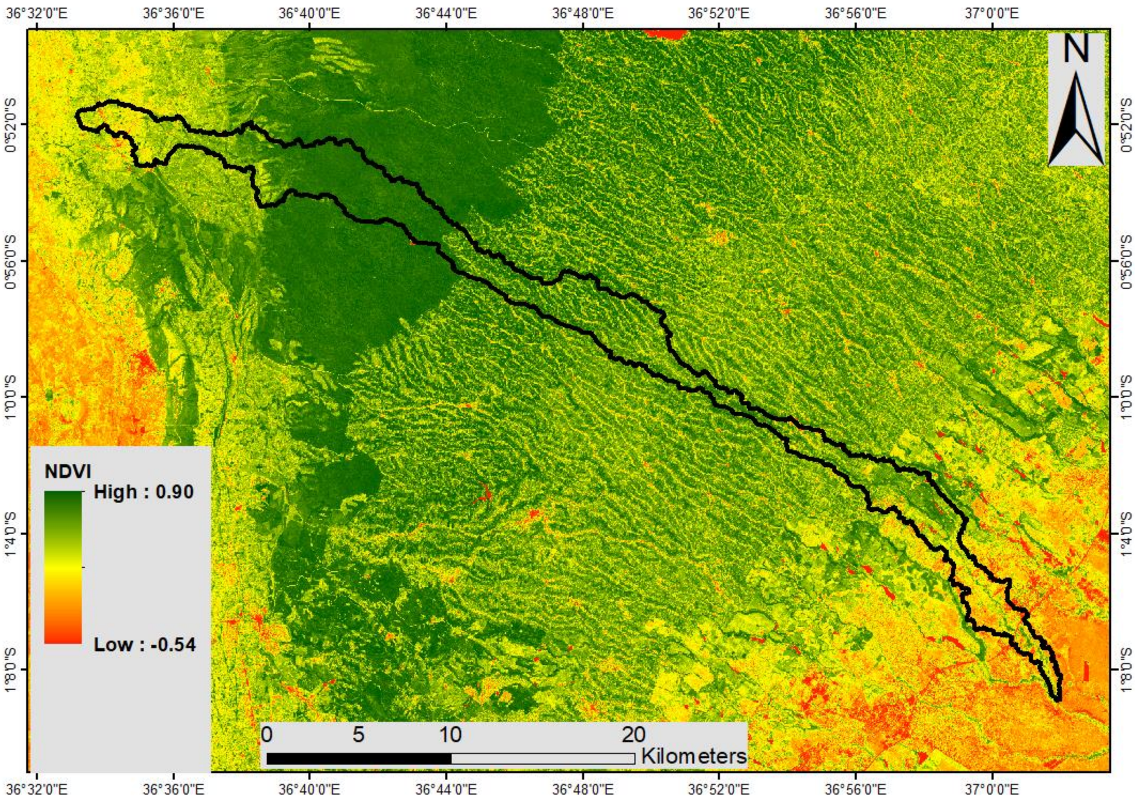

Figure 0.7: A bounding box of Thiririka watershed spatial distribution of Normalized Difference Vegetation Index map

4.4.2 Topographic Wetness Index (TWI) analysis in Thiririka sub watersheds

The Topographic wetness index (TWI) is an index used to depict the spatial moisture distribution within a watershed. As the catchment area increase with a decrease in slope steepness, TWI and soil moisture increases (Ballerine, 2017). High distribution of soil moisture leads to more saturation zones, followed by increased runoff as well as increased soil erosion (Bisht *et al.*, 2016). Lower TWI values represent catchments that dry up easily while high TWI represent areas of potential soil moisture. The high values of TWI are often associated with gully erosion because as the soil becomes more saturated it loses the compactness and falls when water starts to seep underground (A. Sharma, 2010). These slumps are carried away easily by rainfall and overland flow therefore, widening the stream channel hence more erosion. Within the earth surface, cells having lower TWI values depict steep slope and represented by valleys. On contrary, areas of gentle slopes represent higher TWI values and more runoff potential. In Thiririka watershed, the results show that the mean TWI ranges between 6.50 in SW4 to 8.19 in SW1 (**Error! Reference source not found.** and

Table 0.1) indicating that SW1 is highly exposed to erosion which is also supported by low length of the overland flow (

Table 0.).

