



**UNIVERSITY OF NAIROBI**

**FACULTY OF ENGINEERING**

**DEPARTMENT OF ENVIRONMENTAL AND  
BIOSYSTEMS ENGINEERING**

**MODELLING SUITABLE SITES FOR SOLAR HARVESTING IN  
RURAL AREAS OF KENYA: A CASE STUDY OF KIBWEZI EAST  
AND WEST SUB COUNTIES**

**By**

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**MSc (Environmental and Biosystems Engineering)**

**DISSERTATION**

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the Award of the Degree of Master of Science in Environmental  
and Biosystems Engineering in the Department of Environmental  
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## **DEDICATION**

This dissertation is dedicated to the three most important women in my life. These are Entilly Siangala Lyama (My Mother), Matildah M. P. Lyama (my wife) and Myra Entilly Lyama (my daughter). To my late Mum who always pushed me to achieve the most I say I really miss you. To my wife and daughter, I say I love the unit we have become and having you in my life has made me complete.

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## **ABSTRACT**

Project implementors in the photovoltaic (PV) solar farm space have long relied on very little analysis as regards site selection. This in part has been attributed to the fact that small scale solar farm projects requiring relatively low investment costs have been the investment vehicle of choice in the past. With the ongoing need to develop, utility-scale PV solar farms are fast becoming a viable investment vehicle to deliver this valuable resource to even the most rural of communities. Site selection has a direct impact on the power generation performance of the solar farm, economic and social aspects, as well as existing and future infrastructure. Selecting the best site requires a multi-faceted approach. In this study, an attempt was made to model suitable sites for solar PV farms using restriction factors categorized as climatic, topographic, and location factors. The main objective of this study was to model suitable sites for solar harvesting. Using Kibwezi as the study area, several parameters were evaluated using the analytical hierarchy process (AHP).

Weighting of parameters was carried out through a process that involved collecting parameter comparison data from respondents in the form of a questionnaire and using the collected data in a pairwise comparison to come up with weights. Reclassification of data and overlay analysis was then carried out in a GIS environment. The resultant suitability map showed areas that were considered on a scale from most suitable to not suitable. The generated map indicated an area of 3,172.8km<sup>2</sup> as highly suitable, 904.8km<sup>2</sup> as moderately suitable, 169.0km<sup>2</sup> as marginally suitable and 3.4km<sup>2</sup> as not suitable. The high suitability was primarily influenced by three dominant parameters: temperature, solar radiation, and land use/land cover which when analyzed exhibited strong congruence with solar energy infrastructure goals. It was therefore established that by applying this methodology, it is possible to select suitable sites for solar harvesting based not only on the availability of sunlight in the area but also based on

other cardinal geographical factors. The definition of solar potential should therefore be extended to accommodate other factors.

Among the recommendations made is an extension of the methodology to analyze parameters for other renewable energy sources, such as wind, hydroelectric, and geothermal power. It is also suggested that researchers explore the determination of the approximate solar power potential of the study area based on the results of this study.

**Keywords:** Climatic Factors, Topographical Factors, Locational Factors, Solar PV, Standardization Criteria, Suitability Analysis.

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## ACCRONYMS AND ABBREVIATIONS

PV	Photovoltaic
NOAA	National Oceanic & Atmospheric Administration
USGS	United States Geological Service
DEM	Digital Elevation Model
ESA	European Space Agency
LULC	Land Use/ Land Cover
ICT	Information & Communications Technology
SDG's	Sustainable Development Goals
AOI	Area of Interest
NREL	National Renewable Energy Laboratory
MCDM	Multi Criteria Decision Making
AHP	Analytical Hierarchy Process
GIS	Geographic Information System
AVHRR	Advanced Very High-Resolution Radiometer
NIR	Near Infrared
MIR	Mid Infrared
TIR	Thermal Infrared
SWIR	Short Wave Infrared

OLI	Operational Land Imager
VNIR	Visible and Near Infrared
PROMETHUS	Preference Ranking Organization Method For Enrichment of Evaluations
ELECTRE	Elimination and Choice Expressing Reality
FDM	Fuzzy Multi-Criteria Decision Making
ANN	Artificial Neural Networks
QGIS	Quantum Geographic Information System
MS Excel	Microsoft Excel
SAR	Synthetic Aperture Data
SNAP	Sentinel Application Platform

# CHAPTER ONE

## 1.0 INTRODUCTION

### 1.1 Background Information

Access to electricity is one of the key drivers of poverty alleviation as it facilitates industrialization and the provision of essential services essential for human rights, such as water supply, high-quality healthcare, and education (Obayelu and Ogunlade, 2016). Recognized as one of the Sustainable Development Goals (SDGs) – (Goal 7: Ensure access to affordable, reliable, sustainable, and modern energy for all) – access to electricity is crucial for achieving many of the other SDGs (Fuso et al., 2018).

In the case of rural Africa, the provision of electricity remains a highly challenging and resource-intensive endeavor, particularly when employing traditional models of National Grid expansion (Amir et al., 2021). While these models can be profitable in the long term, they require substantial initial capital investments with socioeconomic benefits that may only become evident years later. Despite their long-term profitability, these projects often face challenges in terms of justification, given that most rural areas are remote, possess energy demands that are difficult to quantify, and have low consumption densities (Eltawil et al., 2009). Nonetheless, there are pockets of rural Africa with significant untapped economic potential, which can only be harnessed by addressing the critical issue of electricity supply.

A viable option for project proponents in such a case is the installation of mini grids (Palit et al., 2014). For the purposes of this study the electricity generators will be a solar PV system. The most important factor affecting the cost analysis during the appraisal of such projects is the site selection (Moradi et al., 2020). This is one of the major challenges that implementors have had when dealing with rural areas in Africa. Solar energy is increasingly gaining recognition world over (Wustenhagen et al., 2007). Previous studies have concentrated on the establishment of Distributed Solar Energy Systems that feed into a National Grid (Sambo,

2009). This is however more viable in highly developed countries with National Grids that cover most of the inhabited lands. Furthermore, these developed areas are fully mapped, and updated data is readily available to those that wish to access it.

Rural Africa, on the other hand, finds itself in a unique position, as the distribution network of National Grids is often located at a considerable distance from rural communities (Odou et al., 2020). Consequently, these rural areas have turned to alternative sources of electricity, such as solar power provided by the installation of solar panels. However, the adoption of solar energy resources in Kenya has been sluggish, due to several reasons. One of the reasons is primarily the limited information regarding the spatial variability of solar energy potential (Oloo et al., 2015). This information gap is the focal point of this study, aiming to address this issue, particularly in the sub-counties of Kibwezi East and West.

Recent studies in the site selection for suitable solar PV sites have endeavored to integrate frameworks derived from Multi-Criteria Decision Making (MCDM) and Geographic Information Systems (GIS) (Vafaeipour et al., 2014). One of the most used MCDM techniques is the Analytical Hierarchy Process (AHP), which is employed in this study. AHP is known for its ease of use and comprehensibility (Soydan, 2021), enabling analysts to assign ratings to alternatives and aggregate them for comparison across various options. Consequently, this method facilitates the rating and aggregation of parameters that are most likely to influence the site selection for solar PV installations. The AHP process is then conducted, and the data are analyzed within a GIS environment to produce a map that represents the most suitable sites for solar harvesting.

## **1.2 Statement of the Problem and Problem Analysis**

The importance of optimizing solar energy production and resource efficiency cannot be understated. Although solar energy is abundant in many rural areas of Africa, not all locations offer the same level of solar irradiance. Furthermore, there are other factors apart from solar irradiance that affect solar energy capture. Analyzing solar radiation, declination, and other geographical factors allows for the identification of sites with the highest solar energy potential. This optimization enhances energy generation, which is crucial for powering homes, businesses, and essential services (Hussein et al., 2017). For instance, geographical factors, including solar declination, temperature, solar radiation, rainfall, and dust storms, collectively impact the performance and reliability of solar panels as a source of electricity for households in rural Africa. Solar declination, which varies with latitude, determines the angle of the sun in the sky and influences the amount of sunlight received. Closer to the equator, where solar declination is lower, solar panels receive more direct and consistent sunlight, leading to efficient energy generation throughout the year. Conversely, areas farther from the equator may experience seasonal variations in solar declination, resulting in fluctuations in energy production. Temperature also plays a significant role, as excessive heat can reduce the efficiency of solar panels, particularly in arid regions. In contrast, the presence of rainfall can be beneficial, as it cleans the panels and enhances their performance. However, the same regions that receive rainfall may also be susceptible to dust storms, which can deposit dust and debris on the solar panels, diminishing their efficiency and requiring regular maintenance to ensure optimal performance (Adaramola, et al., 2015).

Multi-Criteria Decision Analysis (MCDA) has been employed to assess the geographic parameters that influence the harnessing of solar energy. The process of selecting these parameters is inherently site-specific recognizing, for example, that the geographic characteristics pertinent to Europe may not be applicable to the unique context of Africa. In



this study, we use MCDA to evaluate and prioritize raw geographic parameters tailored to the specific study area. The primary objective is to classify this region in terms of suitability, considering a diverse set of criteria, to identify optimal sites for the development of solar PV farms."

### **1.3 Objectives**

#### **1.3.1 Overall Objective**

To model suitable sites for solar energy harvesting in rural areas in Kenya using Kibwezi East and Kibwezi East as case studies.

#### **1.3.2 Specific Objectives**

- i. To identify the parameters for modelling suitable areas for solar energy harvesting in rural parts of Kenya. Kibwezi Sub-County will be taken as a sample site.
- ii. To establish a criterion for the standardization of the identified parameters in (1) above and standardizing the parameters.
- iii. To compute weights for the suitability analysis using Analytical Hierarchy Process (AHP).
- iv. To develop a map of suitable sites for solar power harvesting.

#### **1.4 Statement of the Scope**

This study focuses solely on the selection of solar PV sites and does not integrate any other power sources. Economic factors and community dynamics are not considered, except for the study's specific focus on rural settings. Furthermore, the study does not include a demand survey, as it is based on the premise that electricity is vital for human development. The primary objective is to develop a decision-making tool that can illuminate the framework for selecting suitable sites for solar PV farms.

## CHAPTER TWO

### 2.0 LITERATURE REVIEW

#### 2.1 Introduction

As the study is built around the gathering, analysis and manipulation of geographic data, a literature review of the overall solar potential of Kenya, site factors influencing solar power generation, and GIS theory and practice was performed.

#### 2.2 Solar Power Potential of Kenya

Central to this study is the essential review of solar power potential. Kenya stands out as one of the countries receiving a minimum of 6.5 sunshine hours in a single day throughout the year (Oloo et al., 2015). This fact underscores that, based on sunshine hours alone, the potential for solar power is substantial. Consequently, photovoltaic solar energy emerges as one of the most viable options for rural electrification in Kenya. Figure 2-1 illustrates Kenya's solar potential, emphasizing how the establishment of solar power is a feasible energy source.

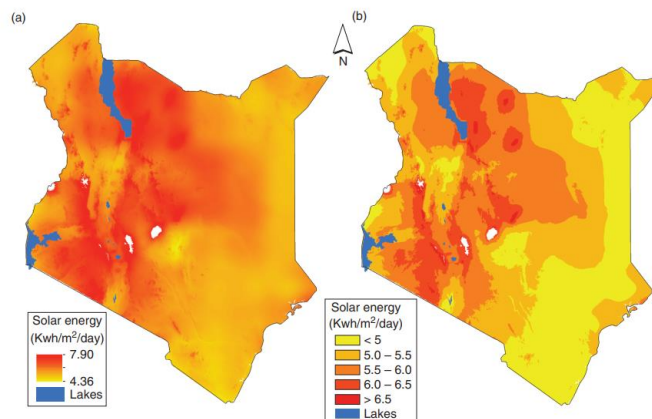


Figure 9: Spatial variation of solar energy potential in Kenya at 100 x 100m spatial resolution. a) Continuous average solar energy potential in kWh/m<sup>2</sup>/day b) Classified average solar energy potential in kWh/m<sup>2</sup>/day.

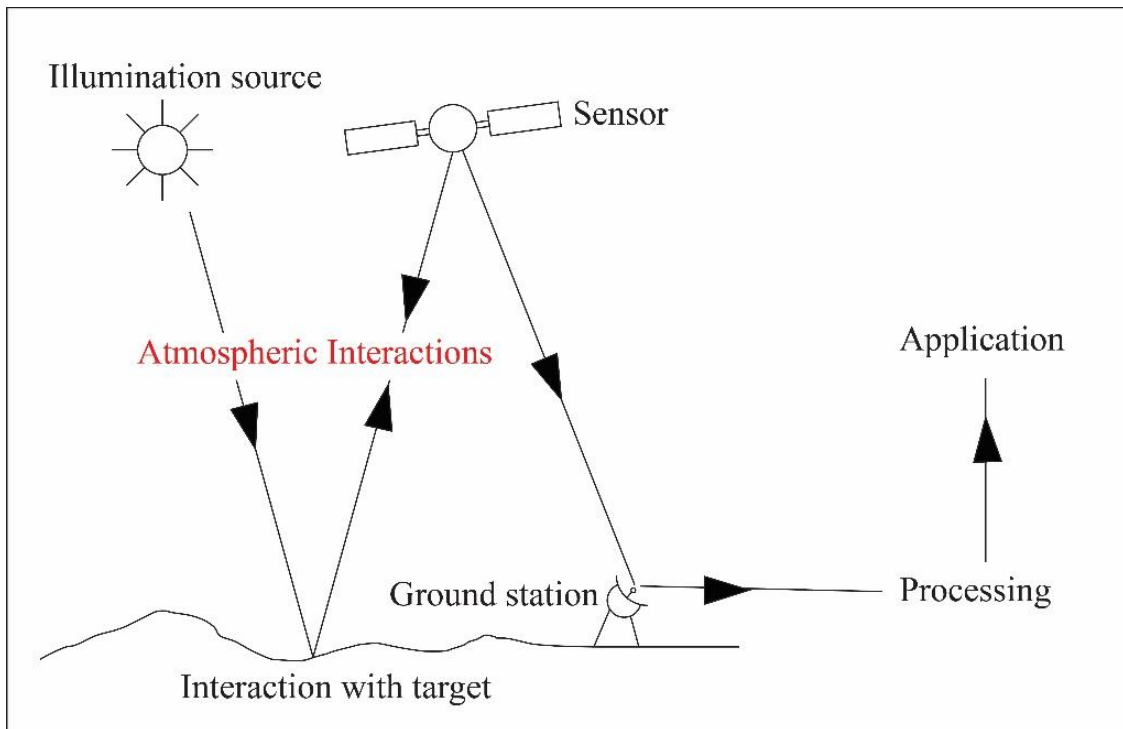
### Figure 2-1: Kenya's Solar Energy Potential

Source: Oloo et al.(2015)

#### 2.3 Remote Sensing

Remote sensing is a special way of observing the earth. In fact, it is also called Earth Observation. It gives an analyst the ability to gather, interrogate and interpret the various

interactions the plane goes through. (Tempfli, 2009). Electromagnetic radiation is the energy that moves with the velocity of light in a harmonic pattern (Khorram, 2012). Energy is then emitted and recorded by sensors and finally transmitted to the ground station for interpretation, analyses and processing into imagery that is finally applied for various uses. Figure 2-2 below is a visual illustration of the remote sensing process:



**Figure 2-2: The Remote Sensing Process**

Atmospheric interactions include absorption, scattering and transmission of electromagnetic energy. The main absorption elements in the atmosphere are ozone, carbon IV oxide and water vapor. The electromagnetic spectrum defines the total range of electromagnetic radiation.

### **2.3.1 Geographical Factors and Remote Sensing**

Geographical factors influence solar power generation, including ultraviolet radiation revealing mineral characteristics, infrared distinguishing vegetation types, and microwaves providing information on soil moisture content and roughness (Smith, 2019). The interaction of electromagnetic energy with target surfaces depends on various factors, leading to absorption, transmission, or reflection (Brown, 2020).

### **2.3.2 Satellite Characteristics and Applications**

Satellites play a crucial role in remote sensing, equipped with sensors like NOAA AVHRR and Landsat, each having distinct spatial, spectral, and radiometric characteristics (Johnson & Lee, 2018). These satellites provide a range of spatial resolutions and valuable environmental information (Van-Western, 2000).

## **2.4 Satellite Missions**

For geographical data, two satellite missions, Landsat and Sentinel, were examined for their potential as data sources (Smith, 2019).

### **2.4.1 Landsat 8**

Landsat 8, launched in 2013, offers various spectral bands and a sun-synchronous orbit at an altitude of 705 km with a 16-day repeat cycle and 98.2° inclination (Smith, 2019).

### **2.4.2 Sentinel 1**

Sentinel1 mission provides C-band Synthetic Aperture Radar (SAR) imaging during day and night, while Sentinel 2 offers a variety of spectral bands and a mission aimed at monitoring land surface variability (Smith, 2019).

#### *2.4.2.1 Improving Sentinel 1 Image Quality*

Pre-processing of Sentinel 1 images involved several essential steps. First, radiometric calibration was performed to transform the digital numbers (DN) in the data into calibrated radar backscatter values expressed in decibels (dB). This calibration step was crucial to maintain data consistency and accuracy, ensuring the reliability of subsequent analyses. Next, thermal noise removal was carried out, a vital step to guarantee high-quality data for analysis. This process significantly enhances the overall quality of the synthetic aperture radar (SAR) image. Finally, terrain correction was applied, utilizing the Range-Doppler Terrain Correction method, to account for distortions induced by the terrain and further improve the accuracy and reliability of the data.

#### *2.4.2.2 Improving Landsat 8 Image Quality*

Pre-processing of Landsat 8 images in order to improve image quality involved the following essential steps:

- i. Radiometric Calibration: Digital numbers (DN) in the data were converted to reflectance values, ensuring radiometric consistency for cross-image and cross-date comparisons.
- ii. Atmospheric Correction: An atmospheric correction was applied to eliminate atmospheric effects, including scattering and absorption, from the image.
- iii. Geometric Correction (Orthorectification): Geometric distortions in the image were corrected to ensure accurate registration with a map projection.
- iv. Cloud Detection and Masking: Clouds were identified and masked out, enhancing the data quality for subsequent analysis.

#### **2.4.3 WorldClim**

WorldClim is a database of global weather and climate data, offering multiple climatic variables at various spatial resolutions (Smith, 2019; "Worldclim.org").

### **2.5 Image Classification**

Image classification, a vital process in geographical data analysis, involves categorizing pixels in satellite images (Smith, 2019). There are two categories of image classification namely supervised and unsupervised classification.

#### **2.5.1 Supervised Classification**

Supervised classification identifies image areas with the same reflectance using training sites (Smith, 2019).

#### **2.5.2 Unsupervised Classification**

Unsupervised classification automatically identifies and assigns image pixels to class groups (Smith, 2019). The primary criterion for unsupervised classification in GIS is similarity.

Unsupervised classification, also known as cluster analysis, groups pixels or features with similar spectral characteristics into clusters or classes without the use of predefined training samples. The algorithm identifies patterns or natural groupings within the data, and the number of clusters is often specified by the user based on data characteristics (Jensen, 2007). Unsupervised classification is suitable when the objective is to explore and discover natural groupings or patterns within the data without prior knowledge of the specific classes or categories that exist. It is useful for hypothesis generation and identifying unexpected features (Richards & Jia, 2006). It was not used for this study as groupings and patterns for Land Use/Land Cover were already established in Training Samples.

## **2.6 Database Choice**

Database choices for geographical parameters depend on considerations such as spatial resolution (Smith, 2019). For climatic data, resampling and spatial correlation were employed to address low spatial resolution, and Landsat 8 was preferred over Sentinel's imagery due to complete coverage and revisit time (Smith, 2019). Relief data with high spatial resolution was obtained from Sentinel's 1 imagery (Smith, 2019).

## **2.7 Factors Influencing Solar Power Generation**

Geographical factors play a crucial role in solar power generation (Smith, 2019). These factors include:

- i. **Solar Radiation:** The amount of sunlight received in a specific location impacts the efficiency of solar panels (Brown, 2020). Data on solar radiation can be obtained from solar resource assessment databases like the National Renewable Energy Laboratory's (NREL) Solar Prospector (NREL, 2022).
- ii. **Temperature:** High temperatures can affect the performance of solar panels (Johnson & Lee, 2018). Temperature data can be sourced from meteorological agencies, such as the National Oceanic and Atmospheric Administration (NOAA) (NOAA, 2029).

- iii. **Topography:** The terrain, including elevation and slope, can influence the positioning and efficiency of solar installations (Garcia, 2017). Digital Elevation Models (DEMs) and satellite imagery provide topographic information. DEMs can be obtained from sources like the United States Geological Survey (USGS) (USGS, 2020).
- iv. **Land Use/Land Cover Data:** The type of land cover in an area may affect the availability of suitable sites for solar power generation (White, 2021). Land use and land cover data can be acquired from government agencies or remote sensing sources. The U.S. Geological Survey (USGS) and the European Space Agency (ESA) offer such data (ESA, 2021).

### **2.8 Multi Criteria Decision Making Methods (MCDM)**

MCDM is concerned with structuring and solving decision and planning problems involving multiple criteria. To this study, there is an array of criteria that must be used to come up with the most suitable sites for solar harvesting. The working principle of MCDM is as follows:

- i. **Criteria Selection:** - The criteria selected should be measurable. For this study, the criteria selected was the analysis of geographical data. This data is real, measurable and the different types of geographical data are independent of each other, for instance slope does not affect solar radiation.
- ii. **Selection of Alternatives:** - Alternatives should be available and comparable. They should also be practical and feasible. For this study, for instance, alternative parameters such as seismic activity would have to be ruled out because of the nature of the study area.
- iii. **Selection of Weighting Methods to Represent Importance:** - There are two kinds of weight determination methods. These are compensatory and outrankable methods.

- iv. **Method of Aggregation:** - An aggregation method must be applied. The various methods are Product, Average, and Use of a Function. The result here will separate the best alternative from the available options.

## 2.9 Selection of Weighting Methods to Represent Importance

Weight determination methods can either be outrankable or compensatory.

Examples of Out-ranking Method are:

- i. **Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHUS):** Promethee is a family of multi-criteria decision-making methods designed to handle complex decision problems where multiple alternatives are evaluated based on multiple criteria. It was developed to deal with both quantitative and qualitative criteria. It considers both positive and negative flows between criteria and alternatives, allowing for the modelling of preference and indifference. Promethee aggregates preferences into partial pre-order rankings, making it useful for situations where alternatives cannot be definitively ranked. The method is capable of handling imprecise or uncertain data, which can be particularly relevant in real-world decision problems. (Brans, M., & Vincke, P., 1985)
- ii. **Elimination and Choice Expressing Reality (ELECTRE):** Electre is another widely used family of multi-criteria decision-making methods, particularly in Europe. It focuses on ranking alternatives by expressing the dominance of some alternatives over others based on preference parameters. Electre uses a concordance and discordance matrix to assess the relationships between alternatives and criteria. It offers a way to handle imprecise information by allowing decision-makers to define preference thresholds. Electre can deal with outranking relations, leading to a ranking that may be incomplete or expressed as a set of feasible alternatives rather than a strict ranking. (Roy, B., 1991).



Examples of Compensatory Method are:

- i. **Analytical Hierarchy Process (AHP):** AHP is a widely used MCDM method that structures a decision problem as a hierarchy, with criteria and sub-criteria, and uses pairwise comparisons to derive priority weights for criteria and alternatives. AHP provides a structured and comprehensive framework for decision-making. It handles both qualitative and quantitative data, making it versatile for various decision problems. AHP allows for sensitivity analysis, ensuring the robustness of decisions under different scenarios. The method is known for its pairwise comparison process, which helps clarify the relative importance of criteria and alternatives. (Saaty, T. L., 2008).
- ii. **Fuzzy Multi-Criteria Decision-Making Process (FDM):** Fuzzy Decision-Making, also known as Fuzzy Multiple Criteria Decision Analysis (MCDA), integrates fuzzy set theory with traditional multi-criteria decision-making techniques to handle uncertainty and imprecision in the evaluation process. FDM is suitable for situations where criteria, alternatives, or performance evaluations are described using linguistic terms or fuzzy numbers. It uses fuzzy logic to represent and manipulate vague or imprecise information, making it applicable in real-world decision problems where exact data may be lacking. FDM is a flexible approach that can be adapted to various multi-criteria decision problems and allows for the integration of expert judgments and imprecise data. (Zadeh, L. A., 1965).

In summary, these MCDM techniques offer different approaches to address multi-criteria decision problems. Promethee focuses on preference modeling and flows, AHP provides a structured framework for pairwise comparisons, Electre emphasizes dominance and concordance, and FDM integrates fuzzy logic to handle imprecise information. The choice of method should be based on the nature of the problem, data availability, and the preferences of decision-makers. AHP was used for this study because it structures a decision problem as a

hierarchy, with criteria and sub-criteria, and uses pairwise comparisons to derive priority weights for criteria and alternatives.

### **2.10 The Analytical Hierarchy Process**

The Analytical Hierarchy Process (AHP) is a widely used and respected method for conducting suitability analysis and multi-criteria decision-making. While it may not always be the "best" choice in every situation, it does offer several advantages that make it a strong contender compared to other methods. Here are some reasons why AHP is often preferred:

- i. **Comprehensive Decision Framework:** AHP provides a structured and comprehensive framework for decision-making. It allows decision-makers to break down complex problems into a hierarchy of criteria and alternatives, which can be especially useful in suitability analysis, where numerous factors need to be considered.
- ii. **Handling of Both Qualitative and Quantitative Data:** AHP can handle both qualitative and quantitative data, which is often a necessity in suitability analysis, where factors can include tangible measurements (quantitative) and expert opinions or subjective evaluations (qualitative).
- iii. **Considers Relative Importance:** AHP allows decision-makers to explicitly consider and prioritize the relative importance of criteria and sub-criteria. This is crucial in suitability analysis where not all factors carry the same weight.
- iv. **Pairwise Comparisons:** The use of pairwise comparisons in AHP helps to clarify and quantify decision-makers' preferences. This approach fosters a better understanding of the relationships between criteria and alternatives.
- v. **Widely Accepted and Used:** AHP is a well-established method with a strong theoretical foundation. Many decision-makers and researchers are familiar with it, making it easier to communicate and defend decisions based on AHP.