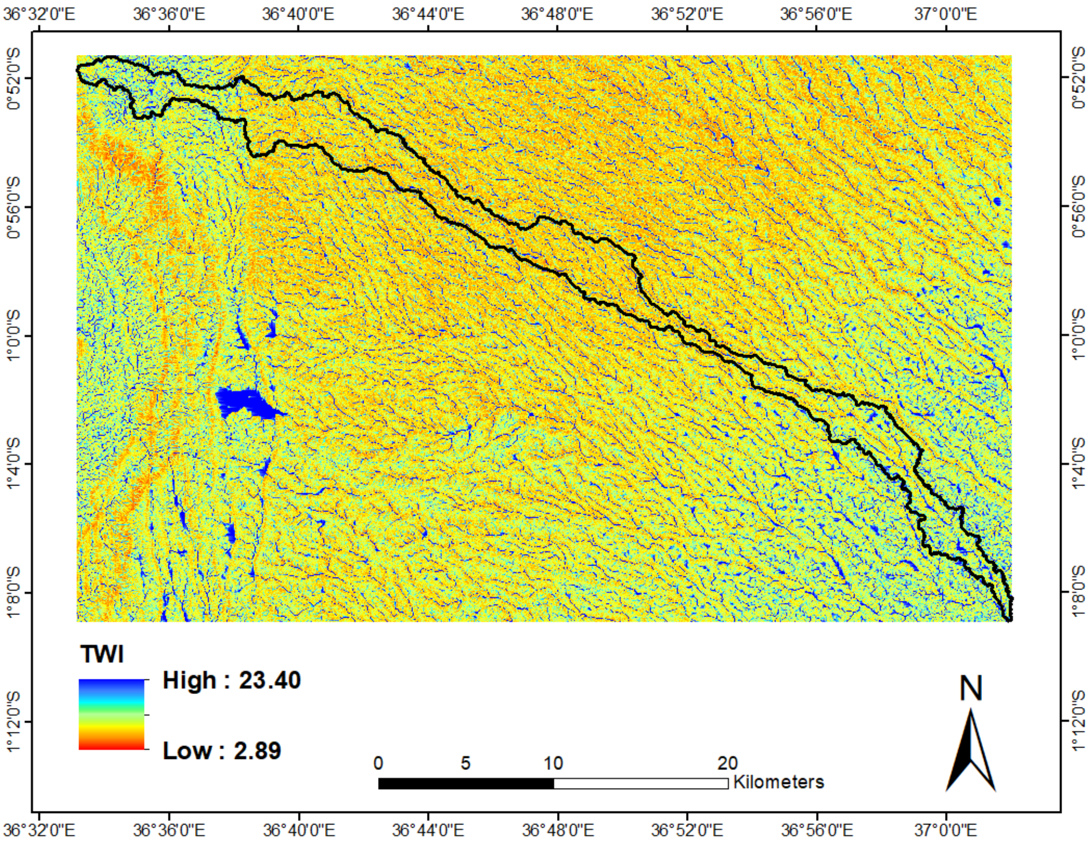

Figure 0.8: Abounding box of Thiririka watershed Topographic Wetness Index spatial distribution map

Table 0.1: Thiririka sub watersheds minimum, maximum, mean and standard deviation Topographic Wetness Index values

Sub watersheds	Minimum	Maximum	Mean	Standard deviation
SW1	4.92	18.75	8.19	2.26
SW2	3.75	20.67	6.83	2.22
SW3	3.71	21.36	6.52	2.3
SW4	4.06	21.53	6.50	2.27
SW5	3.83	22.08	7.72	2.56

4.5 Prioritization of sub watersheds based on land use and land cover, morphometric parameters, TWI and NDVI characteristics.

Table 0.2: Susceptibility of Thiririka sub watersheds to soil erosion based on LULC, morphometric parameters, NDVI and TWI.

The values from 1 to 5 represent1- very high (1), high (2), moderate (3), low (4), and very low (5) susceptibility to soil erosion.

Sub watershed prioritization based on LULC

SW	Closed forest	Built up lands	Water bodies	Shrub lands	Crop lands	Open forest	Mosaics	Compound priority	Priority rank
SW1	1	2	2	2	4	1	5	2.43	2
SW2	5	4	3	3	1	4	4	3.43	3
SW3	4	3	4	4	2	5	3	3.57	4
SW4	2	5	4	4	5	3	2	3.58	5
SW5	3	1	1	1	3	2	1	1.71	1

Sub watershed prioritization based on computed basin morphometric parameters

SW	Bifurcation ratio	Drainage Density	Stream frequency	Form factor	Circulatory ratio	Elongation ratio	Length of overland flow	Relief ratio	Ruggedness number	Compound priority	Priority ranking
SW1	5	2	1	4	5	4	4	5	5	4.38	5
SW2	3	3	4	2	3	2	3	2	1	2.88	3
SW3	2	4	5	2	2	2	2	1	2	2.75	2
SW4	4	1	3	3	4	3	4	3	4	3.63	4
SW5	1	5	2	1	1	1	1	4	3	2.38	1

Sub watershed prioritization based on NDVI and TWI

Sub watershed	NDVI Priority rank	TWI Priority rank
SW1	1	1
SW2	5	3
SW3	4	4
SW4	3	5
SW5	2	2

based on prioritization of sub watersheds based on LULC, it is noted that sub watershed 5 (SW5) was highly exposed to erosion (

Table 0.2). This can be attributed to the watershed having less forest that cannot hold the soil exposing it to agents of erosion, more commercial crop farming and highly populated which is evident by the presents of Handege coffee factory, Theta tea factory. Dams namely Murera dam, Kiahuria dam and Tatu dam supporting large commercial farms are found in the watershed. Despite most land of SW5 having more crop and vegetation mosaics, the area is undergoing high urban sprawl in the lower section (immense clearing of land to create space for urban expansion). The urban sprawl alters the natural landscape, increasing impervious surfaces, reducing vegetation cover, modifying drainage patterns, and causing soil disturbance. In addition, the upper section is experiencing an increase in croplands.

Morphometric parameters have been used as a basis to select critical watersheds for integrated watershed management approaches implementation. This method is proven to be significant with no considerations of soil properties (S. Biswas *et al.,* 1999). Prioritization based on Thiririka river morphometric characteristics indicated that SW5 is highly susceptible to soil erosion (

Table 0.2). The sub watershed is characterized by high length of overland flow subjecting it to high surface runoff. The sub watershed also has a lower form factor, low circulatory ratio and low elongation ratio indicating that it is highly elongated in shape with low infiltration capacity causing a continuous soil erosion activity. The mean bifurcation ratio of SW5 indicate that it experiences flash floods during heavy rains. Again, SW5 has more first and second order stream, which exhibits soil erosion by surface runoff.

For final prioritization of sub watersheds, the ranks 1 to 5 were assigned (one means that the watershed is highly susceptible to soil erosion while five represents sub watersheds that are not exposed to soil erosion). After assigning the ranks on each sub watersheds parameters, the ranks were averaged to get the compound priority (CP) (

Table 0.2). The CP values of each parameter were later averaged to determine the sub watershed susceptibility to soil erosion. In (Table 4.12) the mean compound priority values were extracted from the LULC, TWI, NDVI and the morphometric parameters for final prioritization of sub watersheds. Final priority map (Figure 0.9) was generated from the mean compound values. The CP values were ordered into 5 ranks i.e. very high (1), high (2), moderate (3), low (4), and very low (5) priorities. The sub watersheds with the least mean CP was assigned high priority (1) and vice versa.