- vi. **Flexibility:** AHP is flexible and can be adapted to various types of decision-making problems, including suitability analysis for site selection, project prioritization, and resource allocation.

Many studies (Al Garni, H. Z., & Awasthi, A. (2017)) have used the AHP method for the citing of solar PV plants. This method is both simple and easy to understand among many multi-criteria decision-making methods. It allows the analyst to rate alternatives and to aggregate them to compare an array of options. These variables can be analyzed together whether they be qualitative or quantitative in nature. It is therefore possible to rate and aggregate parameters that are most likely to influence site selection of solar PV sites, carry out the AHP process and analyse the information in a GIS environment to produce a map representative of the best suitable solar harvesting sites.

AHP was selected as the preferred MCDA method after a review of similar studies carried out in the past. This pool of studies was drawn from various parts of the world. The list of studies reviewed is in the table below and referenced accordingly in the reference section of this study.

**Table 2-1: Summary of Studies that used AHP**

Reference	Plant Type	MCDA Method	Country
Ziuku et al., 2014	PV	AHP	Zimbabwe
Aly et al.,	PV	AHP	Tanzania
Uyan, 2013	PV	AHP	Turkey
Watson and Hudson, 2015	PV	AHP	England
Al Garni and Awasthi	PV	AHP	Saudi Arabia
Yushchenko et al., 2018	PV	AHP	West Africa
Tahri et al., 2015	PV	AHP	Morocco

## 2.12 The Parameter Selection Process- Solar Mapping Case Studies

Literature review was relied upon in the determination of the most appropriate set of geographical parameters that would apply to both this study and the area of interest.

Table 2-2 below shows the publications that were reviewed:

**Table 2-2: Publications Reviewed for Parameter Selection**

REFERENCE	TITLE	SUMMARY OF OBJECTIVES
Rumbayan et. al. (2012).	Mapping of solar energy potential in Indonesia using artificial neural network and geographical information system	The objectives of this study were to determine the theoretical potential of solar irradiation in Indonesia by using artificial neural networks (ANNs) method in Indonesia and to visualize the solar irradiation by province as solar map of Indonesia.
Sözen, et. al. (2005).	Forecasting Based on Neural Network Approach of Solar-Energy Potential in Turkey.	The main objective of this study was model the solar energy potential in Turkey using artificial neural networks (ANNs).
Malik, et. al. (2014)	Selection of Most Relevant Input Parameters Using Waikato Environment for Knowledge Analysis (WEKA) for Artificial Neural Network Based Solar Radiation	The aim of this study was to find out the most influencing input parameters for solar radiation prediction in Artificial Neural Network.
Soydan, O. (2021)	Solar power plants site selection for sustainable ecological development in Nigde, Turkey.	The aim of this study is to select the most suitable location for solar energy plants and provide to build solar power plants in suitable places.
Munkhbat, U. & Choi, Y. (2021).	GIS-based site suitability analysis for solar power systems in Mongolia.	GIS-based approach was used to identify sites suitable for large-scale solar photovoltaic power plant installations in Mongolia

## **CHAPTER THREE**

### **3.0 METHODOLOGY**

#### **3.1 Introduction**

The methodology section serves as a crucial guide for understanding the systematic approach employed in this study to achieve its primary objectives. This comprehensive description outlines the steps taken to select geographic and climatic parameters through an in-depth literature review and establishing a standardized criterion for their consideration. Furthermore, it elucidates the method used to gather valuable input from respondents through a structured questionnaire to derive weights. These weights were then meticulously integrated into a Geographic Information System (GIS) environment to generate factor maps, which subsequently culminated in the creation of a site suitability map. This methodology provides the roadmap for the precise and informed process of site selection for our study, ensuring transparency, accuracy, and reliability in our findings.

#### **3.2 Site Analysis and Inventory**

Makueni County is one of Kenya's forty-seven counties, located within the former Eastern Province. It is situated between latitudes 2.992° South and 1.515° South, and longitudes 37.141° East and 38.519° East. The county spans an approximate area of 8,000 square kilometers. The specific area of interest in this study includes Kibwezi East and Kibwezi West sub-counties, two of the six sub-counties within Makueni County. The administrative centers for these sub-counties are Kibwezi town and Makindu town, respectively. Kibwezi East covers an approximate area of 2,366 square kilometers, while Kibwezi West covers about 1,883 square kilometers. The longitudinal extent of the study area ranges from 37.596° West to 38.520° West, and its latitudinal extent spans from 2.079° South to 2.992° South. The Universal Transverse Mercator (UTM) zone for this study area is Zone 37 South. The following figures illustrate the geographical location of Makueni County in relation to the map of Kenya, as well

as the specific placement of Kibwezi East and West Counties within the larger context of Makueni County

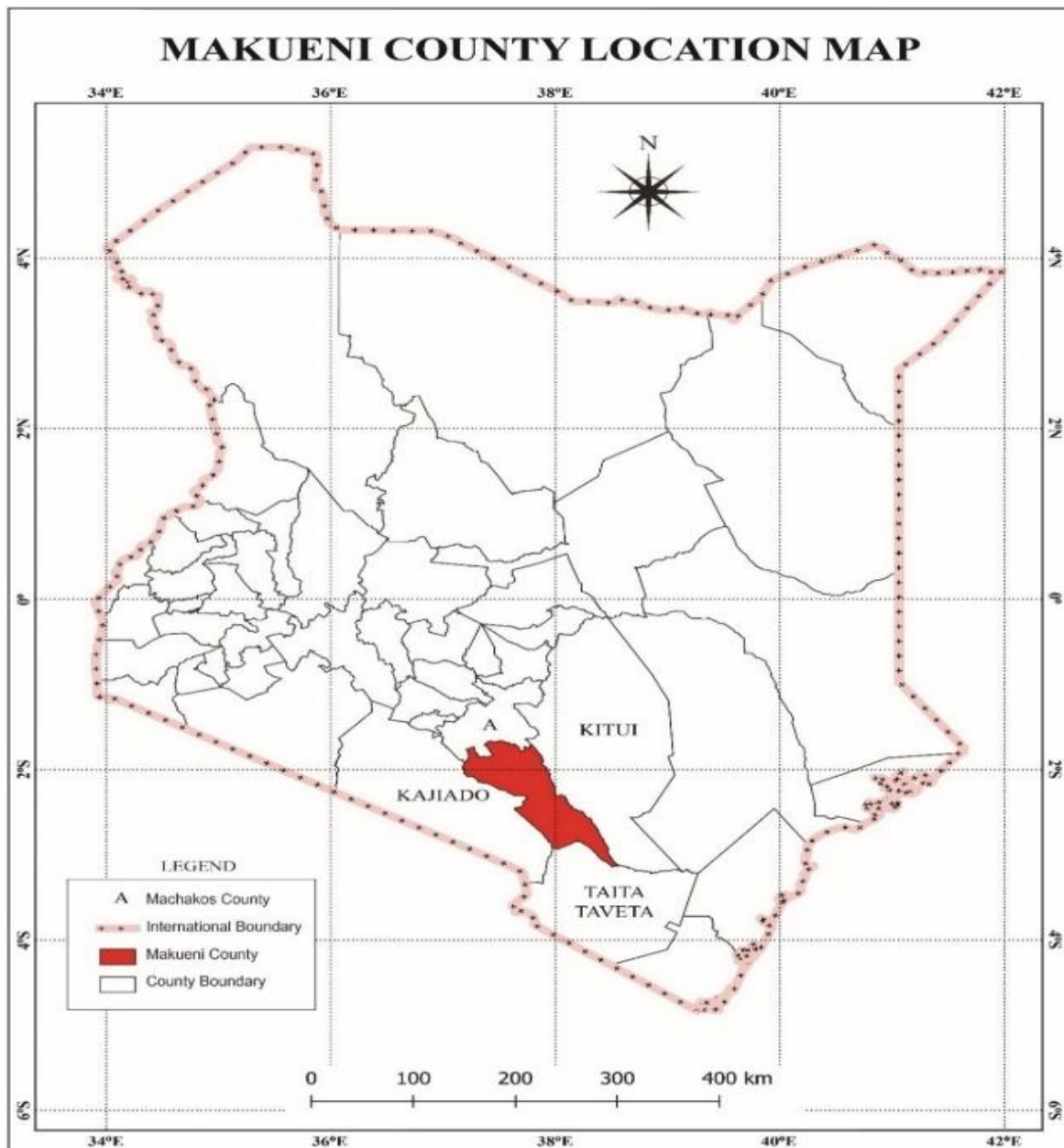
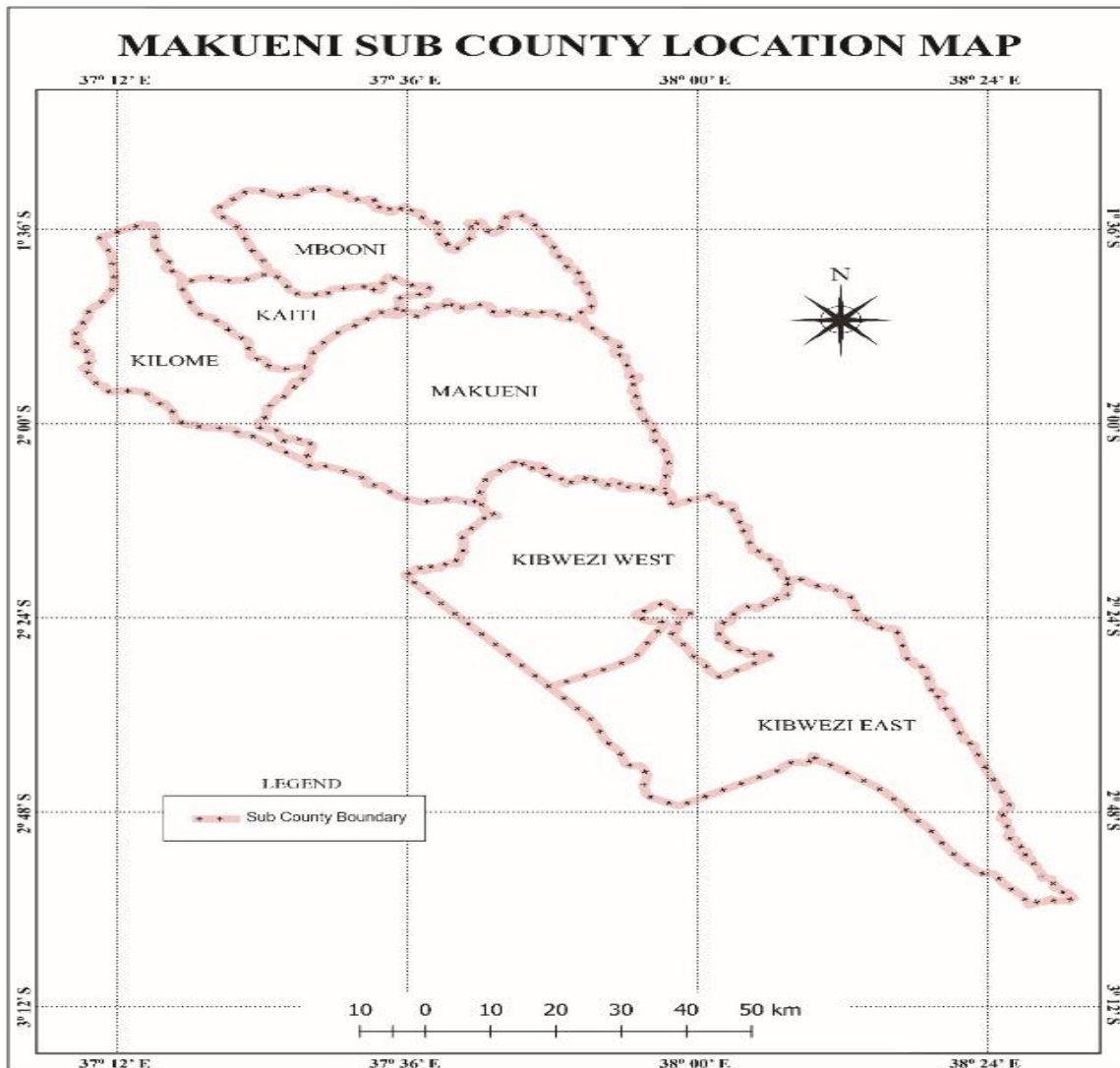


Figure 3-1: Makueni County Location Map



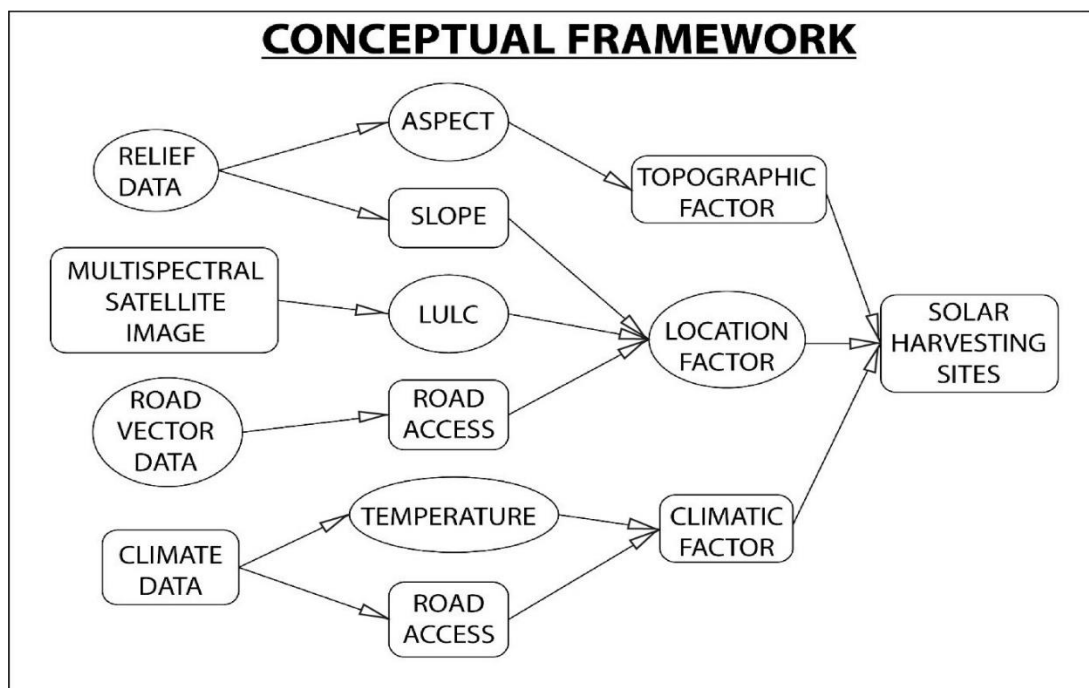
**Figure 3-2: Kibwezi Sub County Location Map**

### 3.3 The Conceptual Framework

In the assessment of suitable solar energy harvesting sites, a comprehensive framework was employed, considering six key parameters: aspect, slope, land use/cover, road access, temperature, and solar radiation. These parameters were initially analysed and grouped into three distinct factor maps to facilitate the suitability analysis. The Locational Factor Map was a combination of slope, land use/cover, and road access. It accounts for the geographical and infrastructural aspects of the study area. Slope influences the ease of installation, while land use/cover and road access impact site accessibility and land usage suitability. The Climatic Factor Map was established using temperature and solar radiation data. It characterizes the

local climate conditions, which have a significant impact on solar energy generation. Temperature affects the efficiency of solar panels, while solar radiation indicates the energy potential of the location. For the Topographic Factor Map, the aspect of the terrain was used to create the topographic factor. It considers the orientation of the site in relation to the sun's path, which plays a crucial role in optimizing energy capture. Different aspects may receive varying amounts of sunlight throughout the day.

Subsequently, a holistic suitability analysis was conducted by integrating these three factors. This comprehensive approach ensures an informed and balanced selection of optimal locations for solar power generation. By considering both the geographical and climatic aspects, this framework provides a robust foundation for identifying suitable sites for solar energy harvesting, ultimately promoting the efficient utilization of renewable energy resources. The figure below is a figurative interpretation of the conceptual framework.



**Figure 3-3: Conceptual Framework**



### 3.4 Parameter Selection

The parameters used in this study were identified from the five studies in the Literature Review. The proportion of each parameter in the five studies was used to determine the weights for each parameter. These weights were then used to select the parameters applicable to this study and the area of interest. The weighting formula below was used to calculate the weight of each parameter.

Let:

- W represent the Parameter Weight.
- P represent the Parameter Occurrence.
- S represent the Sum of Occurrences.

$$W = (P/S) \times 100$$

Equation 3.1

The weights were tabulated in table 3-1 as follows:

**Table 3-1: Weighting Parameters**

No.	Parameters	Parameter Occurrence	Weight
1	Sunlight Duration	3	11.5
2	Solar Radiation	3	11.5
3	Temperature	3	11.5
4	Latitudinal Extents	2	7.7
5	Month of the Year	2	7.7
6	Altitude	2	7.7
7	Power lines	2	7.7
8	Slope	2	7.7
9	Aspect	2	7.7
10	Land use	1	3.8
11	Precipitation	1	3.8
12	Road Access	1	3.8
13	R Humidity	1	3.8
14	Earthquake	1	3.8
15	Sum of occurrences	26	

The following parameters were eliminated for the following reasons:

- i. **Sunlight Duration**- The AOI receives significant sunlight throughout the year.
- ii. **Latitudinal Extents**- Latitude not significant. AOI is a small area (3987 km<sup>2</sup>) bounded by latitudes 38.60°E and 38.52°E
- iii. **Month of the Year**- It affects the sunlight duration in the subtropics; hence, it is not considered in the AOI.
- iv. **Altitude**- Minimal altitude influence in the AOI.
- v. **Power lines**- the study restricts itself to independent mini grids only and would not supply power to national grids as is the case in developed nations.
- vi. **Precipitation**- Rainfall in the AOI doesn't significantly affect temperature and solar radiation the AOI.
- vii. **Relative humidity**- Relative Humidity in the AOI doesn't significantly affect temperature and solar radiation the AOI.
- viii. **Earthquake**- AOI is not an earthquake active zone.

### 3.5 Materials

The following materials section describes the parameters which are considered the key materials for this study. It details the description of these parameters, their source and their preliminary preparation to ensure quality such as maintaining good resolution and considering the year the data was captured. The raw parameters used were temperature, solar radiation, aspect, land use/ land cover, slope, and road access. These are discussed below in detail.

- i. Temperature

Temperature is the measure of the degree of coldness or hotness of a place. Atmospheric temperature is the measure of the air's temperature. The atmosphere is heated through radiation, conduction, and convection. The data, which represents the mean annual temperature, was obtained from <https://www.worldclim.org/data/>. WorldClim data covers the years between

1970 and 2000 and spans the entire world. The data has a resolution of one square kilometer. The temperature range within the area of study was found to vary from 16.62°C to 25.59°C.

ii. Solar radiation

Solar radiation is the electromagnetic energy emitted by the sun. This energy is captured by solar panels and converted into electrical energy. The solar data were obtained from <https://www.worldclim.org/data/>. WorldClim data covers the years between 1970 and 2000 and spans the entire world. The data has a resolution of one square kilometer. The range of solar radiation within the study area falls between 18,390 and 19,600 kW/m<sup>2</sup>/day.

iii. Aspect

Aspect represents the compass direction in which a slope faces. It is determined by identifying the steepest downslope direction from each cell in the DEM. This direction can be defined using the four cardinal points: north, east, south, and west, as well as the intermediate directions known as secondary intercardinal directions, including northwest and southwest, among others. A flat slope is also considered a unit of aspect for non-directional slopes.

iv. Land use/ land cover

Land use is the classification of human activities and natural components of the land that occupies the Earth's surface. In this study, land use and land cover are characterized by water bodies, medium-density vegetation, bare ground, high-density vegetation, urban areas, and linear infrastructure. Land use and land cover data in Geographic Information Systems (GIS) can be obtained from various sources, depending on the scale, accuracy, and specific requirements of your project.

v. Slope

Slope data in Geographic Information Systems (GIS) refers to information about the steepness or gradient of the terrain's surface. DEMs provide elevation data at discrete points across the

landscape. To calculate slope, GIS software computes the change in elevation between neighboring cells in the DEM. Slope data provides insights into how quickly elevation changes as one traverses the landscape. It is typically expressed as a percentage, degree, or gradient, indicating the level of steepness or gentleness at each location. The slope in the area of interest ranges from 0° to 65.8953°.

vi. Road Access

Road access defines the proximity of potential solar harvesting sites to major roads. This access primarily serves construction purposes. The road classes include all-weather roads with a bound surface, all-weather roads with a loose surface, cutlines, dry-weather roads, and motorable tracks.

Table 3-2 below is a summary of the data used in this study.

**Table 3-2: Summary of parameter data source, type & resolution**

Parameter	Data Type	Source	Processing	Resolution
Temperature	Raster	Worldclim.org	Resampled using Landsat 8 Thermal band	30m
Solar Radiation	Raster	Worldclim.org	Resampled using Landsat 8 Thermal band	30m
Aspect	Raster	Sentinel 1	DEM processed from SAR data. Aspect generated from DEM	10 m
Slope	Raster	Sentinel 1	DEM processed from SAR data. Aspect generated from DEM	10 m
Land use/ land cover	Raster	Sentinel 2	Classification done using image composites created from multispectral satellite images	10 m
Roads	Vector	Humanitarian OpenStreet Map	Raster of Euclidean distances created from the road line data	10 m

### 3.6 Methods

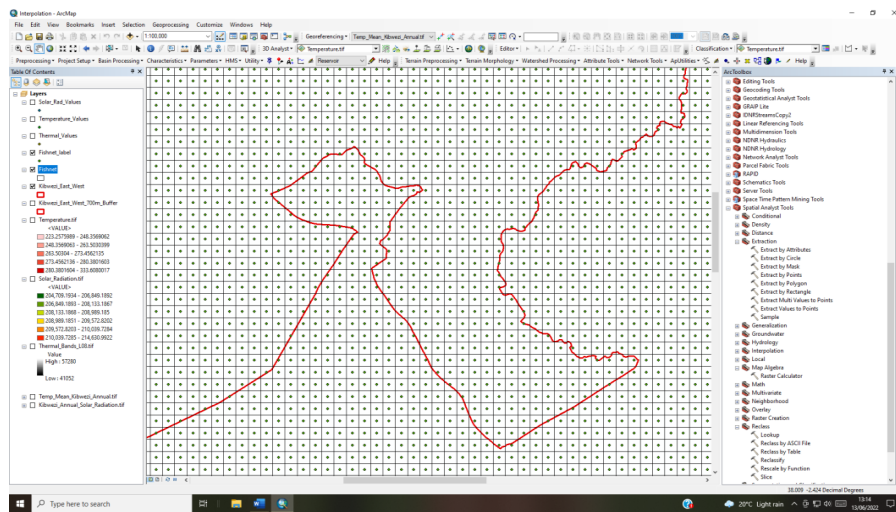
#### 3.6.1 Raw Data Editing and Manipulation

##### 3.6.1.1 Temperature and solar radiation

The solar radiation and temperature data obtained from WorldClim had a spatial resolution of 1km. This resolution was considered very low, given the study's expected results.

Consequently, the data were resampled by establishing a correlation between the thermal band of Landsat 8 and the solar radiation and temperature data using the following procedure:

Using the Create Fishnet spatial analyst tool in ArcMap, a fishnet of rectangular cells was generated, with the area of the study boundary shapefile serving as the template extents. Within each cell, points (Fishnet labels) were generated, employing a layout of 150 rows and 150 columns.



**Figure 3-4: Fishnet of rectangular cells created in ArcMap**

Subsequently, the fishnet label shapefile was imported into QGIS, where columns for X and Y coordinates were established. The X and Y coordinates were auto-generated using the \$x and \$y functions, respectively.

M	Number	X	Y
1	1	37.5802	-3.8932
0	2	37.5802	-3.8932
0	3	37.6002	-3.8932
0	4	37.6202	-3.8932
0	5	37.6402	-3.8932
0	6	37.6602	-3.8932
0	7	37.6802	-3.8932
0	8	37.7002	-3.8932
0	9	37.7202	-3.8932
0	10	37.7402	-3.8932
0	11	37.7602	-3.8932
0	12	37.7802	-3.8932
0	13	37.8002	-3.8932
0	14	37.8202	-3.8932
0	15	37.8402	-3.8932
0	16	37.8602	-3.8932
0	17	37.8802	-3.8932
0	18	37.9002	-3.8932
0	19	37.9202	-3.8932
0	20	37.9402	-3.8932
0	21	37.9602	-3.8932
0	22	37.9802	-3.8932
0	23	38.0002	-3.8932
0	24	38.0202	-3.8932
0	25	38.0402	-3.8932
0	26	38.0602	-3.8932
0	27	38.0802	-3.8932
0	28	38.1002	-3.8932
0	29	38.1202	-3.8932
0	30	38.1402	-3.8932
0	31	38.1602	-3.8932

**Figure 3-5: The fishnet label shapefile imported into QGIS**

Data from the Landsat 8 thermal band, original temperature, and solar radiation, each with a resolution of 1 km, were loaded into ArcMap.

Points were extracted from the Landsat 8 thermal band, original temperature, and solar radiation using the Extract Values to Point spatial analyst tool in ArcMap. A distinct point dataset was created for each of the three rasters.

Subsequently, the database files (.dbf) of the generated points were imported into MS Excel.