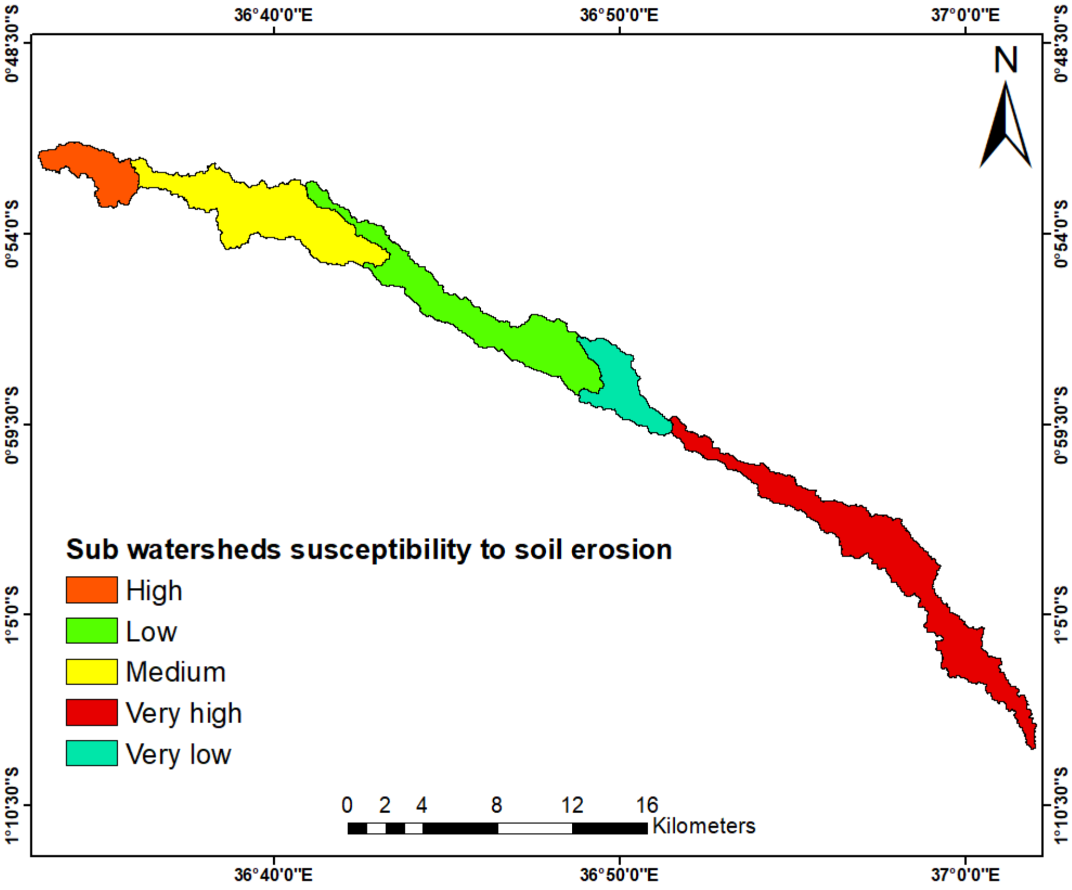

Figure 0.9: Thiririka sub watersheds soil erosion susceptibility map

Table 0.3: Final priority ranks of Thiririka sub watersheds

SW	LULC Compound Priority	Morphometric parameters Compound Priority	NDVI Priority rank	TWI Priority rank	Mean Compound Priority (CP)	Final rank
SW1	2.43	4.38	1	1	2.20	**2**
SW2	3.43	2.88	5	3	3.58	**3**
SW3	3.57	2.75	4	4	3.59	**4**
SW4	3.58	3.63	3	5	3.80	**5**
SW5	1.71	2.38	2	2	2.02	**1**

Results show that SW5 has the highest priority (1) with mean compound value of 2.02 indicating high susceptibility to soil erosion from the effect of critical basin morphometry, LULC, TWI and NDVI. Therefore, suitable watershed conservation measures need to be adopted for soil and water resources sustainability in SW5. SW2 is also highly susceptible to soil erosion. It is noted that most part of SW1 is covered by cropland and built up areas and less forest cover. Both SW5 and SW4 have high moisture content recorded by high TWI index with lower mean NDVI values. On the other hand SW4 recorded less priority (5) having a mean CP value of 3.80, the sub watershed has more crop and vegetation mosaic which tend to protect soil from the agents of erosion. SW1 also has a high drainage density indicating high infiltration and permeability and hence less soil erosion through runoff.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The section covers an overall summary of the results under the various objectives of this study. In addition, some recommendations are outlined. Lastly, some proposed suggestions for further research to address the limitations and aspects not covered by the study are explained.

5.2 Summary of Research Findings

For effective and sustainable utilization of watershed resources, identifying areas that need attention is crucial. The present study shows the steps in delineating watersheds and sub watersheds, quantifying LULC, computing the basin morphometric parameters, understanding the vegetation cover characteristics using NDVI and quantifying for static soil moisture using the TWI of Thiririka watershed. For prioritization of Thiririka sub watershed relative to soil and water resources conservation, five sub watersheds were delineated and their LULC, basin morphometry, TWI and NDVI effects to soil erosion assessed.

The study shows that SW5 is highly susceptible to soil erosion based on LULC parameters, while SW4 is less susceptible to soil erosion with more crop and vegetation mosaic. Based on the morphometric analysis, SW5 has high soil erodibility while SW1 recorded less priority rank. Based on the vegetation cover characteristics, the SW1 was highly susceptible to soil erosion because of the low mean NDVI recorded while SW2 recorded the lowest priority because of high mean NDVI from large forest cover. Moreover, on prioritization based on soil moisture distribution represented by mean

TWI, SW1 is more susceptible to soil erosion while SW4 is less susceptible to soil erosion.

The general rank considering the LULC, morphometric parameters, soil moisture, and NDVI found that SW5 is highly exposed to soil erosion, SW1, SW2, SW3, and SW4 recorded as high, moderate, low, and very low susceptibility to soil erosion respectively. Therefore, soil erosion control measures (improving the vegetative cover by planting trees and construction of gabions) are required in in SW5 and SW1 to avoid further soil erosion.

The standard methods of identifying soil erosion prone areas require many resources, they are time consuming coupled with data unavailability such as geological maps, précised soil characteristics. but with the use of RS and GIS these problems have been reduced. The study shows that remote sensing data and GIS can be utilized to assess the drainage characteristics and LULC. Mapping watersheds characteristics for prioritization is the first step in implementation of integrated watershed management for sustainable livelihoods. Therefore, identifying critical watersheds gives insights to various stakeholders to come up with sustainable measures for conservation and management of soil and water resources within the watersheds. In designing the integrated watershed management plans for managing watersheds, the analysis of LULC characteristics, NDVI, TWI and morphometry has produced useful information.

5.3 Conclusions

The research specifically addresses the issue of soil erosion in the Thiririka watershed in Kenya. Using Geographic Information Systems (GIS) and Remote Sensing (RS) tools, the study delineates sub watersheds and employs morphometric parameters, land use/land cover characteristics, and drainage network properties to identify areas susceptible to soil erosion. Lack of readily available data in Kenya poses a challenge to informed decision-making for watershed managers.

The methodology involves the use of Shuttle Radar Topographic Mission (SRTM) data, ArcGIS software, Sentinel-2 images from Google Earth Engine, and on-the-ground data collection. The classification accuracy of land use/land cover is found to be high, with an overall accuracy of 0.88 and a Kappa statistic of 0.86. Additionally, the study incorporates the Topographic Wetness Index (TWI) to understand the spatial distribution of water in the catchment.

5.3.1 Assessing the land use and land cover characteristics of Thiririka sub watersheds

The detailed analysis of Thiririka sub-watersheds (SW1 to SW5) provides valuable insights into the diverse land use and land cover patterns within the watershed. Each sub-watershed exhibits distinct characteristics, ranging from the dominance of agricultural activities and dense forest cover upstream to the prevalence of built-up areas downstream. The visual interpretation of land cover maps, supported by quantitative estimates in Tables 4.3 and 4.4, emphasizes the variability in land cover composition among the sub-watersheds.

Furthermore, the prioritization of sub-watersheds based on land use and land cover highlights the vulnerability of SW5 to erosion due to factors such as reduced forest cover, extensive commercial crop farming, and high urbanization. The presence of water bodies, especially in SW5, is considered a crucial factor in prioritization, acknowledging their role in soil erosion and runoff control.

Overall, the comprehensive analysis of land use and land cover in the Thiririka watershed contributes to a nuanced understanding of its ecological dynamics. The findings underscore the importance of sustainable land management practices, particularly in areas susceptible to erosion, and provide valuable information for informed decision-making in watershed management and environmental conservation efforts.

the morphometric analysis of the Thiririka drainage basin has provided valuable insights into the geomorphological characteristics influencing soil erosion. The study focused on aerial, linear, and relief parameters, including stream order, stream number, stream length, mean stream length, bifurcation ratio, length of overland flow, watershed perimeter, watershed area, watershed length, elongation ratio, circulatory ratio, form factor, drainage density, stream frequency, basin relief, relief ratio, and ruggedness number.

5.3.2 Influence of morphometric characteristics on soil erosion in Thiririrka drainage basin

The findings indicate that the Thiririka watershed exhibits a parallel drainage pattern with steep slopes, as revealed by the dominance of first-order stream segments and the high stream order. The watershed's susceptibility to flooding is highlighted by its fourth-order classification and the significant number of streams, with SW5 showing the highest vulnerability. Linear aspects such as stream length and bifurcation ratio suggest variations in surface runoff and geological influences, with SW1 and SW4 exhibiting characteristics associated with high soil erosion risk.

Areal aspects, including watershed perimeter, area, and length, provide insights into the shape and size of the catchment. SW5 emerges as the largest and least vulnerable, while SW1, with its elongated shape and high form factor, is identified as highly erodible. The circulatory ratio and elongation ratio further support these findings, emphasizing the potential for erosion in SW1 and reduced vulnerability in SW5. Relief aspects, represented by basin relief, relief ratio, and ruggedness number, contribute to the assessment of the watershed's topography and susceptibility to erosion. SW5 stands out with high basin relief, indicating increased surface runoff and potential erosion risk. The relief ratio and ruggedness number reaffirm the vulnerability of SW1 to erosion due to steep slopes.

In summary, the morphometric characteristics of the Thiririka drainage basin, as analyzed in this study, provide a comprehensive understanding of the factors influencing soil erosion. The results suggest that SW5 is less susceptible to erosion, while SW1 exhibits characteristics associated with high erosion risk. This information can be crucial for implementing effective watershed management strategies, especially in prioritizing areas for soil conservation and erosion control measures.