Lastly, graphs illustrating the relationship between Thermal Band and temperature, as well as Thermal Band and solar radiation, were generated. The graphs as processed in MS Excel are shown below:

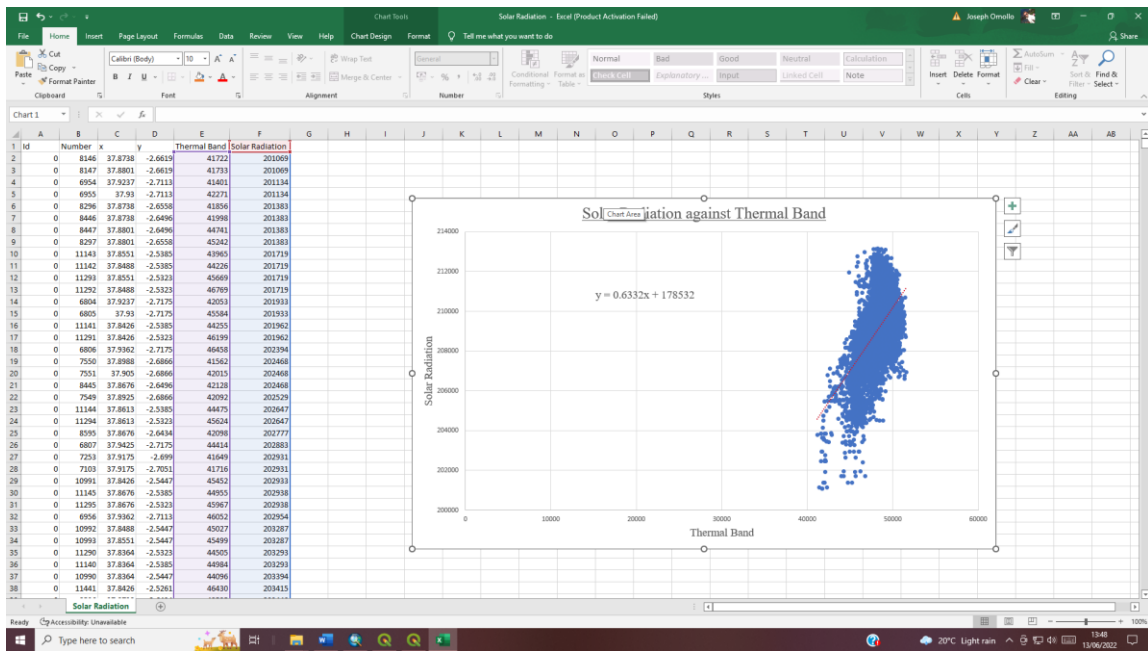


Figure 3-6: Thermal Band vs Solar Radiation

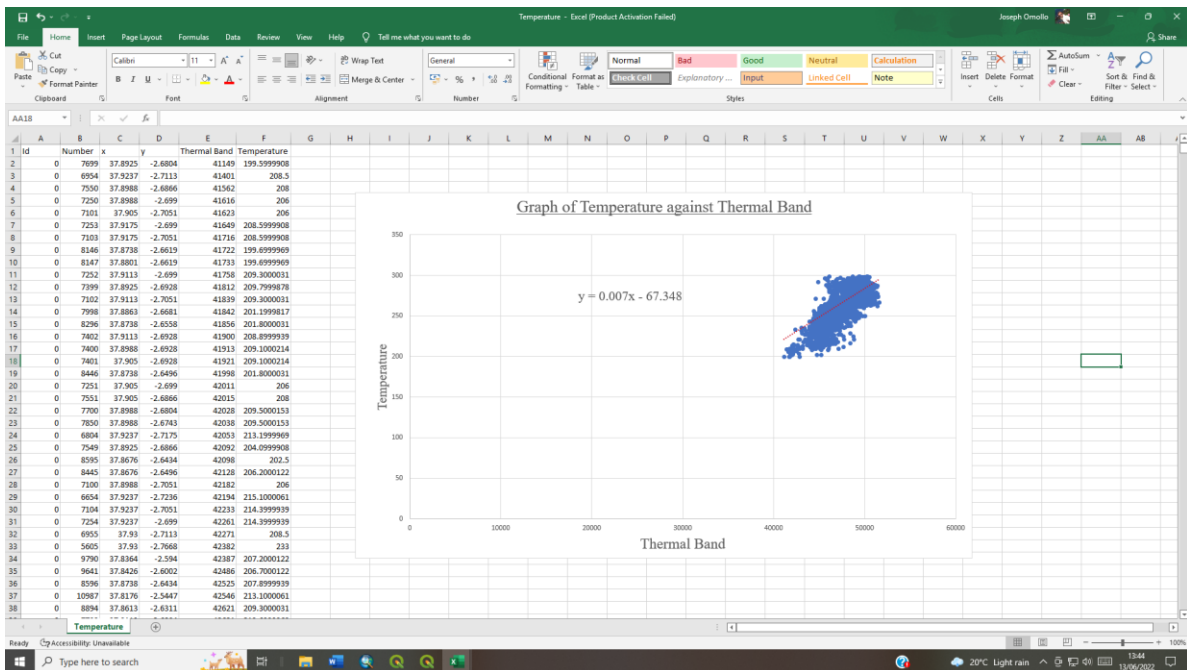
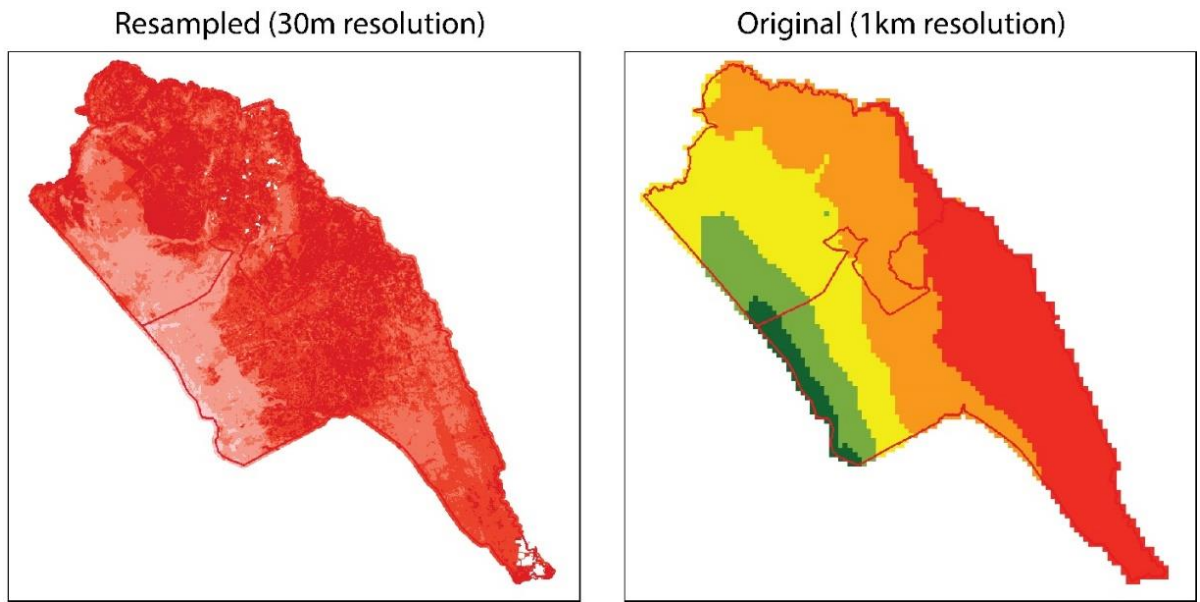


Figure 3-7: Thermal Band vs Temperature

The correlation between the thermal band and temperature was given by the equation:

$$T_r = 0.007 \cdot T_B - 67.348 \quad \text{Equation 3.2}$$

Where:  $T_r$  represents the resampled temperature,  $T_B$  represents the Thermal Band.

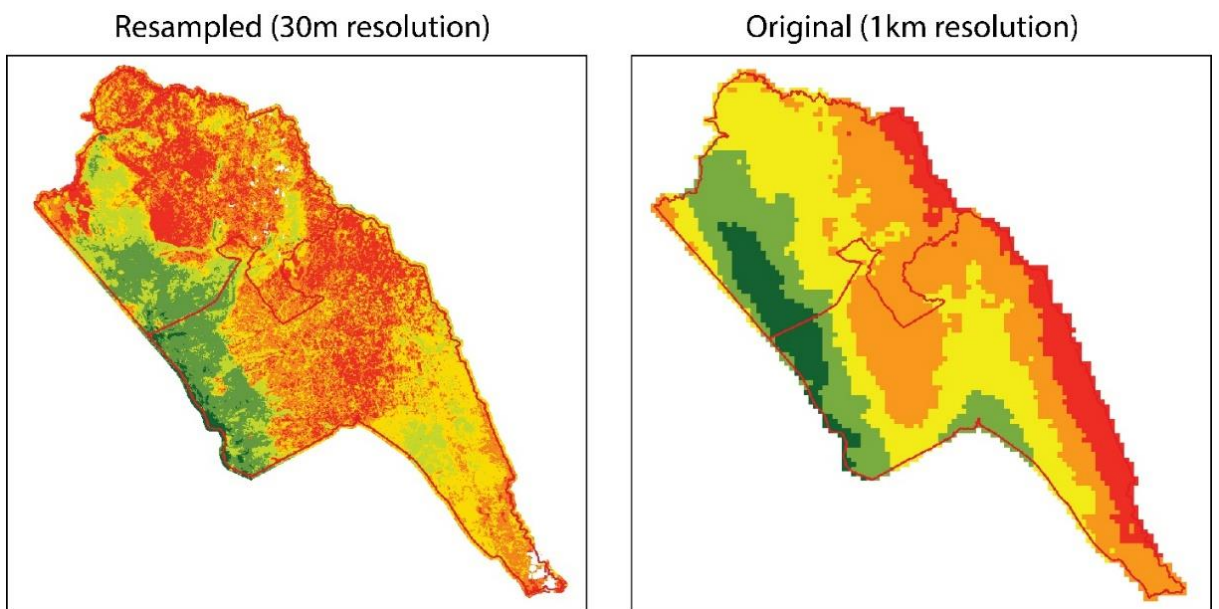


**Figure 3-8: Temperature Map -Resampled versus Original**

The correlation between the thermal band and solar radiation was given by the equation:

$$S_R = 0.6332 \cdot T_B + 178532 \quad \text{Equation 3.3}$$

Where:  $S_R$  represents Solar Radiation,  $T_B$  represents the Thermal Band.



**Figure 3-9: Solar Radiation Map-Resampled versus Original**

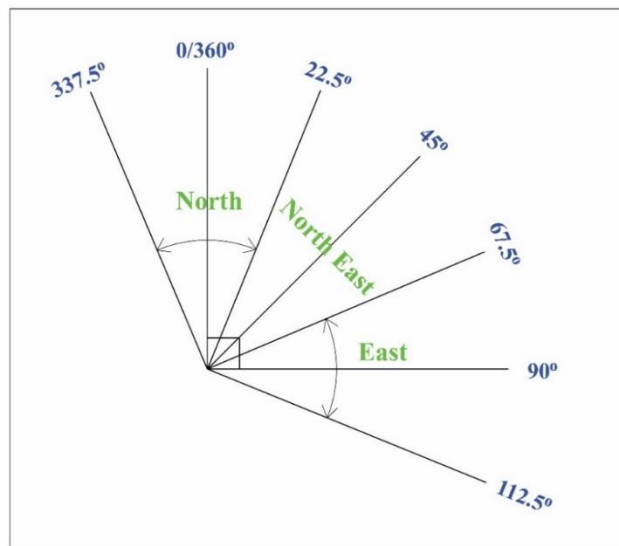


### 3.6.1.2 Aspect

North, east, south, and west typically correspond to  $0^\circ/360^\circ$ ,  $90^\circ$ ,  $180^\circ$ , and  $270^\circ$ , respectively.

In order to represent both the four cardinal points and the four secondary intermediate points for mapping and geospatial analysis, a specific range of directional values is adopted.

Consequently, the north is represented by the range of  $0^\circ$  to  $22.5^\circ$  and  $337.5^\circ$  to  $360^\circ$ , while east is represented by the range of  $67.5^\circ$  to  $112.5^\circ$ . A value of -1 is used to represent flat ground.



**Figure 3-10: Aspects Cardinal Points**

The range of angles covering a given direction are summarized in the following table:

**Table 3-3: Cardinal Points and their Range**

Direction	Angle
North	0° - 22.5°, 337.5° - 360°
North East	22.5° - 67.5°
East	67.5° - 112.5°
South East	112.5° - 157.5°
South	157.5° - 202.5°
South West	202.5° - 247.5°
West	247.5° - 292.5°
North West	292.5° - 337.5°

Elevation data, utilized in generating the aspect, was acquired from <https://scihub.copernicus.eu/dhus/#/home>. This website serves as a source for Sentinel's Synthetic Aperture Radar (SAR) data. The SAR data underwent geometric corrections to transform it into an orthogonal image, a process carried out using SNAP ESA software. The resulting orthorectified SAR data was used as the elevation dataset for creating the aspect. The Aspect spatial analyst tool in ArcMap was employed to generate the aspect map. In this process, the aspect map was derived using the four primary cardinal points. This approach was chosen to mitigate cartographic noise that may arise when representing numerous features on a map.

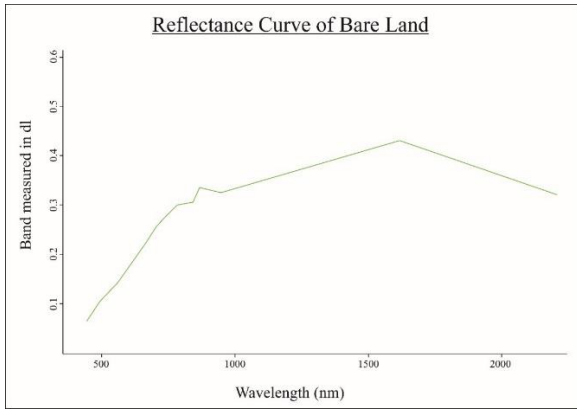
#### *3.6.1.3 Land use/ land cover*

The methodology used for the extraction and processing of this data can be expressed more clearly and consistently as follows:

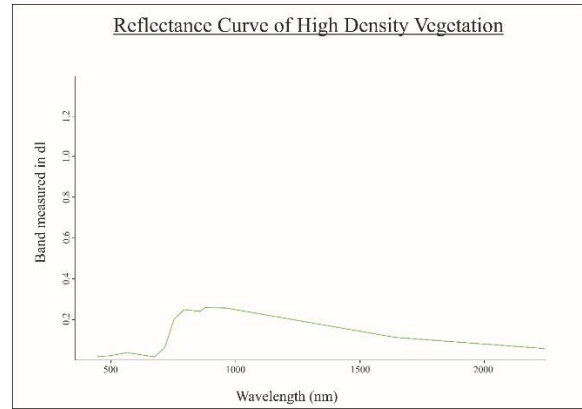
- i. A satellite imagery dataset was acquired from the Sentinel website at <https://scihub.copernicus.eu/dhus/>. This dataset consisted of thirteen image bands. For

the classification process, Bands 2, 3, 4, and 8, corresponding to the blue, green, red, and near-infrared bands, were utilized. These bands were selected based on their high spatial resolution of 10 meters.

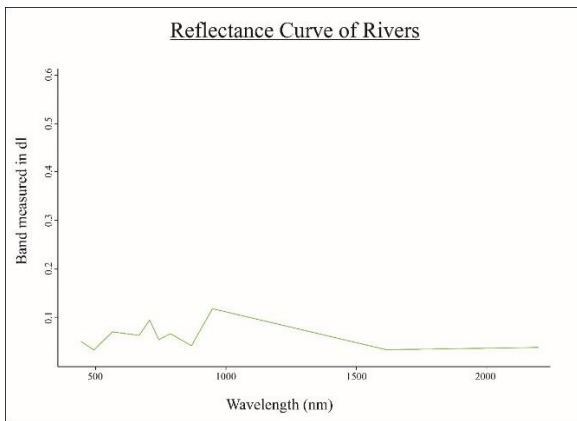
- ii. Subsequently, the imagery was clipped to the study area using the Extract by Mask spatial analyst tool in ArcMap. The mask layer employed for this purpose was the boundary of the area of interest.
- iii. The satellite imagery datasets were further explored to assess the reflectance of various features. Reflectance curves were generated to analyze the distribution of data within these bands.



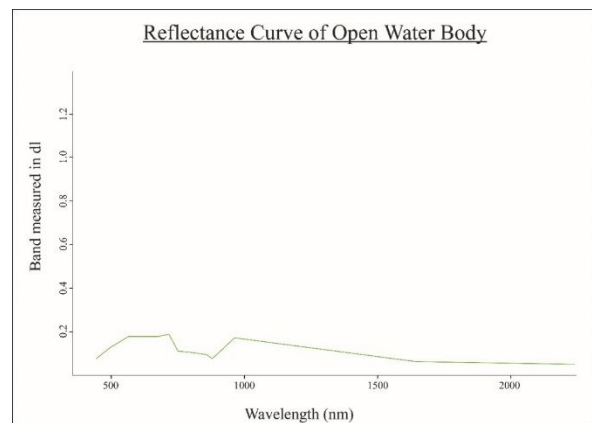
**Figure 3-11: Bare Land Reflectance Curve**



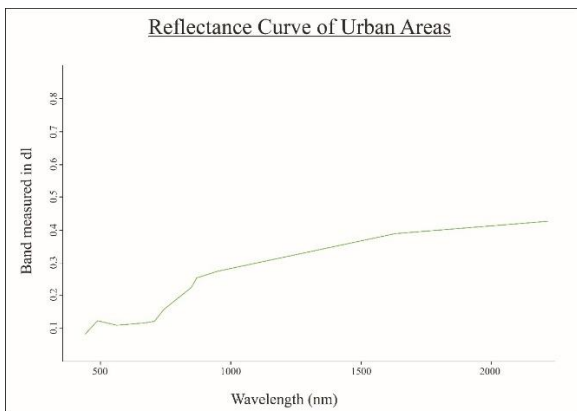
**Figure 3-14: High Density Vegetation Reflectance Curve**



**Figure 3-12: River's Reflectance Curve**



**Figure 3-15: Open Water Body Reflectance Curve**



**Figure 3-13: Urban Areas Reflectance Curve**

- iv. Using the Composite Bands spatial analyst tool in ArcMap, multiband images were generated, resulting in the creation of both color-infrared and true-color composite images..
- v. For the identified land uses and land covers, training samples were collected using the training samples drawing tools available on the Image Classification toolbar. These training samples were subsequently reviewed and edited to ensure their suitability for the classification process. Some samples were merged, others were deleted, and some were divided into other classes as necessary.

ID	Class Name	Value	Color	Count
1	Water Body	1		250
2	Medium Density Vegetation	3		927
3	Bare Ground	7		78772
4	Urban Areas	11		396
5	High Density Vegetation	12		422
6	Linear Infrastructure	15		2276

**Figure 3-16: Training Samples in ArcMap**

(Source: Author's own screenshot, created with ArcMap)

- vi. A signature file was generated using the Create Signature File tool.
- vii. Classification was performed using the Maximum Likelihood Classification tool, which assigns each pixel in the image to a specific class based on the means and variances stored in the previously created signature file.

#### *3.6.1.4 Slope*

The percentage slope was calculated using the Slope spatial analyst tool in ArcMap. The input for this calculation was the elevation data described in the aspect section. A Z factor, which is

a conversion factor used to adjust elevation when it differs from horizontal distance, was applied at a value of 0.00000898.

#### *3.6.1.5 Road Access*

Euclidean distances (direct distances) were computed using the Euclidean Distance spatial analyst tool in ArcMap. The input data for this process included the major roads within the study area.

#### *3.6.2 Data Standardization*

Data standardization was carried out through a reclassification process. Reclassification involves assigning new values to represent the original raw values in a raster dataset. These new values can either be single values or ranges. The Reclassify spatial analyst tool in ArcMap was used for this purpose. The raw data was reclassified into four classes, which are:

- a) Highly suitable
- b) Moderately suitable
- c) Marginally suitable
- d) Not suitable

To represent these suitability classes, the values 1, 2, 3, and 4 were assigned to "Not suitable," "Marginally suitable," "Moderately suitable," and "Highly suitable," respectively. A set of criteria for reclassifying the raw parameters into these four classes was developed and is presented in the table shown on the following page. These criteria were employed in the reclassification process to generate the factor maps.

##### *3.6.2.1 Criteria for Data Standardization*

From the studies looked at in the Literature Review section of this study, a criteria for the standardization of data specific to the area of interest was carried out.

Aspect and road accessibility standardization criteria data were obtained from Wiguna et al. (2016). The table below presents the data extracted from their study.

**Table 3-4: Aspect and Road Access Standardization Data from Wiguna et al.**

Parameter	Unit	Parameter Range	Standardization Weight	Weight Definition
Aspect	Direction	North	5	Highly Stable
		Northeast and Northwest	4	Moderately Stable
		West and East	3	Somewhat Stable
		Southwest and Southeast	2	Marginally Stable
		South	1	Not Stable
Road Accessibility	meter	< 200	1	Highly Stable
		200 - 1000	2	Moderately Stable
		1000 - 3000	3	Somewhat Stable
		3000 - 5000	4	Marginally Stable
		> 5000	5	Not Stable

Solar radiation standardization criteria data were sourced from Soydan (2021). The table below displays the data extracted from this study.

**Table 3-5: Solar Radiation standardization Criteria from Soydan, 2021**

Solar Radiation	kWh/m <sup>2</sup> /year	< 1500	1	Not Stable
		1500 - 1550	2	Marginally Stable
		1550 - 1600	3	Somewhat Stable
		1600 - 1650	4	Moderately Stable
		> 1650	5	Highly Stable

Slope and land use/land cover standardization criteria data were acquired from Potic et al. (2016). The table below presents the data extracted from their study.

**Table 3-6: Slope and LULC Standardization Data from Potic et al., 2016**

Parameter	Unit	Parameter Range	Standardization Weight	Weight Definition
Slope	Degrees	< 2	1	Very favorable for construction
		2 – 5	2	Favorable for construction
		5 – 12	3	Favorable with landscaping
		12 – 32	4	Unfavorable, useful for the construction only after major interventions
		>32	5	Unfavorable for construction
Land use/ land cover		Deciduous forest	4	Suitable
		Bare soil and Pastures	5	Highly suitable where no vast adaptation of terrain for the construction of solar power plant is needed.

Temperature standardization criteria data were obtained from Munkhbat and Choi (2021). The table below displays the data extracted from their study.

**Table 3-7: Temp. Standardization from Munkhbat and Choi, 2021**

Parameter	Unit	Parameter Range	Standardization Weight
Temperature	Degrees Celcius	< 2	1
		2 to 5	2
		5 to 12	3
		12 to 32	4
		>32	5

The overall standardization criteria proposed to be used in this study was aggregated and is presented in the results section of this document as table 4.1.



### 3.6.2 Administration of Questionnaire

A questionnaire was administered to five (5) respondents to collect their responses regarding the ranking of parameters influencing the selection of suitable sites for solar energy harvesting. Questionnaires were chosen due to their effectiveness in data collection, cost-efficiency, and their ability to maintain the confidentiality of this study (Gillham, 2008). The parameters and the ranking scale for this study were defined within the questionnaire.

Respondent selection criteria were based on two main qualifications:

- **Academic background:** - Respondents 1, 2, and 3 are students of Environmental Engineering, possessing a solid understanding of solar energy.
- **Knowledge of solar harvesting sites:** - Respondents 4 and 5 are graduates in Geospatial Engineering, equipped with a fundamental understanding of solar energy farm siting.

The study distributed the questionnaire to only 5 respondents for the following reasons:

- i. **Proof of Concept:** The main goal of this geographical suitability analysis can be considered as proof of concept. Therefore, a small sample size can be used to assess the feasibility of the research design and data collection process.
- ii. **Specialized Expertise:** In this case, the research requires input from highly specialized experts. It would therefore be challenging to gather many respondents. A small but expert sample may provide valuable insights.

#### 3.6.2.1 Sample Questionnaire

Refer to the appendix section to view the sample questionnaire.

### 3.6.2.2 Questionnaire Responses

The completed questionnaires were gathered, and the following scans depict the responses received:

Multi Criteria Evaluation Analysis is used to identify how the factors in this study compare with one another in relation to solar harvesting mapping. The weights for the overlay analysis stated above are then computed from the pairwise comparison tables created from MCEA.

You are, therefore, required to compare how the factors affect the analysis in a scale of 1 to 9. The values of the scale are defined in the table in the next page:

Value	Definition	Description
1	Equal influence	Factors contribute equally to the suitability analysis
3	Moderate influence	Judgement slightly favours one factor over the other
5	Strong influence	Judgement strongly favours one factor over the other
7	Very strong influence	Judgement strongly favours one factor over the other and dominates it
9	Extreme influence	One factor has the highest possible influence there can be
2, 4, 6 and 8	Intermediate influence	

#### Instructions

- I. Tick the circle next to the factors that you feel is the most important in each of the three categories i.e., climatic factors, locational factors and final suitability analysis.
- II. Assign a value for that important factor.

#### 1. Climatic factors

Solar radiation       Temperature      Weight = 2

#### 2. Locational factors

Land use/ land cover       Slope      Weight = 3

Land use/ land cover       Access to roads      Weight = 2

Slope       Access to roads      Weight = 2

Figure 3-17: Respondent A questionnaire feedback page 2

3. Final suitability analysis

- Climatic factors     Topographic factors    Weight =
- ...
- Climatic factors     Locational factors    Weight = 2
- Locational factors     Topographic factors    Weight = 5

Yours sincerely,  
Boniface Lyama,  
University of Nairobi,

**Figure 3-18: Respondent A questionnaire feedback page 3**

Multi Criteria Evaluation Analysis is used to identify how the factors in this study compare with one another in relation to solar harvesting mapping. The weights for the overlay analysis stated above are then computed from the pairwise comparison tables created from MCEA.

You are, therefore, required to compare how the factors affect the analysis in a scale of 1 to 9. The values of the scale are defined in the table in the next page:

Value	Definition	Description
1	Equal influence	Factors contribute equally to the suitability analysis
3	Moderate influence	Judgement slightly favours one factor over the other
5	Strong influence	Judgement strongly favours one factor over the other
7	Very strong influence	Judgement strongly favours one factor over the other and dominates it
9	Extreme influence	One factor has the highest possible influence there can be
2, 4, 6 and 8	Intermediate influence	

#### Instructions

- I. Tick the circle next to the factors that you feel is the most important in each of the three categories i.e., climatic factors, locational factors and final suitability analysis.
- II. Assign a value for that important factor.