5.3.3 Assessing the joint effect of varying soil moisture and vegetation cover on soil erosion in Thiririka sub watersheds

The Normalized Difference Vegetation Index (NDVI) values indicate that SW2 has a higher vegetative cover (mean NDVI of 0.77), while SW1 has lower vegetative density (mean NDVI of 0.53). Notably, SW3 stands out with the highest maximum NDVI value of 0.90, suggesting a more vegetated area. Additionally, SW1 is identified as highly exposed to erosion based on the Topographic Wetness Index (TWI) analysis, with a mean TWI of 8.19, supporting the correlation between soil moisture and erosion susceptibility. These findings underscore the importance of understanding the interplay between vegetation cover and topography in assessing erosion risk within the Thiririka watershed.

5.4 Recommendations

1. The Kenya Forest Service (KFS) need to introduce a strategic tree-planting program to increase the vegetated land cover in SW5 and SW1.
2. Agricultural extension officer should promote agronomic practices such as increasing vegetative cover this will help reduce runoff on croplands and mosaic areas within the catchment.
3. The residence in SW5 are encouraged to practice rainwater harvesting to help reduce surface runoff.
4. Urban planners and agricultural extension officers should create water retention ponds to direct agricultural runoff water specifically in SW5, SW2, and SW3 with more built-up areas. Also agricultural officers should continue educating and training farmers on practices to reduce soil erosion such as proper ways of constructing terraces and gabions.

5.5 Suggestions for further research

1. Some improvements in the methodology such as the use of very high-resolution satellite data obtained by using drone and worldview data can provide more insights for précised estimates for morphometric parameters and LULC. Future research should explore the use of morphometric parameters with high-resolution satellite images following a decision-support system to identify the best sites for water harvesting to reduce surface runoff in Thiririka watershed.
2. Future studies should focus on how the individual LULC affect soil erosion, to quantify the individual land use/ land cover effects on soil erosion.

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APPENDICES

Appendix I: Thiririka sub watersheds morphometric parameters values

SW1 stream numbers, stream length and bifurcation ratios

Stream order	Stream number	Total Stream length (km)	Mean stream length	Bifurcation ratio (R_b)	Mean R_b
1st	28	12.65	0.45	4.67	
2nd	6	2.56	0.43	2	**3.2**
3rd	3	0.76	0.25	3	
4th	1	0.43	0.43		
Total	**38**	**16.4**	**0.43**		

SW2 stream numbers, stream length and bifurcation ratios

Stream order	Stream number	Total Stream length (km)	Mean stream length	Bifurcation ratio (R_b)	Mean R_b
1st	49	32.35	0.66	3.77	
2nd	13	10.62	0.82	6.50	**4.09**
3rd	2	1.74	0.87	2.00	
4th	1	0.26	0.26		
Total	**65**	**44.97**	**0.69**		

SW3 stream numbers, stream length and bifurcation ratios

Stream Order	Stream number	Total stream length (km)	Mean stream length	Bifurcation ratio (R_b)	Mean R_b
1st	51	29.68	0.58	7.29	
2nd	7	8.18	1.17	3.50	
3rd	2	2.69	1.35	2	**4.26**
4th	1	1.33	1.33		
Total	**61**	**41.89**	**0.69**		

SW4 Stream numbers, stream length and bifurcation ratios

Stream Order	Stream number	Total stream length (km)	Mean stream length	Bifurcation ratio (R_b)	Mean R_b
1st	19	13.65	0.72	4.75	
2nd	4	3.65	0.91	4	**3.25**
3rd	1	0.87	0.87	1	
4th	1	0.81	0.81		
Total	**25**	**18.99**	**0.76**		

SW5 Stream numbers, stream length and bifurcation ratios

Stream Order	Stream number	Total stream length (km)	Mean stream length	Bifurcation ratio (R_b)	Mean R_b
1st	80	35.59	0.44	7.27	**4.65**
2nd	11	5.51	0.5	3.67	
3rd	3	2.42	0.81	3	
4th	1	0.28	0.28		
Total	95	43.8	0.46		

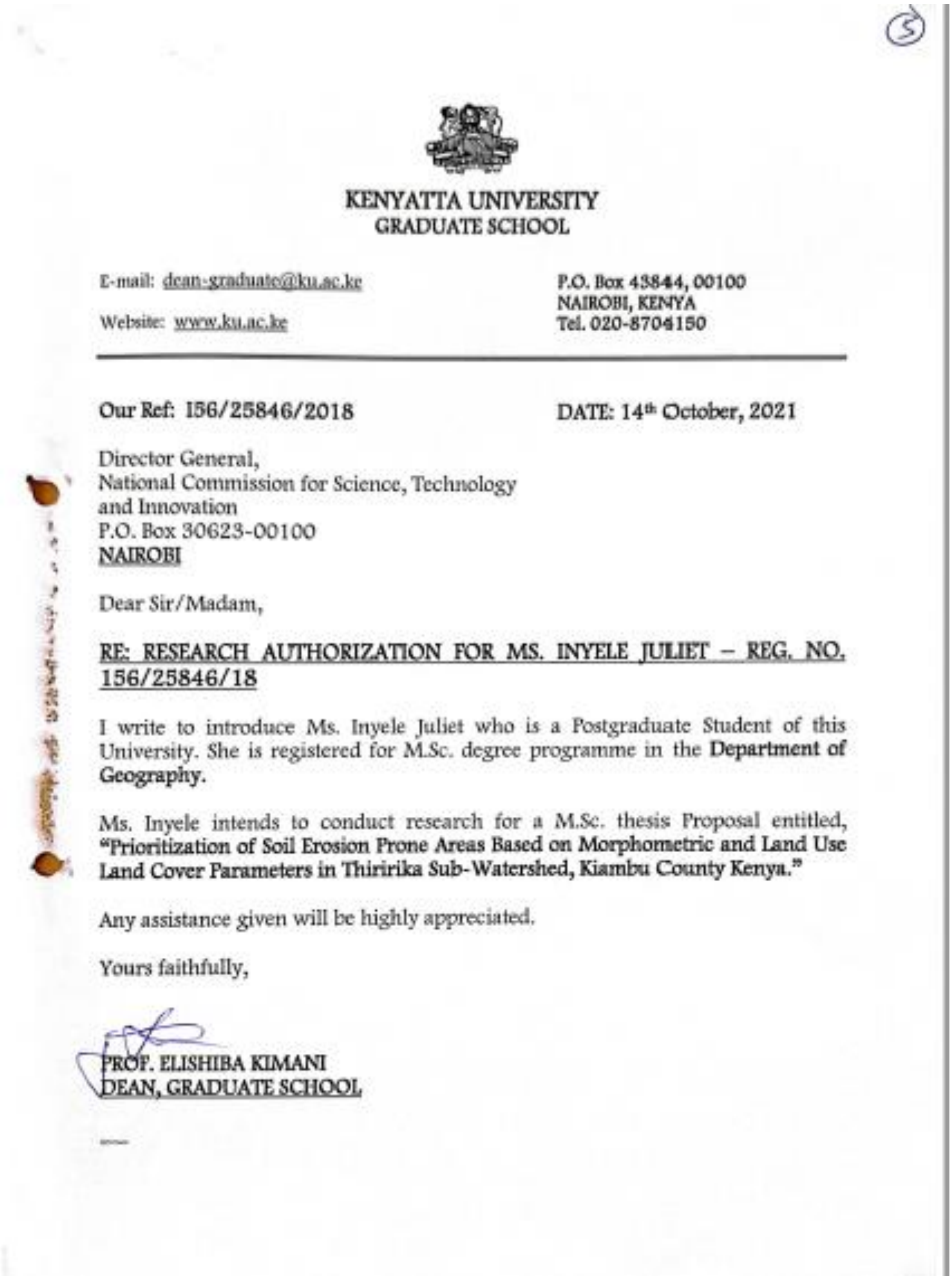
Appendix II: Gully erosion observed from the field in SW4

Plate 0.1: Gully erosion observed in SW5 Githugushu village in Gatundu South, latitude -1.01359 and longitude 36.91689 (image taken on 15 April 2022)

Appendix III: A section of Thiririka River

Plate 0.2: A section of Thiririka River at Ngenda village latitude 1.01784 and longitude 36.89937 showing polluted water from sediments (image taken on 7 April 2022)

Appendix IV: Research Authorization



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KENYATTA UNIVERSITY
GRADUATE SCHOOL

E-mail: dean-graduate@ku.ac.ke
Website: www.ku.ac.ke

P.O. Box 43844, 00100
NAIROBI, KENYA
Tel. 020-8704150

Our Ref: 156/25846/2018

DATE: 14th October, 2021

Director General,
National Commission for Science, Technology
and Innovation
P.O. Box 30623-00100
NAIROBI

Dear Sir/Madam,

RE: RESEARCH AUTHORIZATION FOR MS. INYELE JULIET – REG. NO. 156/25846/18

I write to introduce Ms. Inyele Juliet who is a Postgraduate Student of this University. She is registered for M.Sc. degree programme in the **Department of Geography.**