#### 1. Climatic factors

Solar radiation       Temperature      Weight =

#### 2. Locational factors

Land use/ land cover       Slope      Weight = 5

Land use/ land cover       Access to roads      Weight = 5

Slope       Access to roads      Weight = 4

**Figure 3-19: Respondent B questionnaire feedback page 2**

3. Final suitability analysis

- |                                  |                    |                                  |                     |            |
|----------------------------------|--------------------|----------------------------------|---------------------|------------|
| <input type="radio"/>            | Climatic factors   | <input checked="" type="radio"/> | Topographic factors | Weight = 4 |
| <input checked="" type="radio"/> | Climatic factors   | <input type="radio"/>            | Locational factors  | Weight = 7 |
| <input type="radio"/>            | Locational factors | <input checked="" type="radio"/> | Topographic factors | Weight = 5 |

Yours sincerely,  
Boniface Lyama,  
University of Nairobi,

**Figure 3-20: Respondent B questionnaire feedback page 3**

Multi Criteria Evaluation Analysis is used to identify how the factors in this study compare with one another in relation to solar harvesting mapping. The weights for the overlay analysis stated above are then computed from the pairwise comparison tables created from MCEA.

You are, therefore, required to compare how the factors affect the analysis in a scale of 1 to 9. The values of the scale are defined in the table in the next page:

Value	Definition	Description
1	Equal influence	Factors contribute equally to the suitability analysis
3	Moderate influence	Judgement slightly favours one factor over the other
5	Strong influence	Judgement strongly favours one factor over the other
7	Very strong influence	Judgement strongly favours one factor over the other and dominates it
9	Extreme influence	One factor has the highest possible influence there can be
2, 4, 6 and 8	Intermediate influence	

Instructions

- I. Tick the circle next to the factors that you feel is the most important in each of the three categories i.e., climatic factors, locational factors and final suitability analysis.
- II. Assign a value for that important factor.

1. Climatic factors

Solar radiation       Temperature      Weight = 2

2. Locational factors

Land use/ land cover       Slope      Weight = 3

Land use/ land cover       Access to roads      Weight = 2

Slope       Access to roads      Weight = 2

**Figure 3-21: Respondent C questionnaire feedback page 2**

3. Final suitability analysis

- Climatic factors     Topographic factors    Weight =
- ...
- Climatic factors     Locational factors    Weight = 2
- Locational factors     Topographic factors    Weight = 5

Yours sincerely,  
Boniface Lyama,  
University of Nairobi,

**Figure 3-22: Respondent C questionnaire feedback page 3**

Multi Criteria Evaluation Analysis is used to identify how the factors in this study compare with one another in relation to solar harvesting mapping. The weights for the overlay analysis stated above are then computed from the pairwise comparison tables created from MCEA.

You are, therefore, required to compare how the factors affect the analysis in a scale of 1 to 9. The values of the scale are defined in the table in the next page:

Value	Definition	Description
1	Equal influence	Factors contribute equally to the suitability analysis
3	Moderate influence	Judgement slightly favours one factor over the other
5	Strong influence	Judgement strongly favours one factor over the other
7	Very strong influence	Judgement strongly favours one factor over the other and dominates it
9	Extreme influence	One factor has the highest possible influence there can be
2, 4, 6 and 8	Intermediate influence	

#### Instructions

- I. Tick the circle next to the factors that you feel is the most important in each of the three categories i.e., climatic factors, locational factors and final suitability analysis.
- II. Assign a value for that important factor.

##### 1. Climatic factors

Solar radiation       Temperature      Weight = 3

##### 2. Locational factors

Land use/ land cover       Slope      Weight = 3

Land use/ land cover       Access to roads      Weight = 3

Slope       Access to roads      Weight = 2

**Figure 3-23: Respondent D questionnaire feedback page 2**



3. Final suitability analysis

- Climatic factors     Topographic factors    Weight = 4
- Climatic factors     Locational factors    Weight = 3
- Locational factors     Topographic factors    Weight = 3

Yours sincerely,  
Boniface Lyama,  
University of Nairobi,

**Figure 3-24: Respondent D questionnaire feedback page 3**

Multi Criteria Evaluation Analysis is used to identify how the factors in this study compare with one another in relation to solar harvesting mapping. The weights for the overlay analysis stated above are then computed from the pairwise comparison tables created from MCEA.

You are, therefore, required to compare how the factors affect the analysis in a scale of 1 to 9. The values of the scale are defined in the table in the next page:

Value	Definition	Description
1	Equal influence	Factors contribute equally to the suitability analysis
3	Moderate influence	Judgement slightly favours one factor over the other
5	Strong influence	Judgement strongly favours one factor over the other
7	Very strong influence	Judgement strongly favours one factor over the other and dominates it
9	Extreme influence	One factor has the highest possible influence there can be
2, 4, 6 and 8	Intermediate influence	

Instructions

- I. Tick the circle next to the factors that you feel is the most important in each of the three categories i.e., climatic factors, locational factors and final suitability analysis.
- II. Assign a value for that important factor.

1. Climatic factors

Solar radiation       Temperature      Weight = 4

2. Locational factors

Land use/ land cover       Slope      Weight = 4

Land use/ land cover       Access to roads      Weight = 5

Slope       Access to roads      Weight = 4

**Figure 3-25: Respondent E questionnaire feedback page 2**

3. Final suitability analysis

- Climatic factors  Topographic factors Weight = 3
- Climatic factors  Locational factors Weight = 3
- Locational factors  Topographic factors Weight = 2

Yours sincerely,  
Boniface Lyama,  
University of Nairobi,

**Figure 3-26: Respondent E questionnaire feedback page 3**

### 3.6.3 Pairwise Tables and Weight Computations

The following procedure was employed to calculate weights for the factor maps, including climatic and locational data, as well as for the suitability analysis:

- i. Calculate the sum of row values for a parameter to obtain  $P_{sum}$ .
- ii. Calculate the sum of all  $P_{sum}$  values to obtain  $\Sigma P_{sum}$ .
- iii. To calculate the proportions of the totals for each parameter, we determine  $P_{sum}$  as a percentage of the total  $\Sigma P_{sum}$ , as indicated by the following formula:

$$\text{Weight} = \frac{P_{sum}}{\Sigma P_{sum}} \times 100\%$$

Equation 3.3

- iv. The weights were subsequently averaged to derive the weights employed in the standardization process.

#### 3.6.3.1 Respondent A Weight Computations

The table below presents the calculations performed for respondent A, starting from the creation of pairwise tables.

**Table 3-8: Respondent A- Weight Computations**

RESPONDENT A							
<b>Climatic Factors</b>							
	Solar Rad.	Temp.		<b>Sum</b>	<b>Weights</b>	<b>Avg Weights</b>	
Solar Rad.	1.0	2.0		3.00	66.67	66.67	
Temp.	0.5	1.0		1.50	33.33	33.33	
				<b>4.50</b>		<b>100.00</b>	
<b>Locational Factors</b>							
	LULC	Slope	Acc to Road				
LULC	1.0	0.3	0.5	1.83	16.18	16.18	
Slope	3.0	1.0	0.5	4.50	39.71	39.71	
Acc to Road	2.0	2.0	1.0	5.00	44.12	44.12	
				<b>11.33</b>		<b>100.00</b>	
<b>Final Suitability</b>							
	Clim. Factors	Top. Factors	Loc. Factors				
Clim. Factors	1.0	1.0	0.5	2.50	19.69	19.69	
Top. Factors	1.0	1.0	5.0	7.00	55.12	55.12	
Loc. Factors	2.0	0.2	1.0	3.20	25.20	25.20	
				<b>12.70</b>		<b>100.00</b>	

### 3.6.3.2 Respondent B Weight Computations

The table below presents the calculations performed for respondent B, starting from the creation of pairwise tables.

**Table 3-9: Respondent B- Weight Computations**

<b>RESPONDENT B</b>						
<b>Climatic Factors</b>						
	<b>Solar Rad.</b>	<b>Temp.</b>		<b>Sum</b>	<b>Weights</b>	<b>Avg Weights</b>
<b>Solar Rad.</b>	1.0	1.0		2.00	50.00	50.00
<b>Temp.</b>	1.0	1.0		2.00	50.00	50.00
				<b>4.00</b>		<b>100.00</b>
<b>Locational Factors</b>						
	<b>LULC</b>	<b>Slope</b>	<b>Acc to Road</b>			
<b>LULC</b>	1.0	5.0	0.2	6.20	35.13	35.13
<b>Slope</b>	0.2	1.0	4.0	5.20	29.46	29.46
<b>Acc to Road</b>	5.0	0.3	1.0	6.25	35.41	35.41
				<b>17.65</b>		<b>100.00</b>
<b>Final Suitability</b>						
	<b>Clim. Factors</b>	<b>Top. Factors</b>	<b>Loc. Factors</b>			
<b>Clim. Factors</b>	1.0	0.3	7.0	8.25	42.11	42.11
<b>Top. Factors</b>	4.0	1.0	5.0	10.00	51.04	51.04
<b>Loc. Factors</b>	0.1	0.2	1.0	1.34	6.85	6.85
				<b>19.59</b>		<b>100.00</b>

### 3.6.3.3 Respondent C Weight Computations

The table below presents the calculations performed for respondent C, starting from the creation of pairwise tables.

**Table 3-10: Respondent C- Weight Computations**

RESPONDENT C						
Climatic Factors						
	Solar Rad.	Temp.		Sum	Weights	Avg Weights
Solar Rad.	1.0	2.0		3.00	66.67	66.67
Temp.	0.5	1.0		1.50	33.33	33.33
				<b>4.50</b>		<b>100.00</b>
Locational Factors						
	LULC	Slope	Acc to Road			
LULC	1.0	0.3	2.0	3.33	29.41	29.41
Slope	3.0	1.0	2.0	6.00	52.94	52.94
Acc to Road	0.5	0.5	1.0	2.00	17.65	17.65
				<b>11.33</b>		<b>100.00</b>
Final Suitability						
	Clim. Factors	Top. Factors	Loc. Factors			
Clim. Factors	1.0	1.0	0.5	2.50	19.69	19.69
Top. Factors	1.0	1.0	5.0	7.00	55.12	55.12
Loc. Factors	2.0	0.2	1.0	3.20	25.20	25.20
				<b>12.70</b>		<b>100.00</b>

*3.6.3.4 Respondent D Weight Computations*

The table below presents the calculations performed for respondent D, starting from the creation of pairwise tables.

**Table 3-11: Respondent D- Weight Computations**

RESPONDENT D						
Climatic Factors						
	Solar Rad.	Temp.		Sum	Weights	Avg Weights
Solar Rad.	1.0	3.0		4.00	75.00	75.00
Temp.	0.3	1.0		1.33	25.00	25.00
				<b>5.33</b>		<b>100.00</b>
Locational Factors						
	LULC	Slope	Acc to Road			
LULC	1.0	3.0	3.0	7.00	57.53	57.53
Slope	0.3	1.0	2.0	3.33	27.40	27.40
Acc to Road	0.3	0.5	1.0	1.83	15.07	15.07
				<b>12.17</b>		<b>100.00</b>
Final Suitability						
	Clim. Factors	Top. Factors	Loc. Factors			
Clim. Factors	1.0	4.0	3.0	8.00	57.49	57.49
Top. Factors	0.3	1.0	3.0	4.25	30.54	30.54
Loc. Factors	0.3	0.3	1.0	1.67	11.98	11.98
				<b>13.92</b>		<b>100.00</b>

### 3.6.3.5 Respondent E Weight Computations

The table below presents the calculations performed for respondent E, starting from the creation of pairwise tables.

**Table 3-12: Respondent E- Weight Computations**

RESPONDENT E						
<b>Climatic Factors</b>						
	<b>Solar Rad.</b>	<b>Temp.</b>		<b>Sum</b>	<b>Weights</b>	<b>Avg Weights</b>
<b>Solar Rad.</b>	1.0	4.0		5.00	80.00	80.00
<b>Temp.</b>	0.3	1.0		1.25	20.00	20.00
				<b>6.25</b>		<b>100.00</b>
<b>Locational Factors</b>						
	<b>LULC</b>	<b>Slope</b>	<b>Acc to Road</b>			
<b>LULC</b>	1.0	0.3	5.0	6.25	37.43	37.43
<b>Slope</b>	4.0	1.0	4.0	9.00	53.89	53.89
<b>Acc to Road</b>	0.2	0.3	1.0	1.45	8.68	8.68
				16.70		100.00
<b>Final Suitability</b>						
	<b>Clim. Factors</b>	<b>Top. Factors</b>	<b>Loc. Factors</b>			
<b>Clim. Factors</b>	1.0	0.3	3.0	4.33	35.62	35.62
<b>Top. Factors</b>	3.0	1.0	2.0	6.00	49.32	49.32
<b>Loc. Factors</b>	0.3	0.5	1.0	1.83	15.07	15.07
				<b>12.17</b>		<b>100.00</b>

### 3.6.4 Weight Computations Summary

The comprehensive insights derived from the pairwise comparison tables are summarized in the following table, offering a clear and concise overview of the weights assigned to each factor. The weights are then calculated using equation 4.

**Table 3-13: Weight Computations Aggregated Table**

		Respondents					Average Weight %
		A	B	C	D	E	
		Weight (%)					
Climatic	Temperature	33	50	33	25	20	<b>32</b>
	Solar radiation	67	50	67	75	80	<b>68</b>
Location	Land use/land cover	16	35	29	58	37	<b>35</b>
	Slope	40	30	53	27	54	<b>41</b>
	Road access	44	35	18	15	9	<b>24</b>
Suitability Analysis	Climatic factors	20	42	20	57	36	<b>35</b>
	Topographic factors	55	51	55	31	49	<b>48</b>
	Location factor	25	7	25	12	15	<b>17</b>

### 3.6.5 Weight Computations and GIS

The weights obtained previously were applied within the Raster Calculator tool in ArcMap to generate the factor maps and the final suitability map. Utilizing the Raster Calculator, map algebra operations were conducted on raster datasets, enabling the integration of tabular data (weights) into the process, ultimately yielding the intended outcomes, including the factor maps and the final suitability map.



## CHAPTER FOUR

### 4.0 RESULTS, ANALYSIS AND DISCUSSIONS

#### 4.1 Results

The Results section of this thesis is dedicated to the presentation and analysis of findings related to the objectives outlined in the introduction section of this study. These objectives were devised to comprehensively model suitable sites for solar energy harvesting in rural areas of Kenya, with a specific focus on Kibwezi East and Kibwezi West.

##### 4.1.1 The Identified Parameters

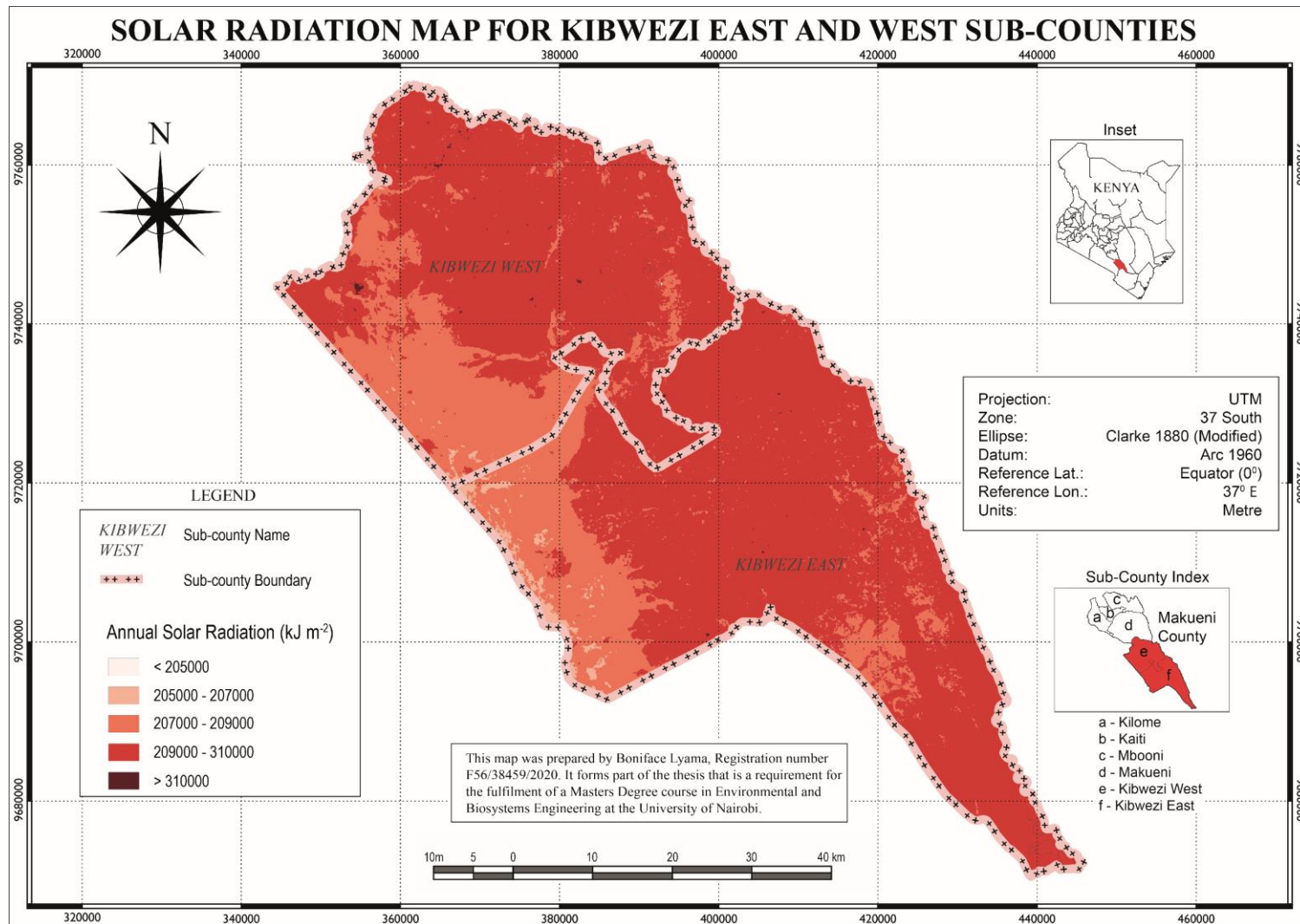
One of the objectives, as specified in Specific Objective 1, was to identify the crucial parameters necessary for modeling suitable areas for solar energy harvesting in rural regions of Kenya. This objective focused its examination on Kibwezi Sub-County, which served as a representative sample site. The results pertaining to this objective were attained through an extensive literature review, detailed in Section 3.3 of this document. The following parameters were adopted for use in this study:

- i. Solar Radiation
- ii. Temperature
- iii. Slope
- iv. Aspect
- v. Land Use
- vi. Road Access

##### 4.1.1.2 Raw Parameter Maps

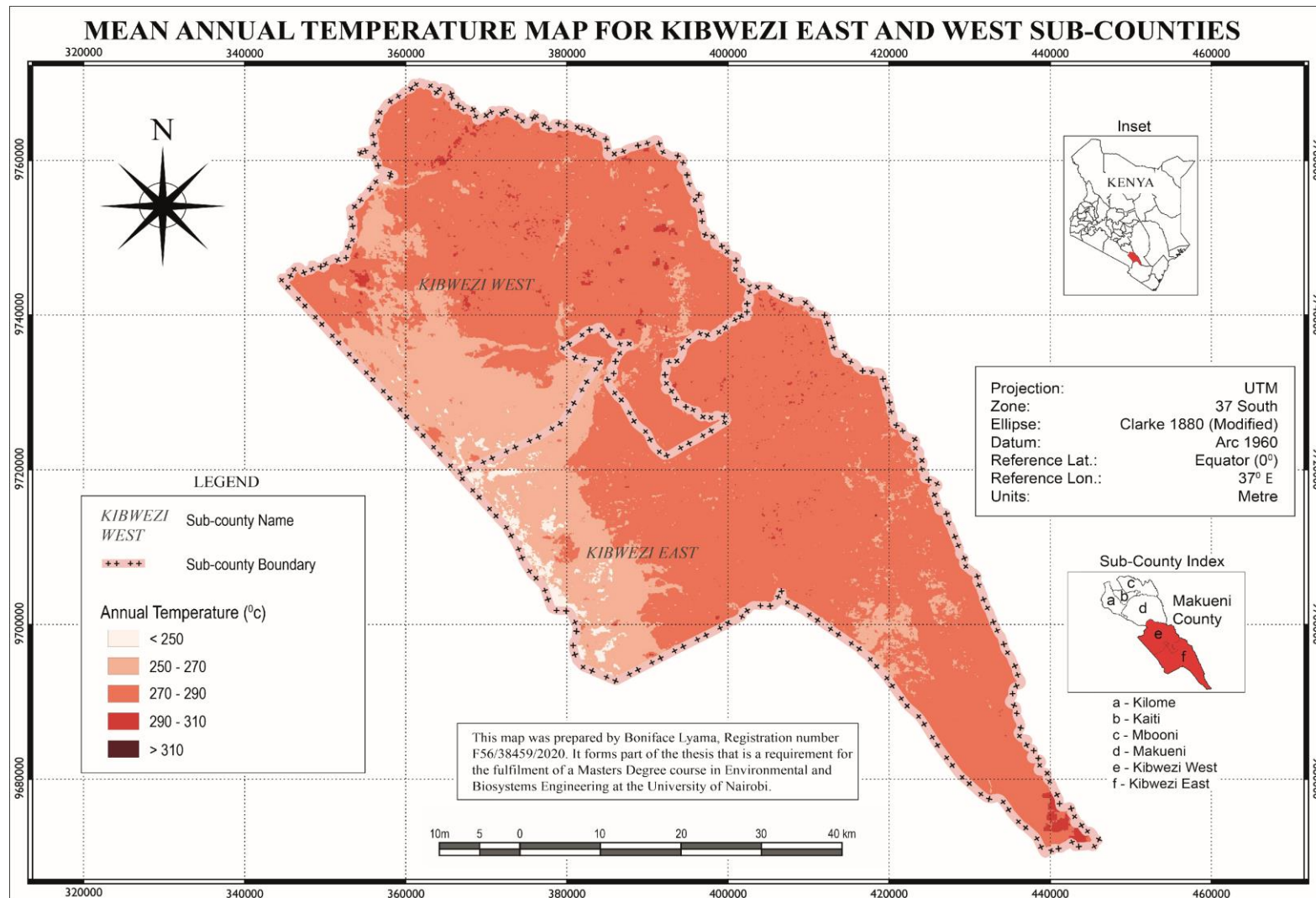
Raw parameter maps were subsequently generated for all six parameters. The following maps represent the geographic and climatic parameters within the study area:

## Solar Radiation Map



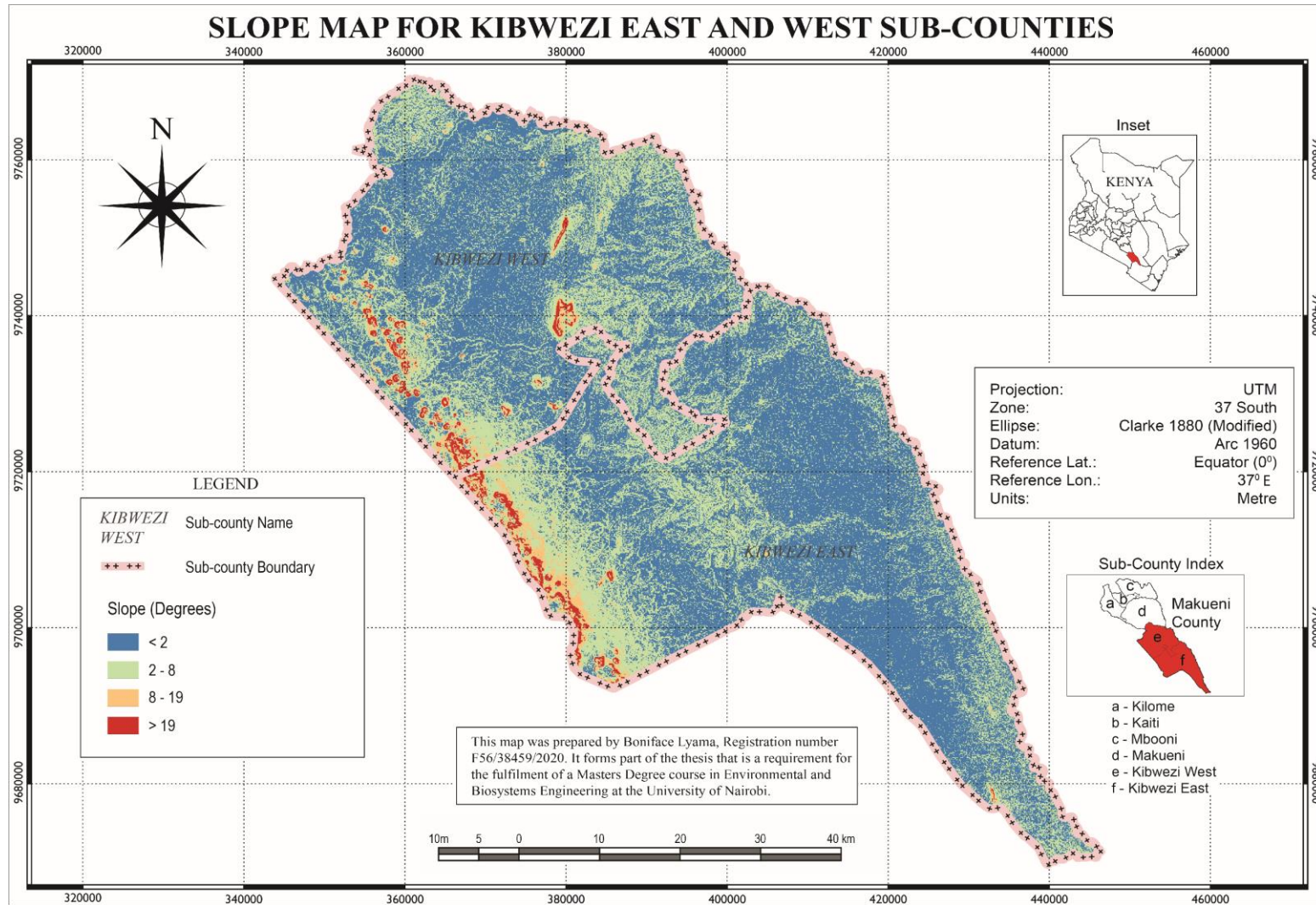
**Figure 4-1: Raw Solar Radiation Map**

# Temperature Map



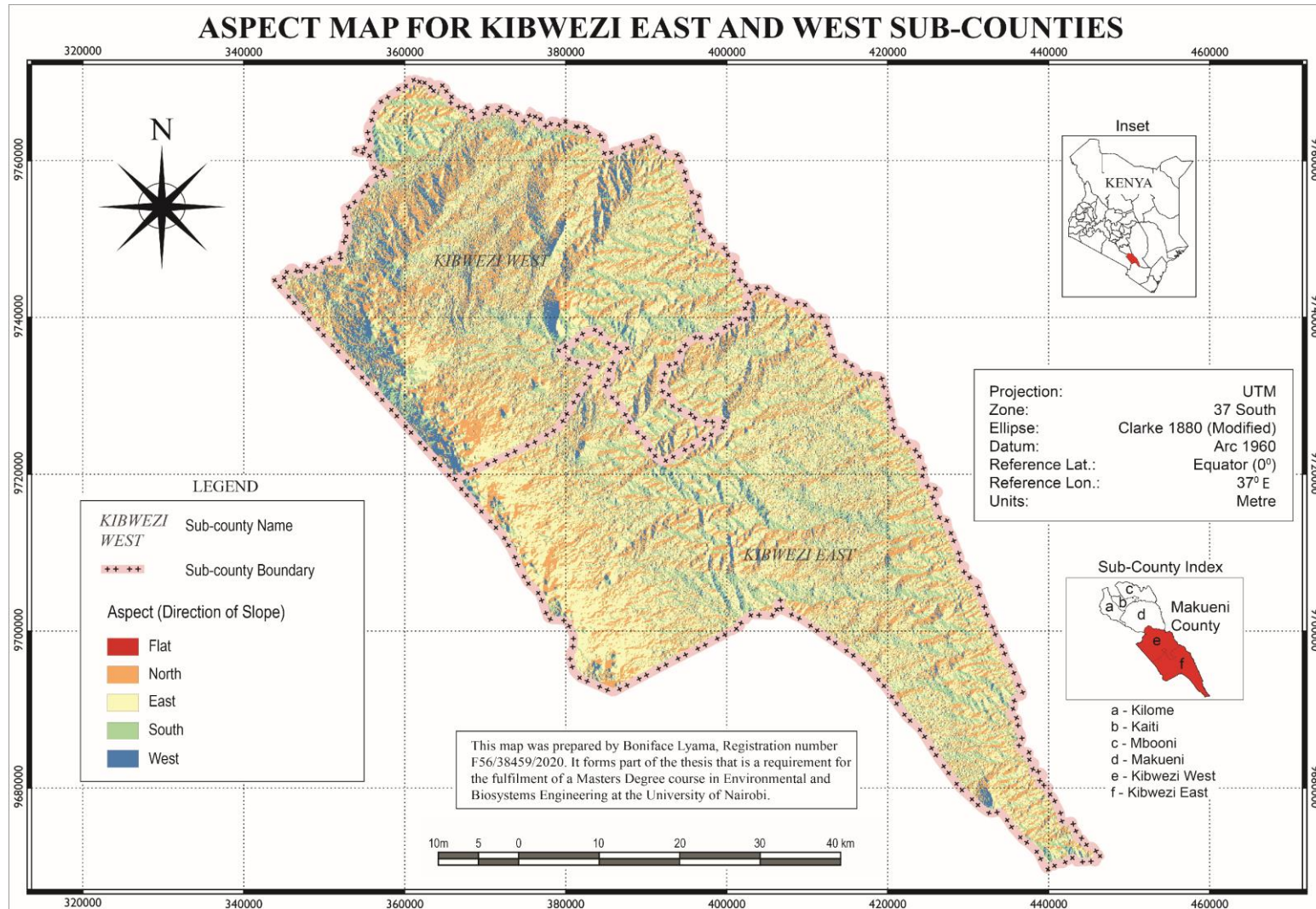
**Figure 4-2: Raw Temperature Map**

# Slope



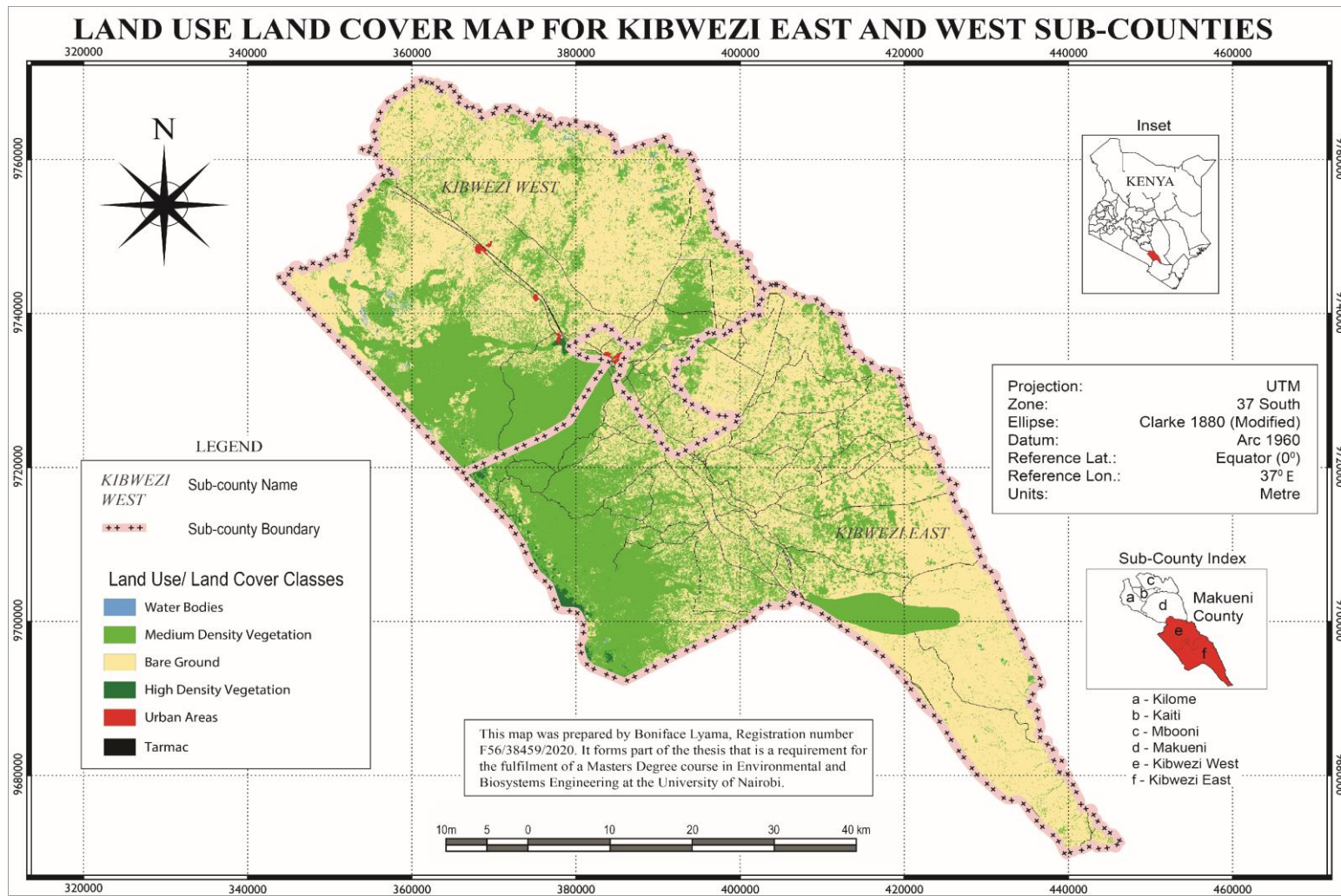
**Figure 4-3: Raw Slope Map**

# Aspect Map



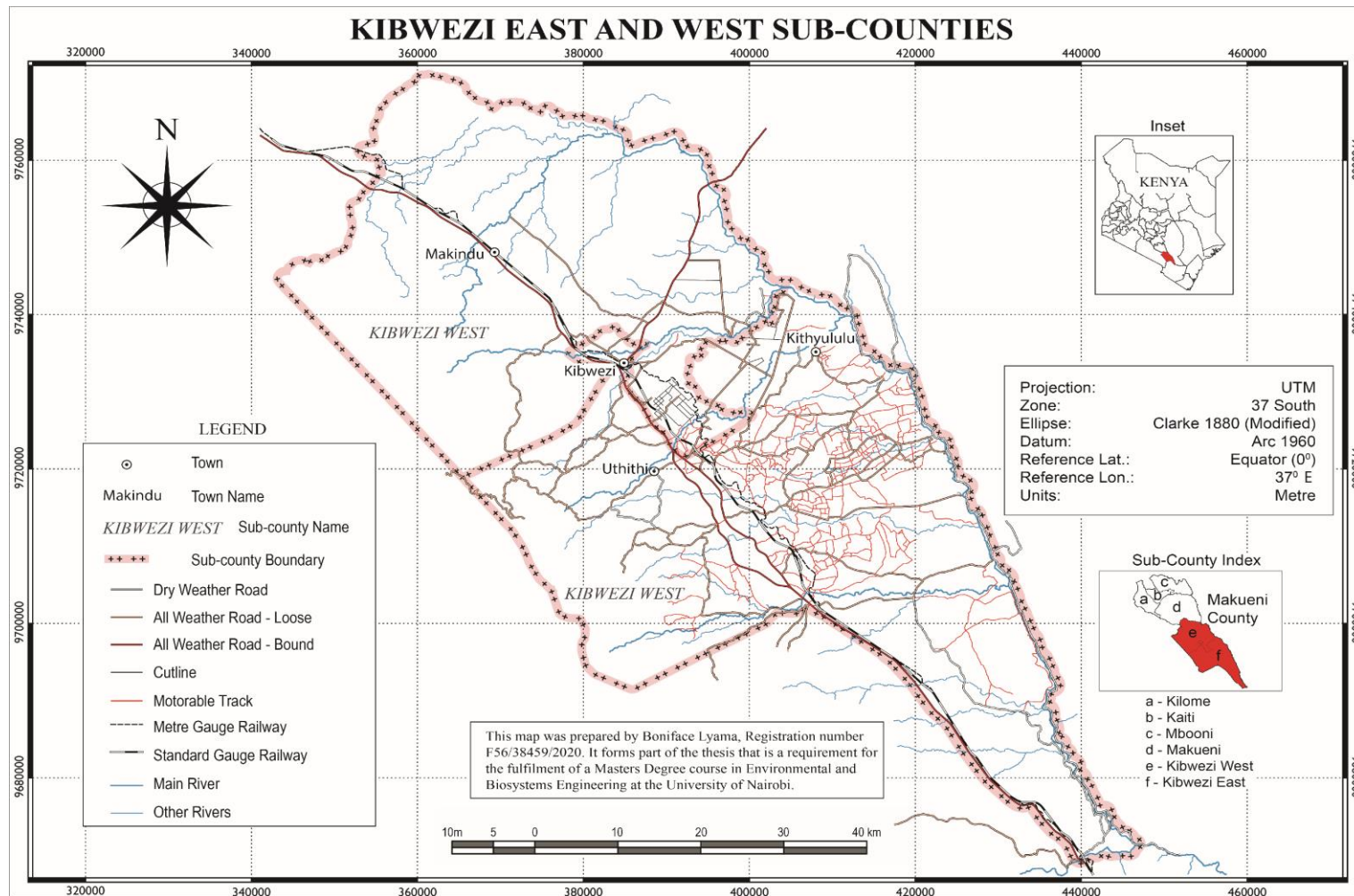
**Figure 4-4: Raw Aspect Map**

## Land Use and Land Cover Map



**Figure 4-5: Raw Land Use and Land Cover Map**

# Road Access Map



**Figure 4-6: Raw Road Access Map**

#### 4.1.2 Criterion for Standardization of Adopted Parameters

The second specific objective of this study was dedicated to establishing a standardization criterion for the identified parameters. To accomplish this, an extensive desk survey of relevant prior publications was undertaken. These publications, along with the criteria extracted from them to standardize the raw parameters, are thoroughly discussed in the literature section of this document.

For a clear reference, the ensuing table presented below provides an illustration of the standardization criteria that have been utilized in the process of standardizing the raw parameters.



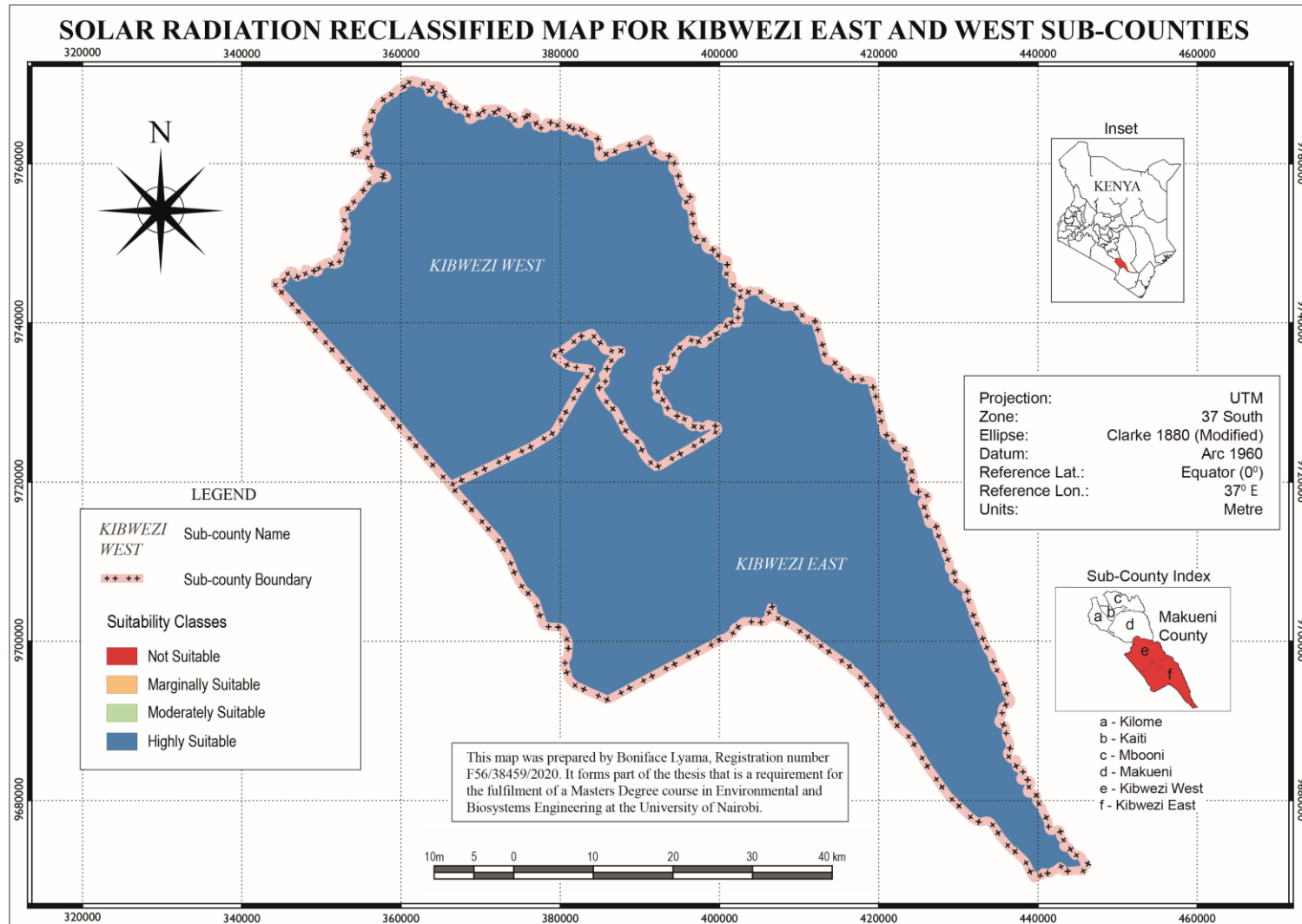
**Table 4-1: Reclassification Criterion of Standardization**

<b>PARAMETER</b>	<b>UNIT</b>	<b>RANGE</b>	<b>WEIGHT</b>	<b>DEFINITION</b>
<b>CLIMATIC FACTORS</b>				
<b>Temperature</b>	Degrees Celsius	< 36	1	Not Suitable
		36 – 72	2	Marginally Suitable
		72 – 120, > 240	3	Moderately Suitable
		120 – 240	4	Highly Suitable
<b>Solar Radiation</b>	kJ/m2/day	< 1500	1	Not Suitable
		1500 – 1600	2	Marginally Suitable
		1600 – 1650	3	Moderately Suitable
		> 1650	4	Highly Suitable
<b>TOPOGRAPHIC FACTORS</b>				
<b>Aspect</b>	Direction	North	4	Highly Suitable
		Northeast, Northwest, West, East	3	Moderately Suitable
		Southwest, Southeast	2	Marginally Suitable
		South	1	Not Suitable
<b>LOCATION FACTORS</b>				
<b>Road Access</b>	meters	< 200	1	Highly Suitable
		200 – 2000	2	Moderately Suitable
		2000 – 5000	3	Marginally Suitable
		> 5000	4	Not Suitable
<b>Slope</b>	Degrees	< 2	1	Highly Suitable
		2 – 12	2	Moderately Suitable
		12 – 32	3	Marginally Suitable
		> 32	4	Not Suitable
<b>Land use/ land cover</b>	Land Use/ Cover Classes	Bare ground	4	Highly Suitable
		Medium density vegetation	3	Moderately Suitable
		High density vegetation	2	Marginally Suitable
		Linear infrastructure, Water bodies, Urban	1	Not Suitable

#### *4.1.2.1 Reclassified Maps*

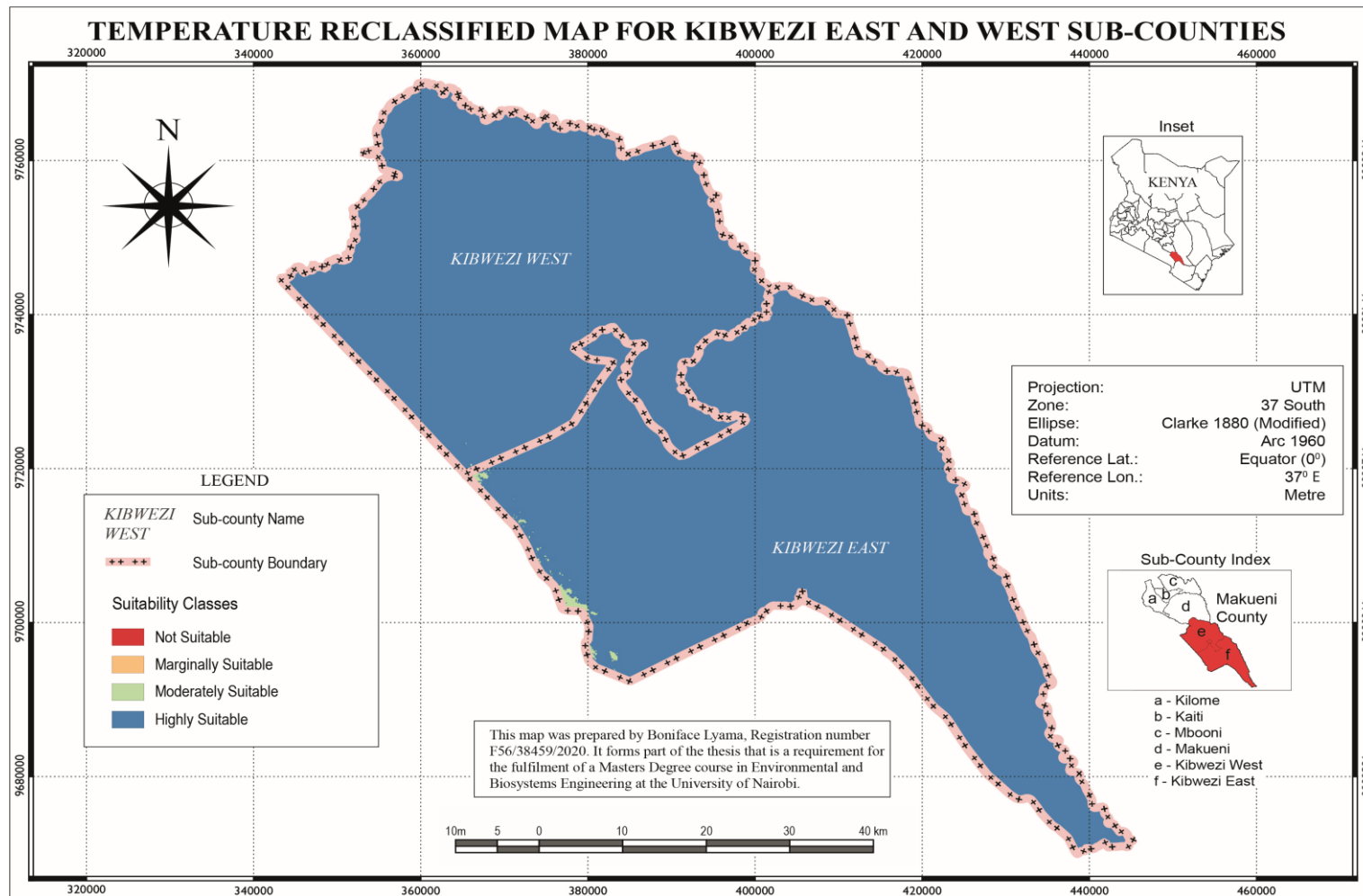
After applying the prescribed standardization criteria, the Geographic Information System (GIS) techniques outlined in the methodology section of this document were put into action to convert the initial parameter maps into reclassified versions. The resulting visual representations, found in the subsequent figures, showcase the study area maps that have been subject to reclassification in accordance with the predefined standardization criteria. This process allowed for a more refined and consistent depiction of the data, aligning it with the established standards, thereby enhancing the accuracy and utility of the information for our analysis and interpretation.