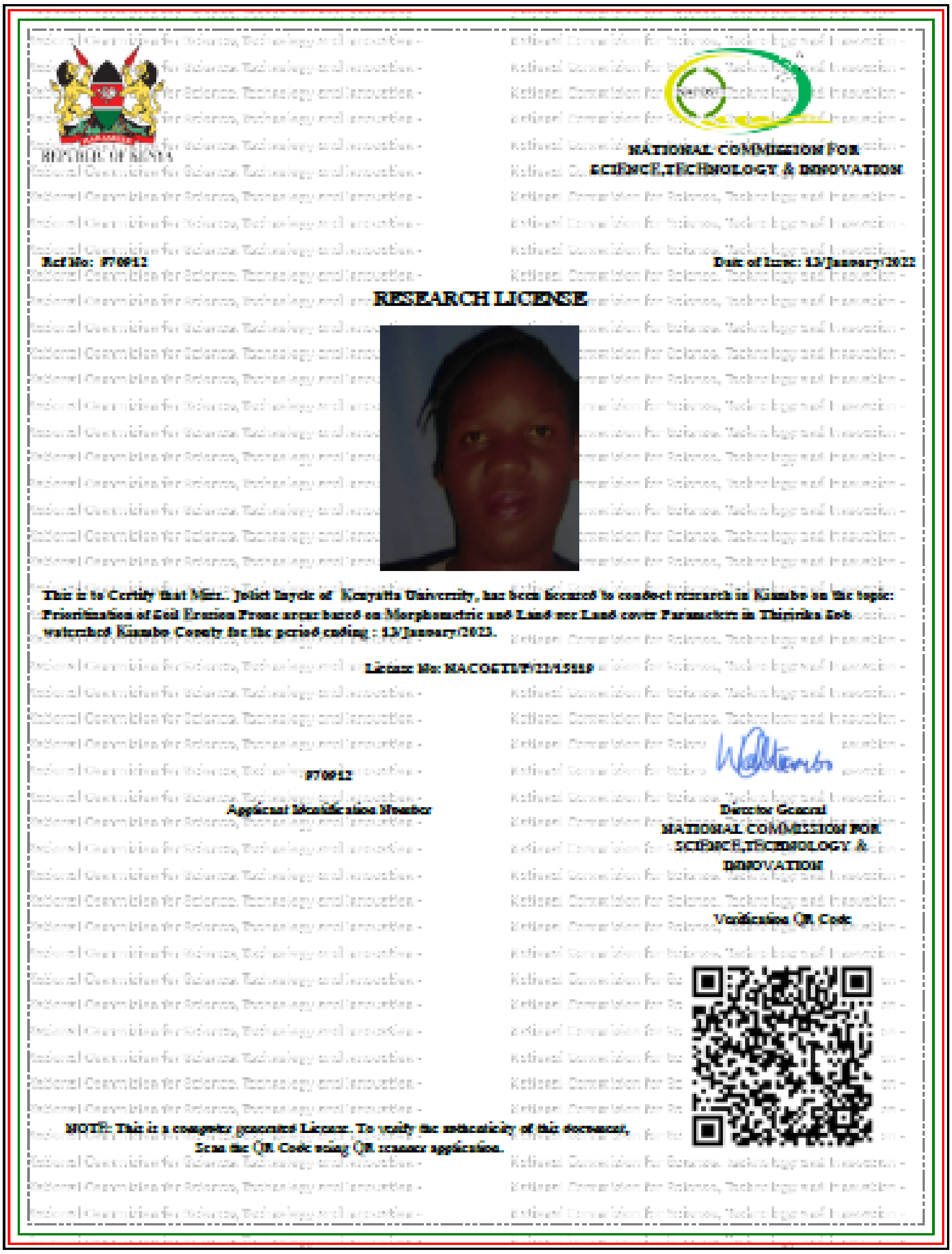
Ms. Inyele intends to conduct research for a M.Sc. thesis Proposal entitled, **"Prioritization of Soil Erosion Prone Areas Based on Morphometric and Land Use Land Cover Parameters in Thiririka Sub-Watershed, Kiambu County Kenya."**

Any assistance given will be highly appreciated.

Yours faithfully,

PROF. ELISHIBA KIMANI
DEAN, GRADUATE SCHOOL

Appendix V: Research Permit



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RESEARCH LICENSE

This is to Certify that Miss.. Juliet Inyele of Kenyatta University, has been licensed to conduct research in Kiambu on the topic: Prioritization of Soil Erosion Prone areas based on Morphometric and Land use Land cover Parameters in Thiririka Sub watershed Kiambu County for the period ending : 13/January/2023.

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