## Reclassified Solar Radiation Map



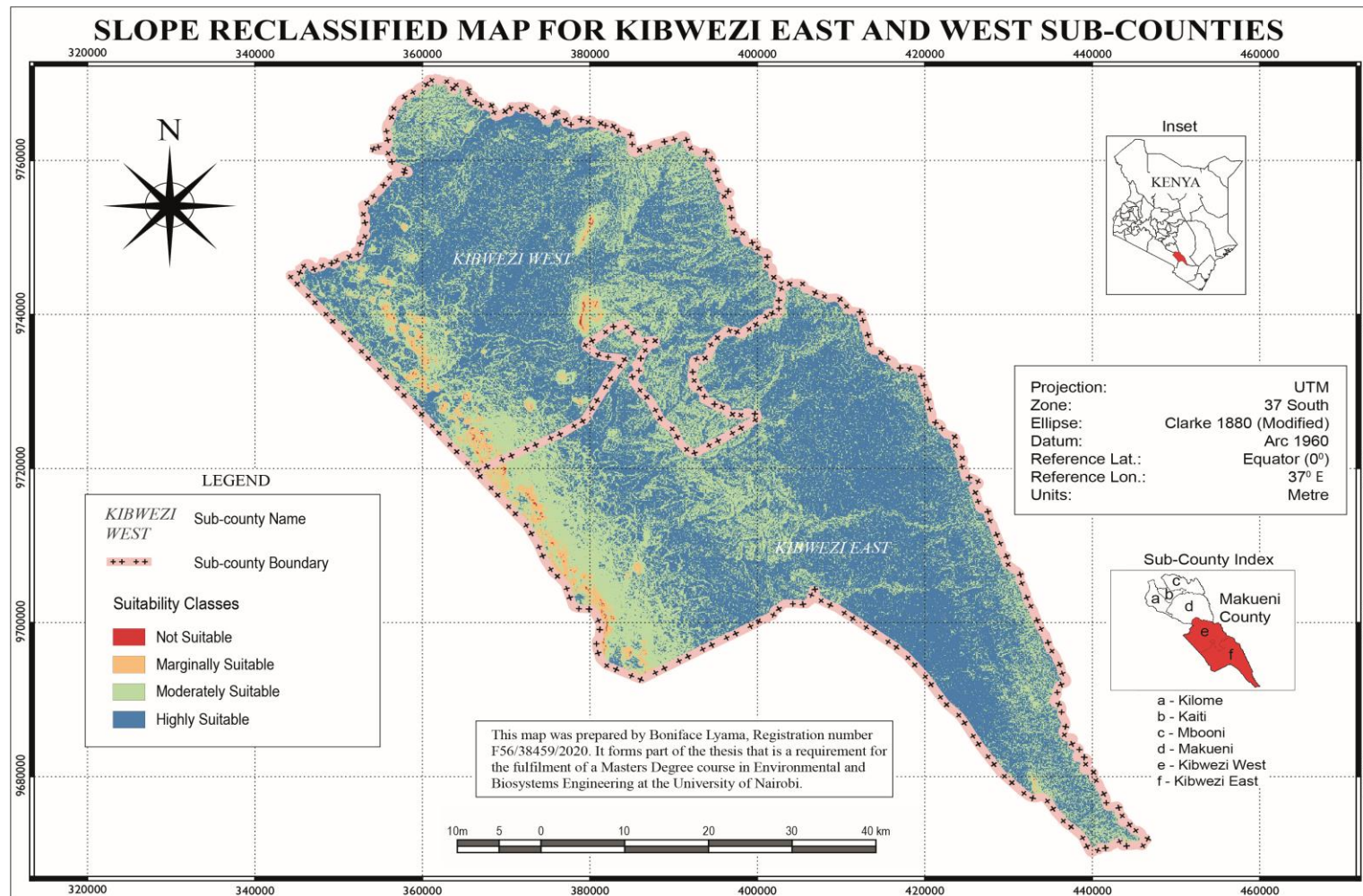
**Figure 4-7: Reclassified Solar Radiation Map**

## Reclassified Temperature Map



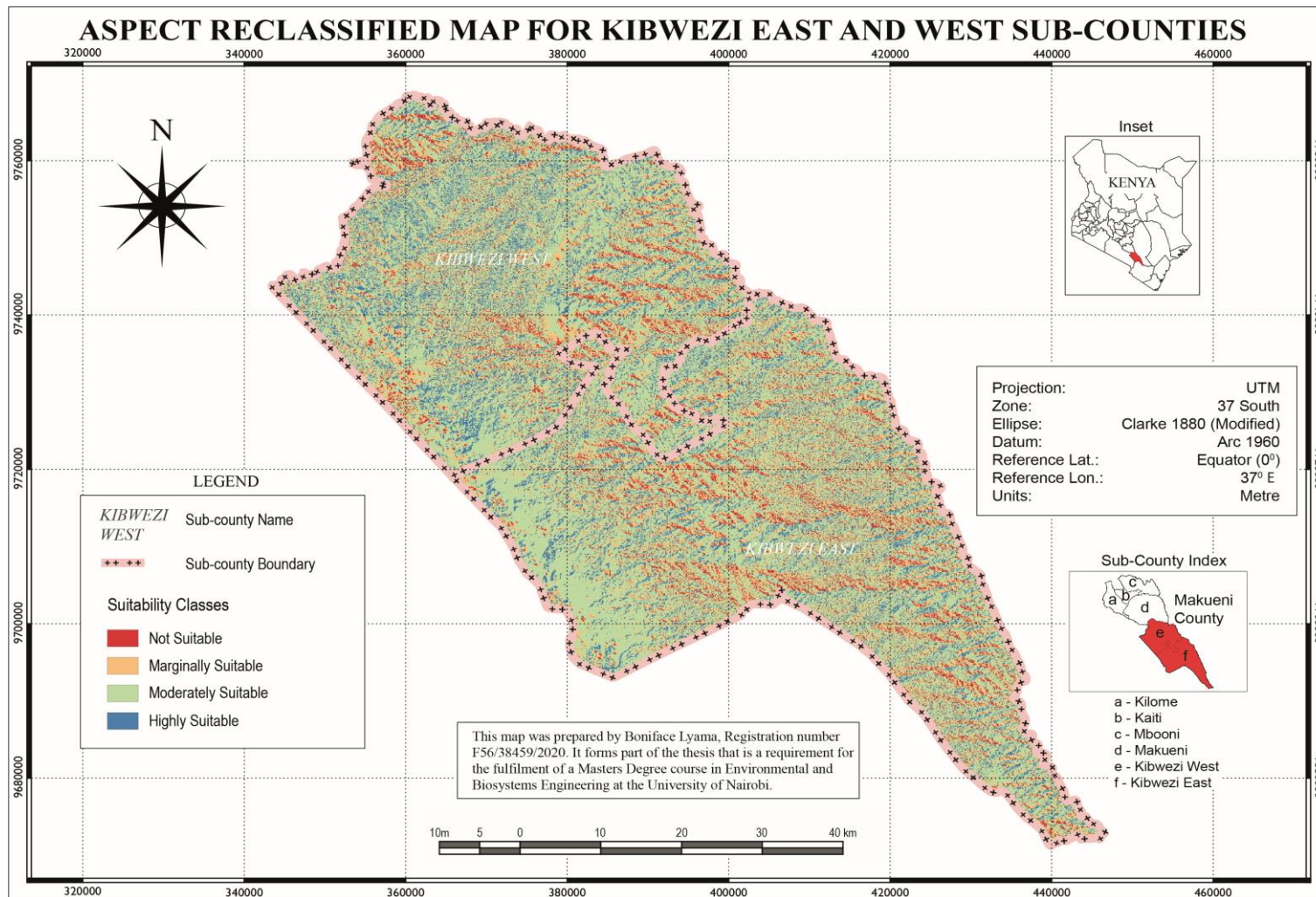
**Figure 4-8: Reclassified Temperature Map**

## Reclassified Slope Map



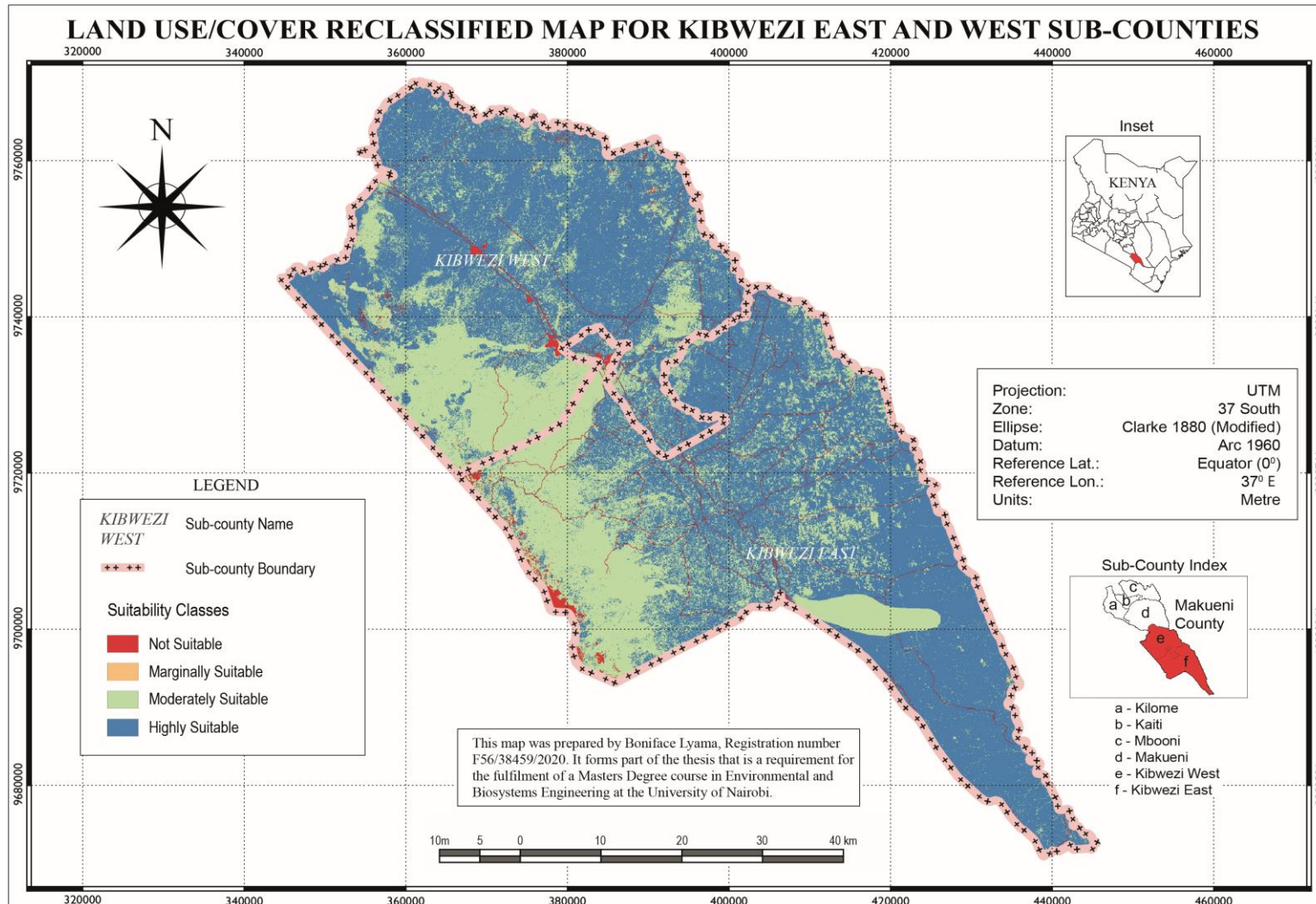
**Figure 4-9: Reclassified Slope Map**

## Reclassified Aspect Map



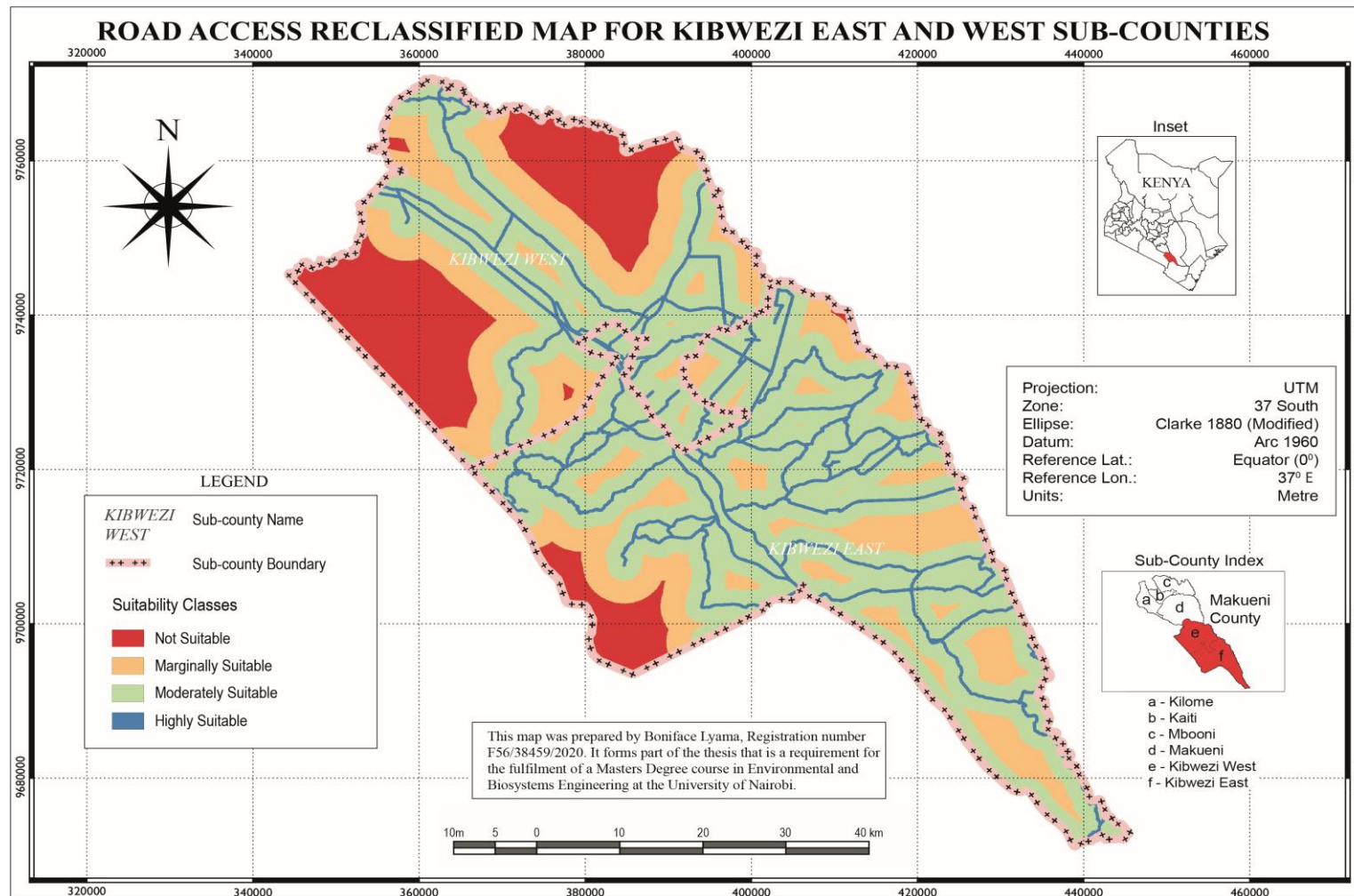
**Figure 4-10: Reclassified Aspect Map**

## Reclassified Land Use Land Cover Map



**Figure 4-11: Reclassified Land Use Land Cover Map**

## Reclassified Road Access Map



**Figure 4-12: Reclassified Road Access Map**



#### 4.1.3 Weight Computations for Suitability Analysis

Resulting from the questionnaire distribution and data processing process described in the methodology section of this document, weights intended for the factor maps and the final suitability map were determined. The weights were calculated as per equation 4. These weights are presented in the table below.

**Table 4-2: Averaged Weights Table**

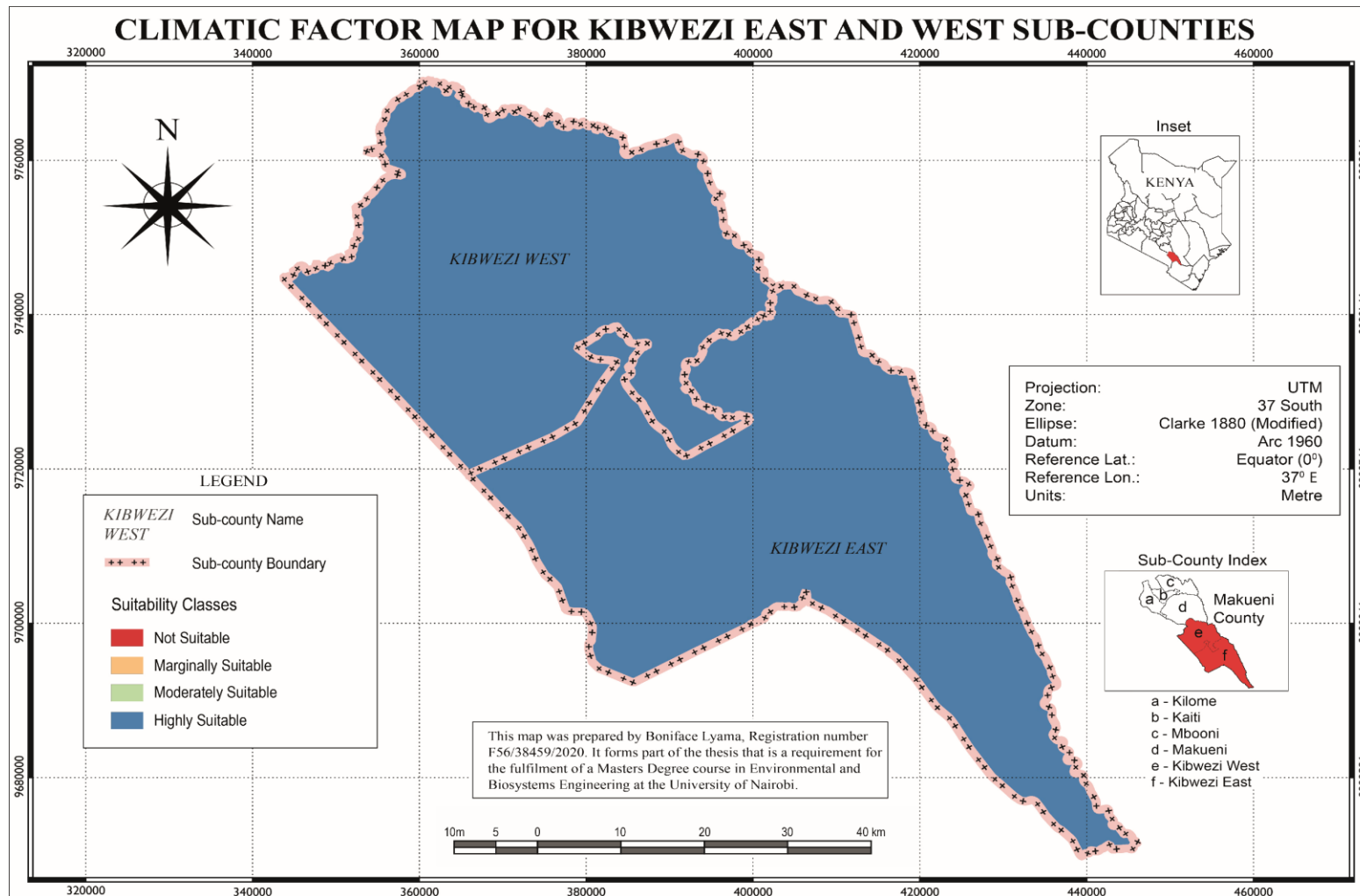
		Respondents					Average Weight %
		A	B	C	D	E	
		Weight (%)					
Climatic	Temperature	33	50	33	25	20	<b>32</b>
	Solar radiation	67	50	67	75	80	<b>68</b>
Location	Land use/land cover	16	35	29	58	37	<b>35</b>
	Slope	40	30	53	27	54	<b>41</b>
	Road access	44	35	18	15	9	<b>24</b>
Suitability Analysis	Climatic factors	20	42	20	57	36	<b>35</b>
	Topographic factors	55	51	55	31	49	<b>48</b>
	Location factor	25	7	25	12	15	<b>17</b>

These weights were instrumental in the creation of both the climatic factor map and the locational factor maps. The topographic factor map, on the other hand, did not undergo the same processing procedure due to its singular parameter, which was aspect.

#### 4.1.4 The Factor Maps

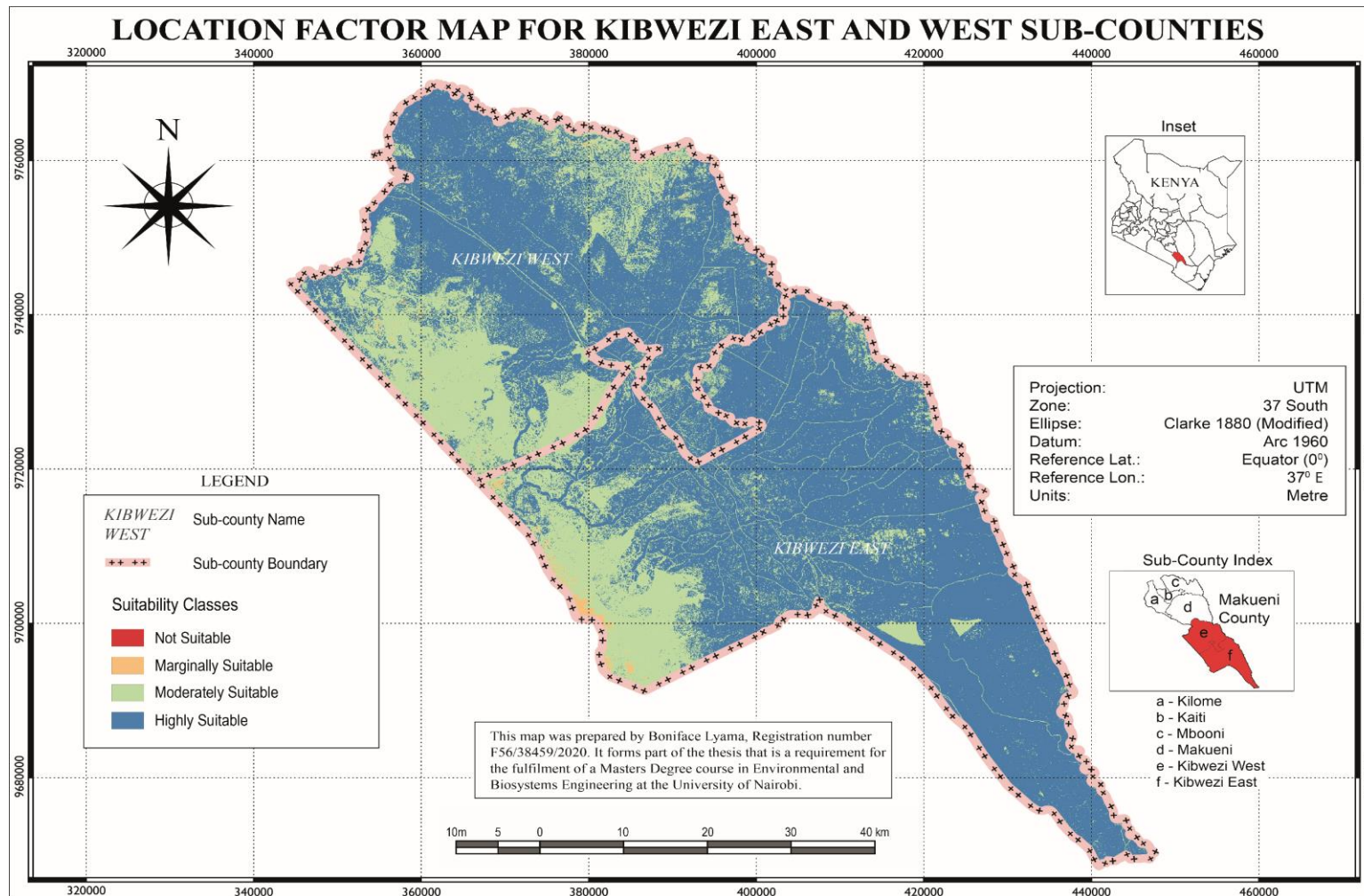
Equipped with the allocated weights, the process of developing the three factor maps was executed meticulously, adhering to the step-by-step methodology expounded in this document. The resultant factor maps are displayed below:

## Climatic Factor Map



**Figure 4-13: Climatic Factor Map**

## Locational Factor Map



**Figure 4-14: Locational Factor Map**

# Topographical Factor Map

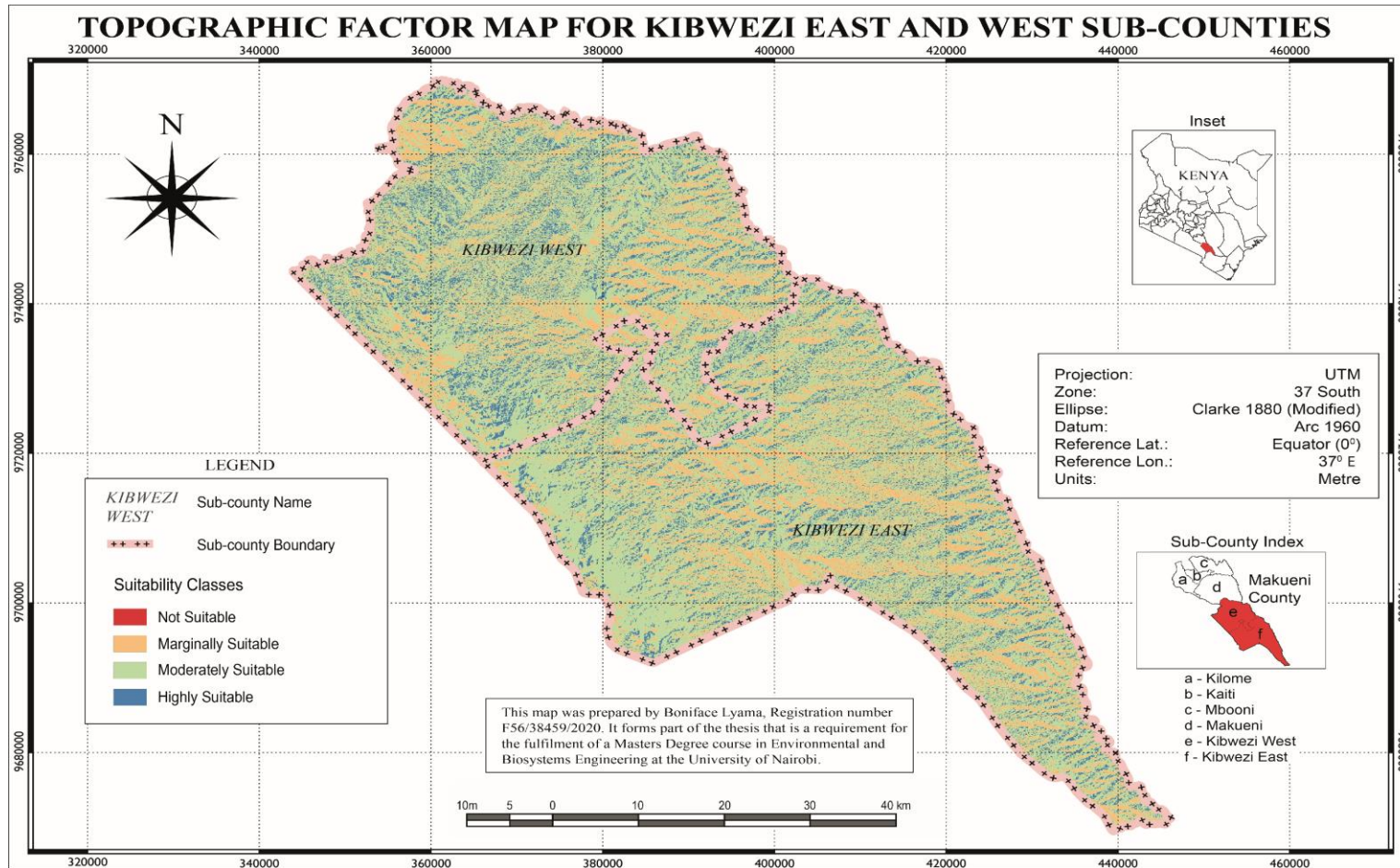
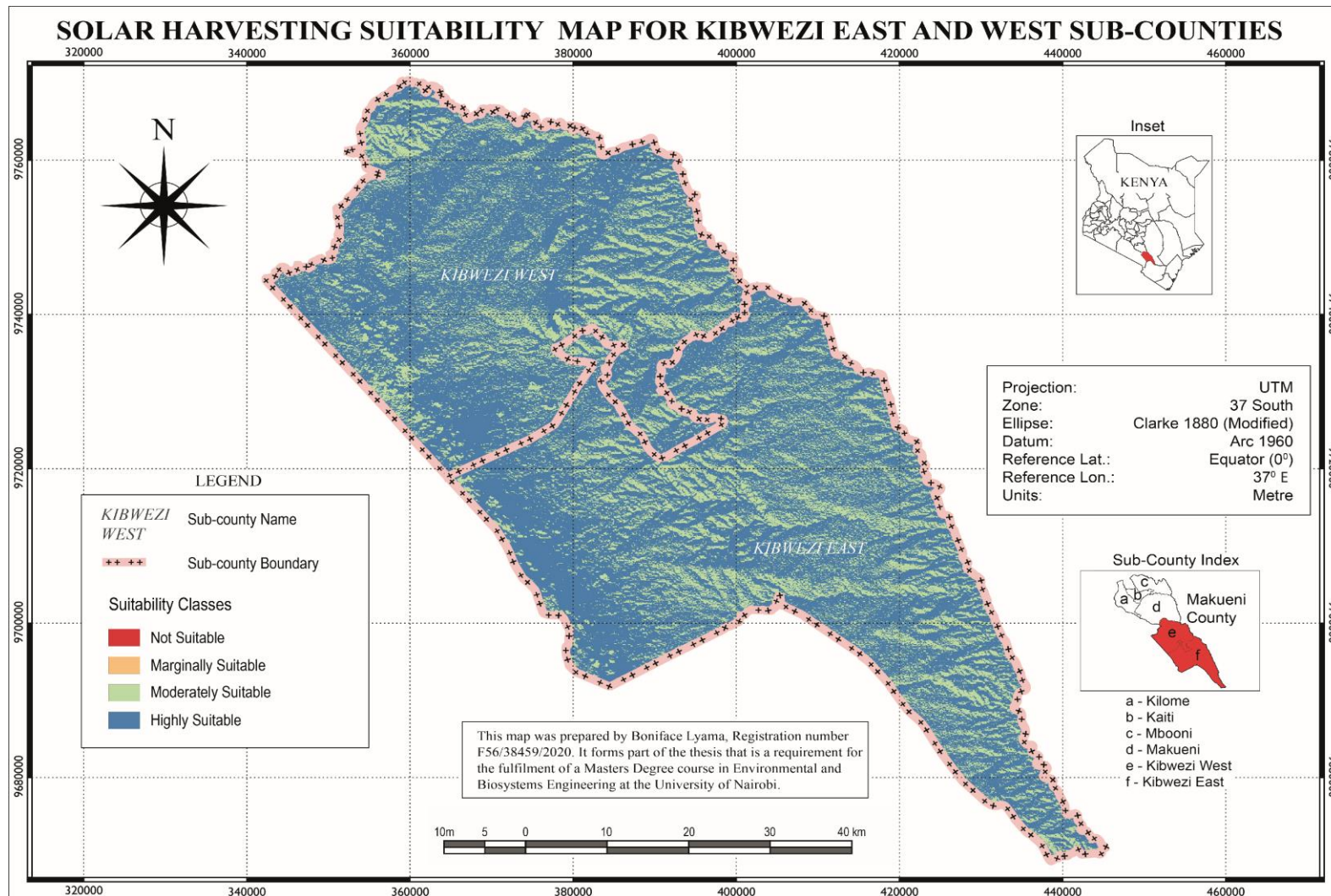


Figure 4-15: Topographical Factor Map

#### 4.1.5 Final Suitability Map

In accordance with the fourth and final specific objective, the final suitability map was developed. This achievement involved the integration of factor maps in accordance with the weightings derived in specific objective 3, a process exhaustively detailed in the methodology section of this document. The final suitability map encapsulates the overarching objective by providing a comprehensive model of suitable sites for solar harvesting. The final suitability map is presented below:



**Figure 4-16: Final Suitability Map**

## 4.2 Analysis

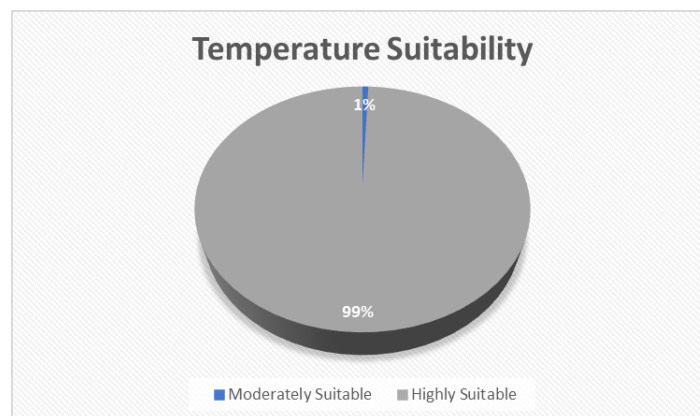
The data collected in the study underwent an analytical phase to extract meaningful interpretations. Each parameter was individually analyzed in accordance with the standardization criteria established within this study.

### 4.2.1 Climatic Factor Suitability

The climatic factors that were deemed to influence site suitability in this study were temperature and solar radiation. These two parameters are analyzed below w.r.t the standardization criteria and the total land area of Kibwezi East and Kibwezi West.

#### 4.2.1.1 Temperature Suitability

The study area is highly suitable for solar power harvesting, with 4,219.3 km<sup>2</sup> rated as highly suitable and 28.63 km<sup>2</sup> as moderately suitable. This means that 99% of the total area is considered highly suitable in terms of temperature.



**Figure 4-17: Temperature Suitability by km<sup>2</sup>**

#### 4.2.1.2 Solar Radiation Suitability

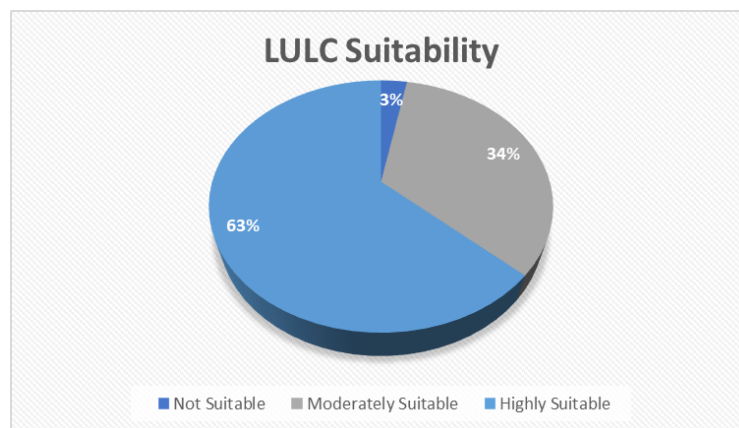
When it comes to solar radiation, the study area is exceptionally well-suited for solar power harvesting, as the entire area is deemed highly suitable. This translates to 100% of the total area being considered highly suitable in terms of solar radiation.

#### 4.2.2 Locational factor Suitability

The locational factors that were deemed to influence site suitability in this study were land Use/Land Cover, Road Access, and Slope. These three parameters are analyzed below w.r.t the standardization criteria and the total land area of Kibwezi East and Kibwezi West.

##### 4.2.2.1 Land Use/ Land Cover Suitability

Regarding Land Use and Land Cover (LULC), the study identified 2,687.59 km<sup>2</sup> of land as highly suitable, with an additional 1,435.66 km<sup>2</sup> classified as moderately suitable. A smaller portion, 125.09 km<sup>2</sup>, was considered marginally or not suitable for the intended purpose. To put it in perspective, this corresponds to 63% for highly suitable, 34% for moderately suitable, and 3% for marginally or not suitable areas. This data is graphically depicted in the accompanying pie chart.

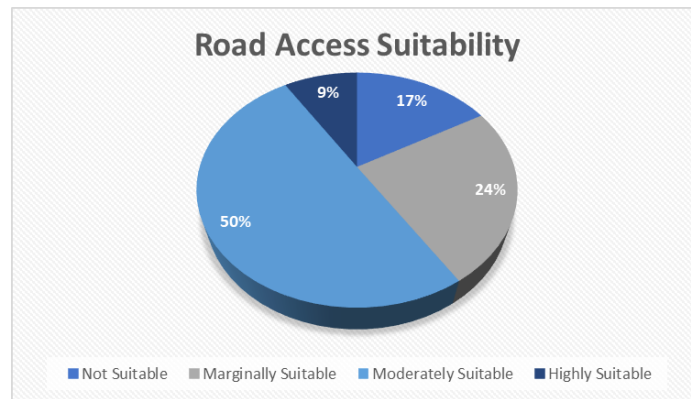


**Figure 4-18: LULC Suitability by km<sup>2</sup>**

##### 4.2.2.2 Road Access Suitability

In terms of Access to Roads, the study classified the land area into four categories: highly suitable, moderately suitable, marginally suitable, and not suitable, encompassing areas of 379.52 km<sup>2</sup>, 2,130.69 km<sup>2</sup>, 1,028.96 km<sup>2</sup>, and 709.17 km<sup>2</sup>, respectively. These figures translate to 9% for highly suitable, 50% for moderately suitable, 24% for marginally suitable, and 17% for not suitable areas, as depicted in the accompanying pie chart.

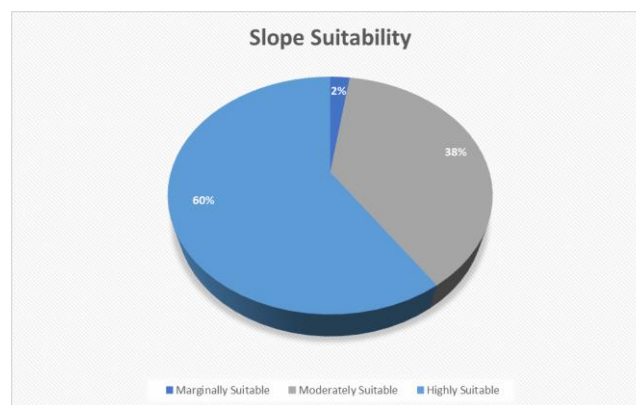




**Figure 4-19: Road Access Suitability by km<sup>2</sup>**

#### 4.2.2.3 Slope Suitability

Regarding slope suitability, the study found that 2,523.53 km<sup>2</sup> of the land is highly suitable, while 1,622.07 km<sup>2</sup> is moderately suitable. In addition, there is a smaller portion of 99.25 km<sup>2</sup> considered marginally suitable. To provide a clearer perspective, this data can be represented as 60% for highly suitable areas, 38% for moderately suitable areas, and 2% for marginally suitable areas, as shown in the accompanying pie chart.

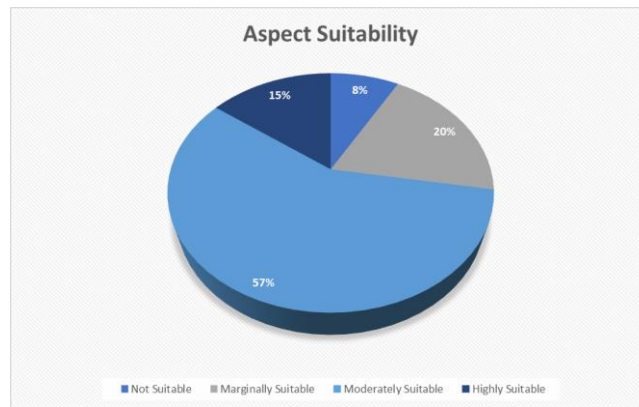


**Figure 4-20: Slope Suitability by km<sup>2</sup>**

#### 4.2.3 Topographic Factors

In this study, the sole topographic factor found to affect site suitability was the aspect. The analysis of this parameter was conducted based on standardized criteria and encompassed the entire land area of Kibwezi East and Kibwezi West. Of this combined area, 628.3 km<sup>2</sup> was identified as highly suitable, while 2,442.89 km<sup>2</sup> fell into the moderately suitable category. There was also an area of 828.63 km<sup>2</sup> considered marginally suitable and 348.51 km<sup>2</sup>

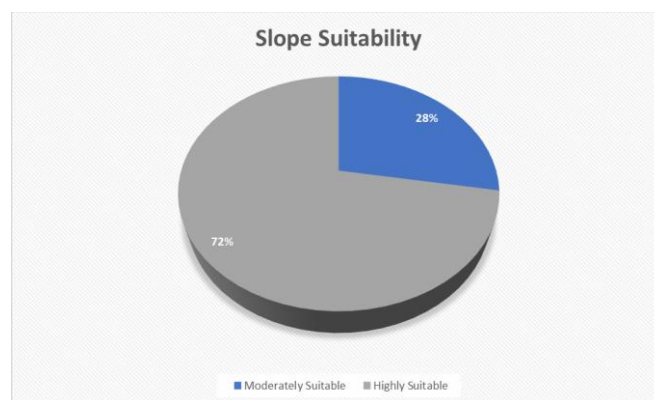
classified as not suitable. You can visually explore these proportions in the accompanying pie chart.



**Figure 4-21: Slope Suitability by km<sup>2</sup>**

#### 4.2.4 Final Suitability Map

The final suitability, representing the culmination of the methods and materials applied in this study, shows that there is a total land area of 3,070.97 km<sup>2</sup> deemed highly suitable for solar harvesting, alongside a moderately suitable area spanning 1,177.42 km<sup>2</sup>. In summary, this study suggests that 72% of the entire land area of Kibwezi East and Kibwezi West is highly suitable for solar harvesting, while the remaining 28% falls into the moderately suitable category. You can visualize these proportions in the accompanying pie chart.



**Figure 4-22: Final Suitability by km<sup>2</sup>**

### 4.3 Discussion

The above analysis reveals some interesting insights. Some are discussed below:

The reclassified maps depict the transformation of raw parameters into four distinct classes, each representing suitability for solar harvesting. These four classes are designated as Highly, Moderately, Marginally, and Not Suitable. Given that the Highly and Moderately suitable land areas exhibit a stronger compatibility with solar harvesting, analyzing the parameters concerning these two categories yields valuable insights. The following table provides an overview of the total land area deemed highly and moderately suitable in this study.

**Table 4-3: Total Land Area Highly and Moderately Suitable for the Study**

	Total Land Area in km <sup>2</sup>					
	Climatic Factors		Locational factors			Top. Factors
	Temperature	Solar Radiation	LULC	Road Access	Slope	Aspect
Highly Suitable	4219.71	4248.33	2687.59	379.52	2523.53	628.30
Moderately Suitable	28.63	0.00	1435.66	2130.69	1622.07	2442.89
<b>TOTAL ( km<sup>2</sup> )</b>	<b>4248.33</b>	<b>4248.33</b>	<b>4123.25</b>	<b>2510.20</b>	<b>4145.60</b>	<b>3071.20</b>

From the information presented in the table, several significant discussions can be drawn:

Firstly, it becomes evident that climatic factors, particularly temperature and solar radiation, stand out as the primary drivers of site suitability for solar energy harnessing. These factors play a pivotal role in determining the feasibility of solar power projects.

Secondly, the most noteworthy non-conforming parameter identified in this study is road accessibility, which falls under the category of locational factors. It's worth noting that road accessibility is not a naturally occurring factor but rather a manmade element. This observation underscores the need for a multifaceted approach to suitability analysis that takes into account both natural and anthropogenic factors. Moreover, it highlights how manmade elements can significantly impact various decision-making processes, particularly in the context of solar

energy development. Therefore, recognizing and integrating these diverse factors into the decision-making process is crucial for a comprehensive and effective site suitability analysis.

## **CHAPTER FIVE**

### **5.0 CONCLUSION AND RECOMMENDATIONS**

#### **5.1 Conclusion**

In conclusion, this thesis successfully accomplished the stated overall and specific objectives, which were designed to provide a comprehensive framework for modelling suitable sites for solar energy harvesting in rural areas of Kenya, with Kibwezi East and Kibwezi West serving as case studies.

Specific Objective 1 focused on the identification of relevant parameters crucial for modelling solar energy suitability in rural parts of Kenya, using Kibwezi Sub-County as a representative sample site. Through meticulous research and data collection, critical factors influencing solar energy suitability were identified.

Specific Objective 2 involved the establishment of a robust standardization criterion for the identified parameters, ensuring consistency and comparability in our analysis. This laid the foundation for accurate and meaningful interpretations of the data.

For Specific Objective 3, the Analytical Hierarchy Process (AHP) was employed to compute weights for the suitability analysis, which played a pivotal role in the final outcome. These weights were used to quantify the relative importance of each parameter and refine the suitability model.

Finally, with Specific Objective 4 as our ultimate goal, a comprehensive map of suitable sites for solar power harvesting was developed. This culmination serves as a valuable tool for decision-makers, stakeholders, and researchers interested in harnessing solar energy potential in rural areas of Kenya.

In achieving these objectives, the researcher has contributed to the knowledge base surrounding sustainable energy solutions and provided a practical resource for promoting solar energy adoption in rural regions, ultimately contributing to a more sustainable and environmentally friendly energy landscape in Kenya.

## **5.2 Recommendations**

Based on the successful accomplishment of the specific objectives and the comprehensive framework developed in this thesis, the following recommendations can be considered to further advance research and promote solar energy adoption in rural areas of Kenya:

- i. **Expand the Study:** While this thesis has made significant progress in modeling the suitability of solar energy in Kibwezi East and Kibwezi West, it is advisable to extend the research to include other rural areas in Kenya. This broader approach can offer a more comprehensive insight into the solar energy potential across the nation, allowing for the consideration of additional parameters such as solar declination angle, sunshine hours, dust storms, and cloud cover.
- ii. **Long-Term Monitoring:** Implement a system for long-term monitoring of the suitability map's recommendations. Regular updates and adjustments can help ensure the sustainability and relevance of solar energy projects over time. This would account for changes in key parameters such as improved road networks in the geographical area under investigation.
- iii. **Micro/ Mini Grid Development:** The feasibility of establishing microgrid systems in Kibwezi East and Kibwezi West based on this study can be explored. Such an initiative has the capacity to significantly improve energy access and reliability when executed effectively. Particular attention should be directed towards areas with the potential for economic activities that rely on a consistent supply of electricity.

- iv. **Infrastructure Development:** Investments in the necessary infrastructure, such as improved access roads and energy storage solutions, to make solar energy adoption more feasible in rural areas is encouraged.
- v. **Application of AHP:** It is further recommended to consider the continued use of the Analytical Hierarchy Process (AHP) in future suitability analyses, given its demonstrated effectiveness in assigning weights to parameters. This method can be applicable not only in studies conducted in different geographical regions but also in research exploring other renewable energy sources such as wind.
- vi. **Interdisciplinary Collaboration:** It is further recommended that interdisciplinary collaboration be encouraged between engineers and policymakers to implement the findings effectively. Cross-disciplinary efforts can help bridge the gap between research and practical application.
- vii. **Capacity Building:** It is recommended that key stakeholders consider investing in training and capacity-building initiatives aimed at empowering the residents of Kibwezi East and Kibwezi West with the necessary expertise to install, maintain, and repair solar energy systems. Such efforts, in conjunction with studies such as this one would not only promote the adoption of solar technology but also foster the creation of local employment opportunities, diminishing the need for external expertise and thereby enhancing self-reliance.

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# APPENDICES

## Appendix 1: Sample Questionnaire



### UNIVERSITY OF NAIROBI

#### DEPARTMENT OF ENVIRONMENTAL AND BIOSYSTEMS ENGINEERING

Dear participant,

I'm inviting you to participate in this study by completing this questionnaire. It is aimed at obtaining expert opinion on the factors that affect the location of suitable solar harvesting sites. It forms part of his thesis that is a requirement for the fulfilment of a Masters degree course in Environmental and Biosystems Engineering at the University of Nairobi.

This questionnaire will require at least fifteen minutes to complete. There is no circumstance under which you are obliged to respond to any of the questions. However, in doing you greatly assist me in my study. The data obtained from you is treated with utmost confidentiality and is solely for academic purpose.

The factors for this study are climatic, topographic and locational factors.

- a) Climatic factors- solar radiation and temperature.
- b) Topographic factors- aspect.
- c) Locational factors- land use/ land cover, slope and access to road network.

Each of the factors are defined below:

- a) Solar radiation- the electromagnetic waves emitted by the sun.
- b) Temperature- the degree of coldness or hotness of a place.
- c) Aspect- the direction a slope faces with respect to the direction of the sun.
- d) Land use/ land cover- the usage of land for various purposes and the features that occupy the land.
- e) Slope- the gradient of land.
- f) Access to road network- the proximity of a place from the nearest road network.

To perform suitability analysis, overlay analysis is to be done to create the Climatic Factor map, and Location Factor map. The two maps created are then used together with Topographic factor in an overlay analysis to create the final suitability analysis.

Multi Criteria Evaluation Analysis is used to identify how the factors in this study compare with one another in relation to solar harvesting mapping. The weights for the overlay analysis stated above are then computed from the pairwise comparison tables created from MCEA.

You are, therefore, required to compare how the factors affect the analysis in a scale of 1 to 9. The values of the scale are defined in the table in the next page:

Value	Definition	Description
1	Equal influence	Factors contribute equally to the suitability analysis
3	Moderate influence	Judgement slightly favours one factor over the other
5	Strong influence	Judgement strongly favours one factor over the other
7	Very strong influence	Judgement strongly favours one factor over the other and dominates it
9	Extreme influence	One factor has the highest possible influence there can be
2, 4, 6 and 8	Intermediate influence	

**Instructions**

- I. Tick the circle next to the factors that you feel is the most important in each of the three categories i.e., climatic factors, locational factors and final suitability analysis.
- II. Assign a value for that important factor.

1. Climatic factors

Solar radiation       Temperature      Weight =

2. Locational factors

Land use/ land cover       Slope      Weight =

Land use/ land cover       Access to roads      Weight =

Slope       Access to roads      Weight =

Multi Criteria Evaluation Analysis is used to identify how the factors in this study compare with one another in relation to solar harvesting mapping. The weights for the overlay analysis stated above are then computed from the pairwise comparison tables created from MCEA.

You are, therefore, required to compare how the factors affect the analysis in a scale of 1 to 9. The values of the scale are defined in the table in the next page:

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9	Extreme influence	One factor has the highest possible influence there can be
2, 4, 6 and 8	Intermediate influence	

**Instructions**

- I. Tick the circle next to the factors that you feel is the most important in each of the three categories i.e., climatic factors, locational factors and final suitability analysis.
- II. Assign a value for that important factor.

1. Climatic factors

Solar radiation       Temperature      Weight =

2. Locational factors

Land use/ land cover       Slope      Weight =

Land use/ land cover       Access to roads      Weight =

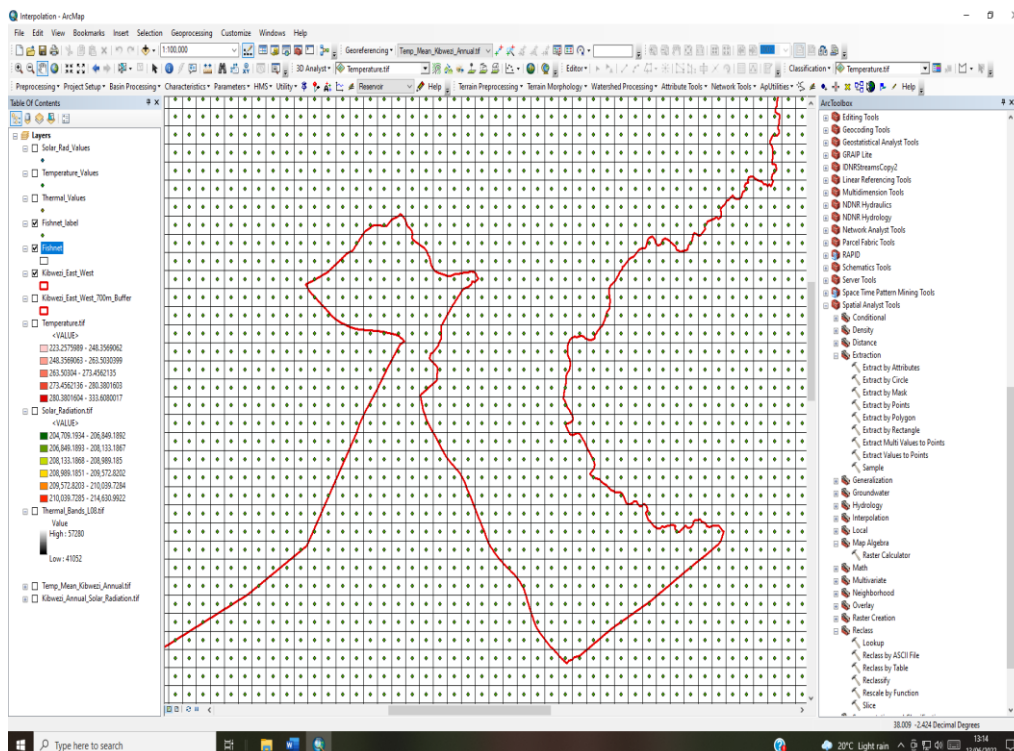
Slope       Access to roads      Weight =

## Appendix 2: Reviewed studies and parameter occurrences

PARAMETERS	Rumbayan et al, 2012	Sozen et al, 2005	Malik et al, 2009	Munkhbat and Choi, 2021	Soydan, 2021	Parameter Occurrence	WEIGHTS
Latitudinal extent	●	●				2	11.5
Sunlight duration	●	●			●	3	11.5
Month of the year	●	●				2	11.5
Solar radiation			●	●	●	3	7.7
Altitude		●		●		2	7.7
Land use/ land cover					●	1	7.7
Precipitation	●					1	7.7
Temperature	●	●		●		3	7.7
Power lines				●	●	2	7.7
Road access				●		1	3.8
Relative Humidity	●					1	3.8
Slope				●	●	2	3.8
Aspect				●	●	2	3.8
Earthquake					●	1	3.8

Parameters adopted
  Parameters eliminated

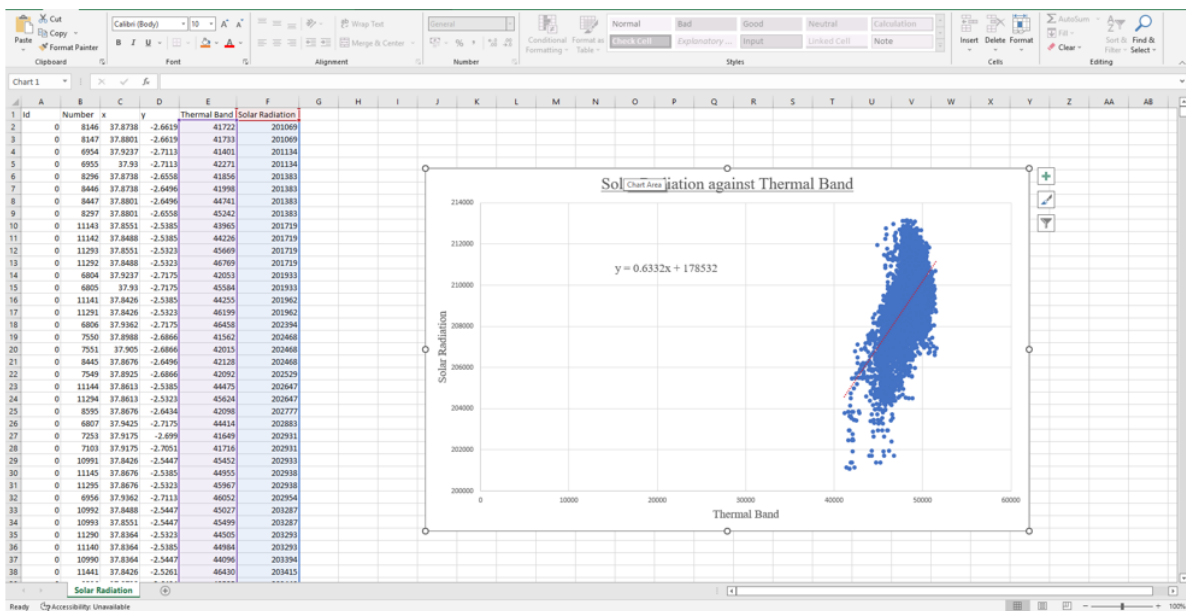
## Appendix 3: Fishnet/ rectangular cells created in ArcMap



## Appendix 4: The fishnet label shapefile loaded into QGIS

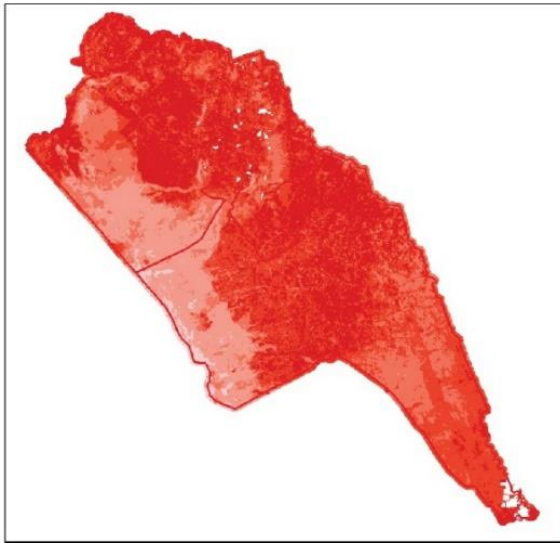
Id	Number	x	y
1	0	37.5930	-2.9952
2	0	37.5962	-2.9952
3	0	37.6055	-2.9952
4	0	37.6117	-2.9952
5	0	37.6179	-2.9952
6	0	37.6242	-2.9952
7	0	37.6304	-2.9952
8	0	37.6367	-2.9952
9	0	37.6429	-2.9952
10	0	37.6491	-2.9952
11	0	37.6554	-2.9952
12	0	37.6616	-2.9952
13	0	37.6679	-2.9952
14	0	37.6741	-2.9952
15	0	37.6803	-2.9952
16	0	37.6866	-2.9952
17	0	37.6928	-2.9952
18	0	37.6991	-2.9952
19	0	37.7053	-2.9952
20	0	37.7116	-2.9952
21	0	37.7178	-2.9952
22	0	37.7240	-2.9952
23	0	37.7303	-2.9952
24	0	37.7365	-2.9952
25	0	37.7428	-2.9952
26	0	37.7490	-2.9952
27	0	37.7552	-2.9952
28	0	37.7615	-2.9952
29	0	37.7677	-2.9952
30	0	37.7740	-2.9952
31	0	37.7802	-2.9952

## Appendix 5: Graph of Solar Radiation vs Thermal Band

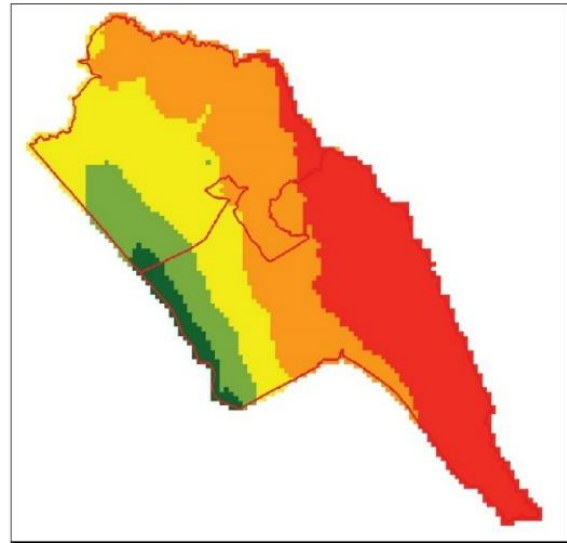


## Appendix 6: Resampled versus Original Temperature Map

Resampled (30m resolution)

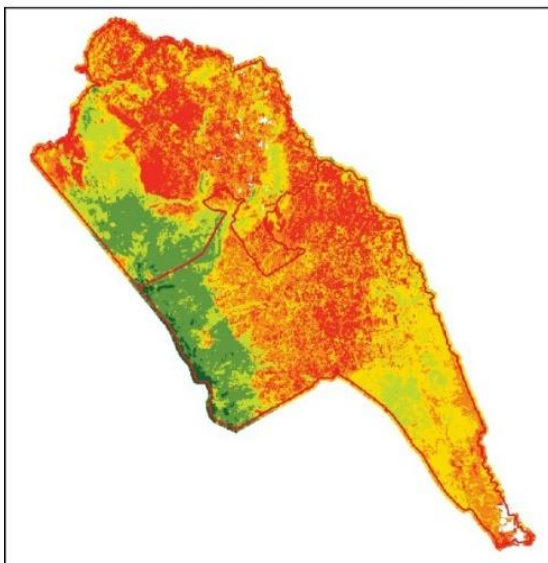


Original (1km resolution)

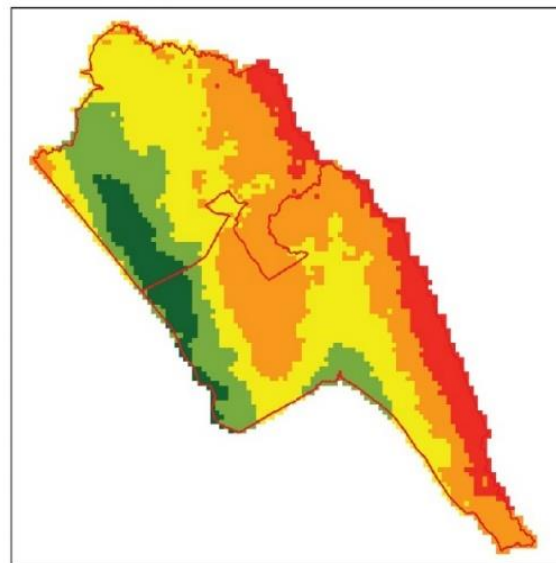


**Appendix 7: Resampled versus Original Solar Radiation Map**

Resampled (30m resolution)

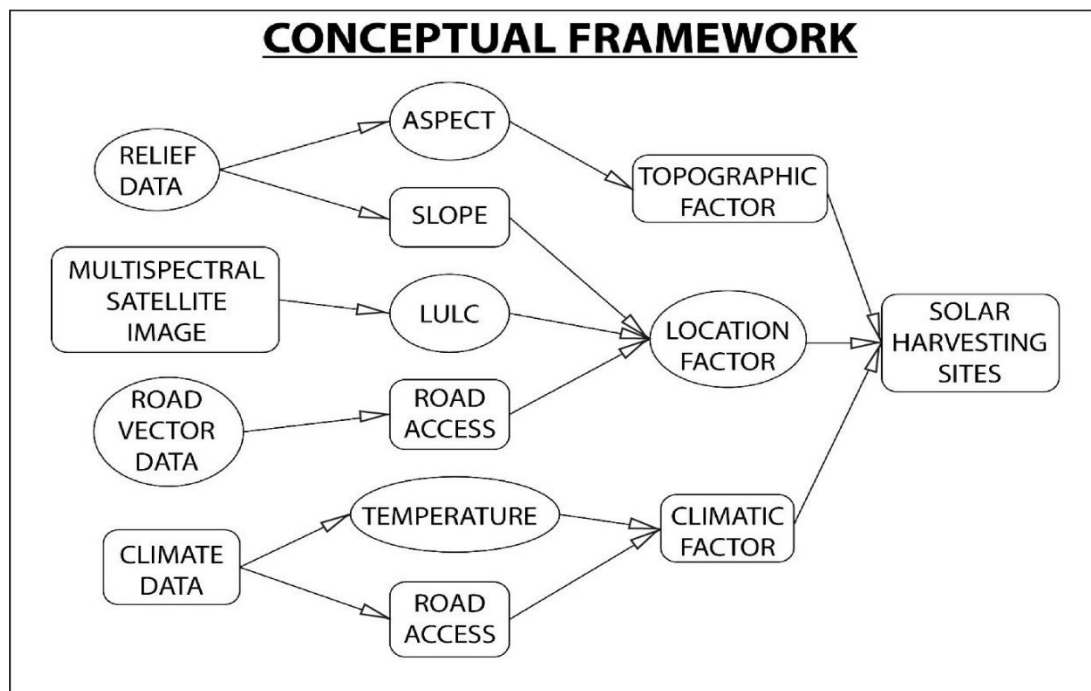


Original (1km resolution)

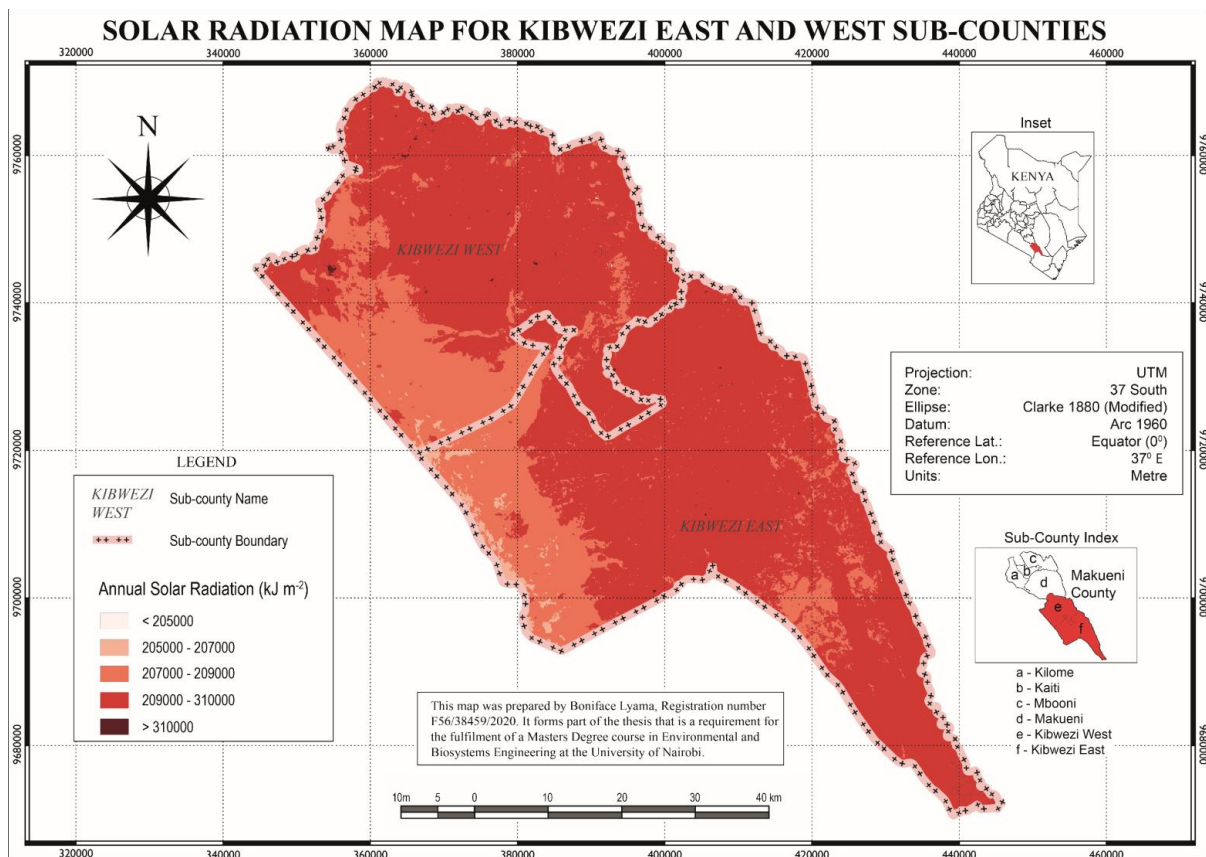




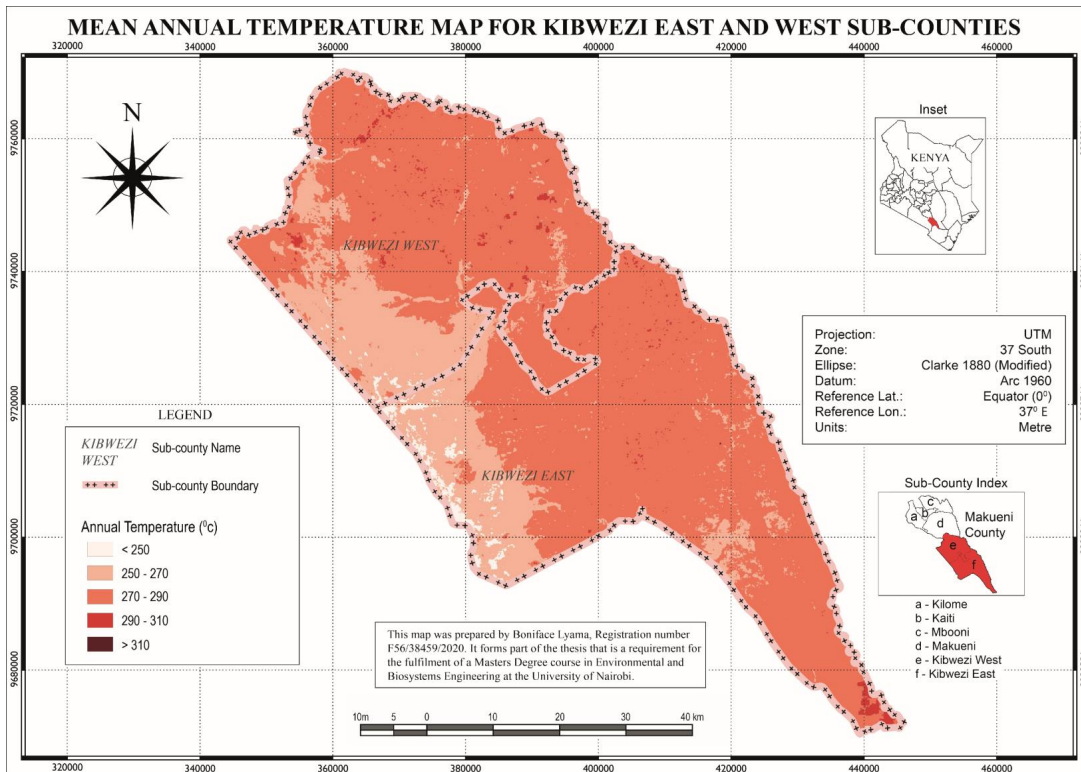
## Appendix 8: Conceptual Framework



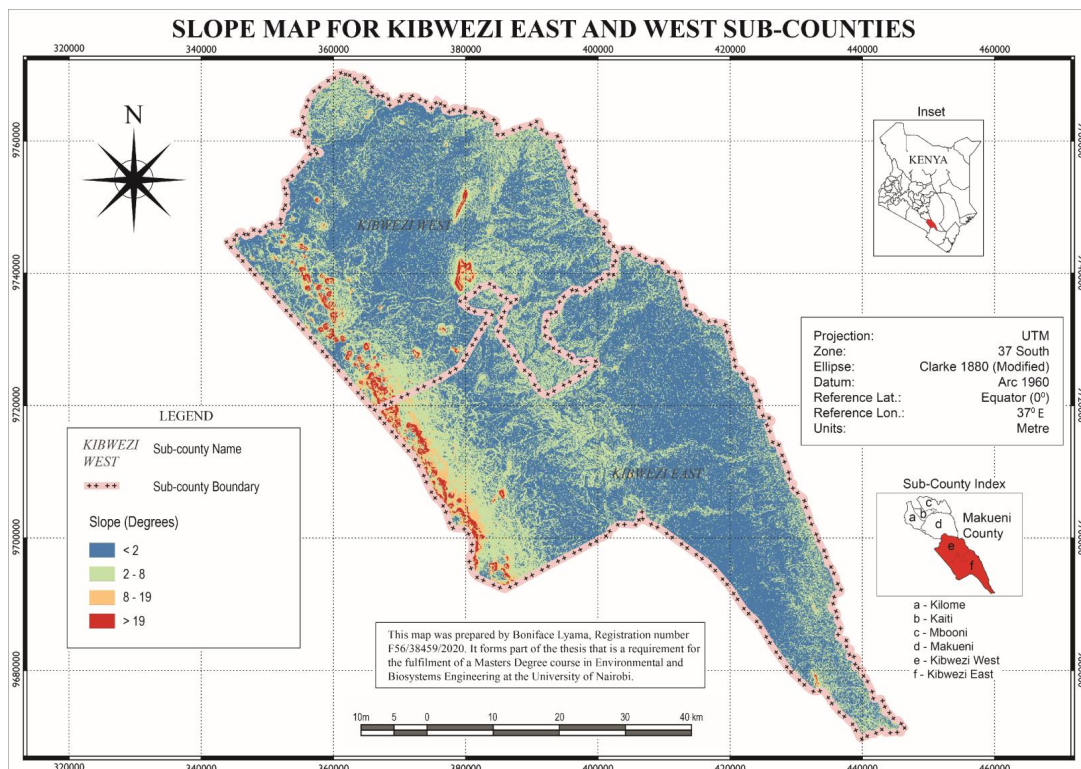
## Appendix 9: Solar Radiation Map



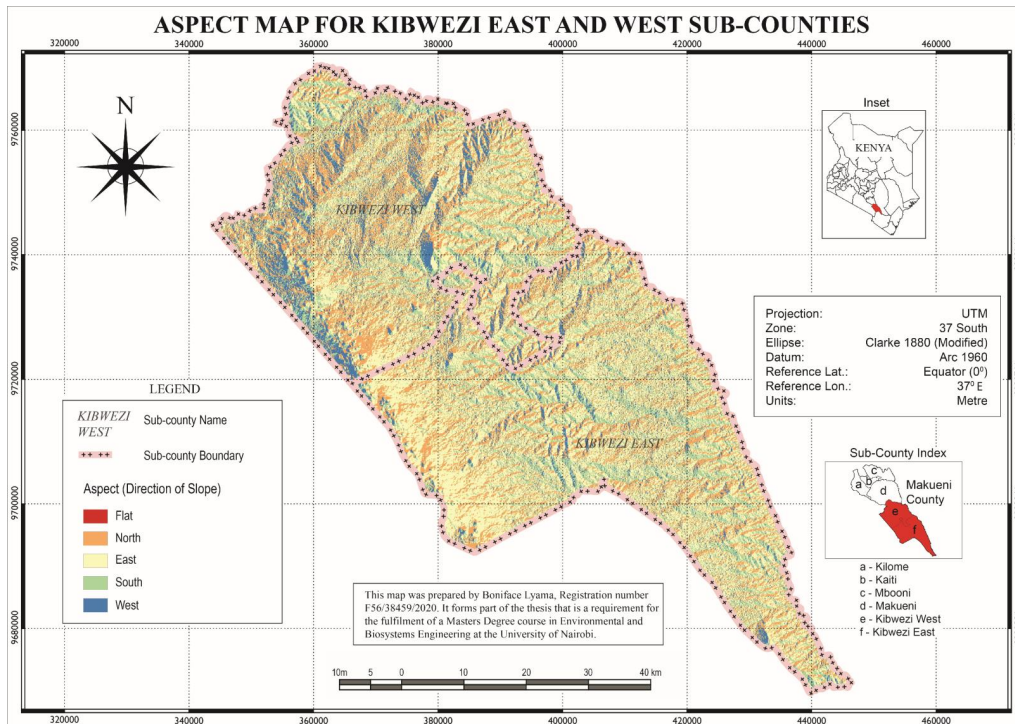
## Appendix 10: Raw Temperature Map



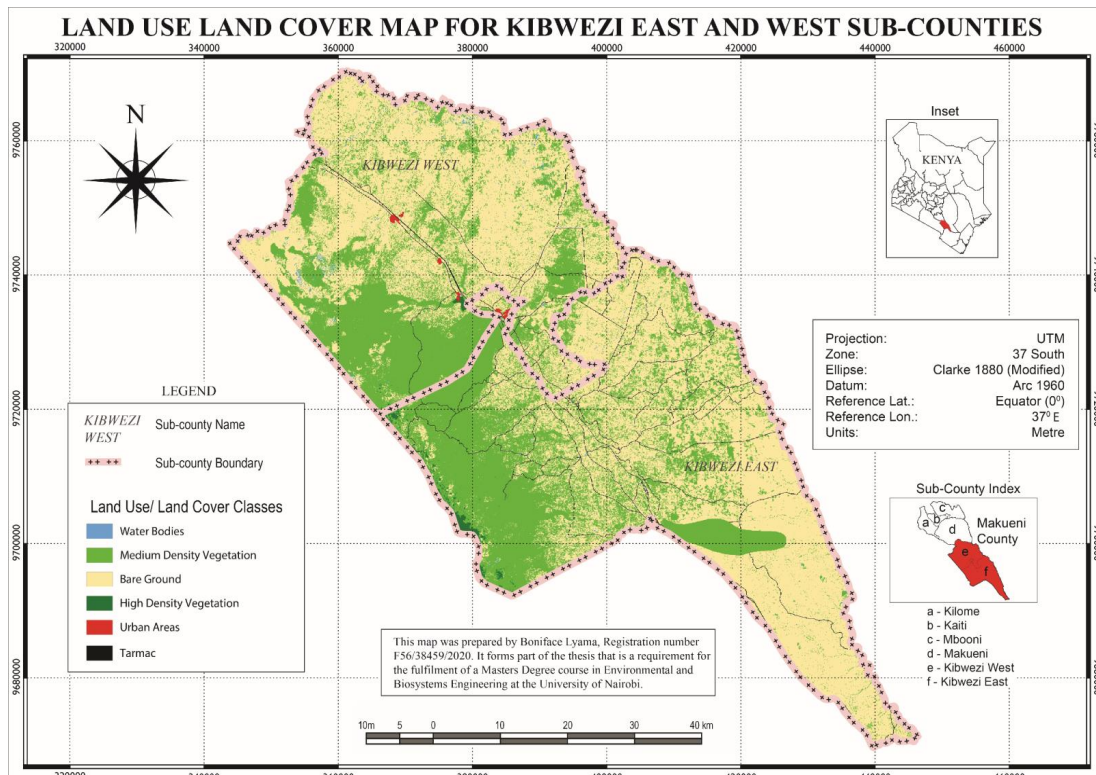
## Appendix 11: Slope Map



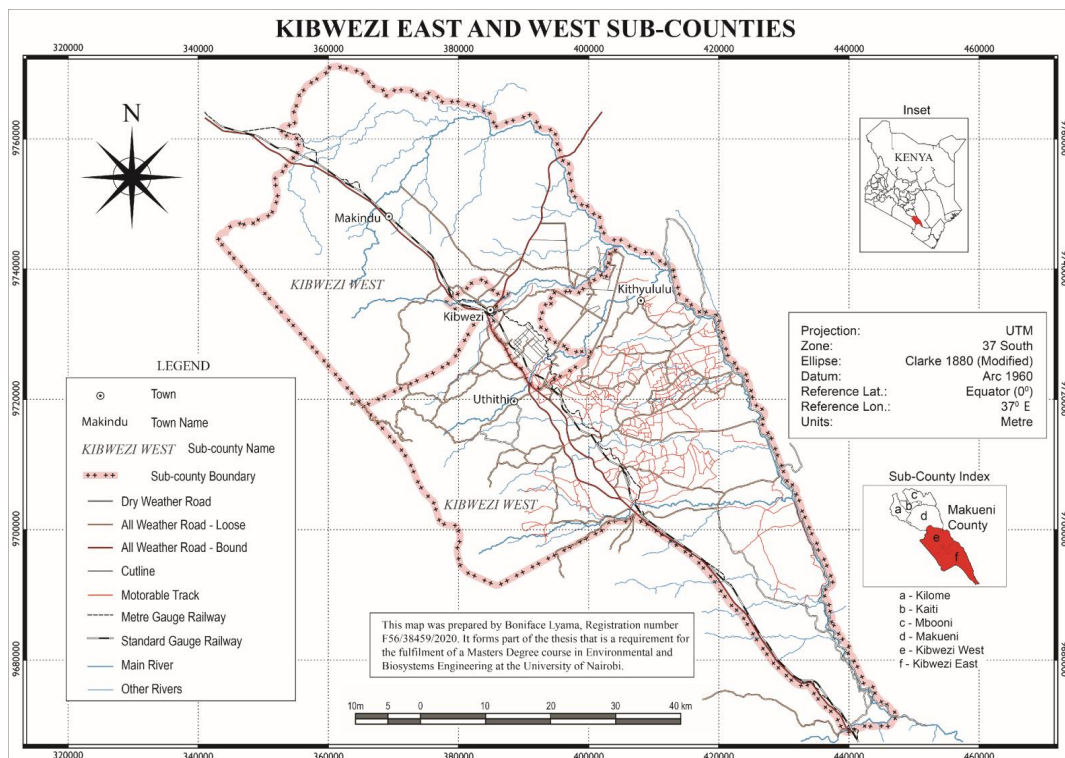
## Appendix 12: Aspect Map



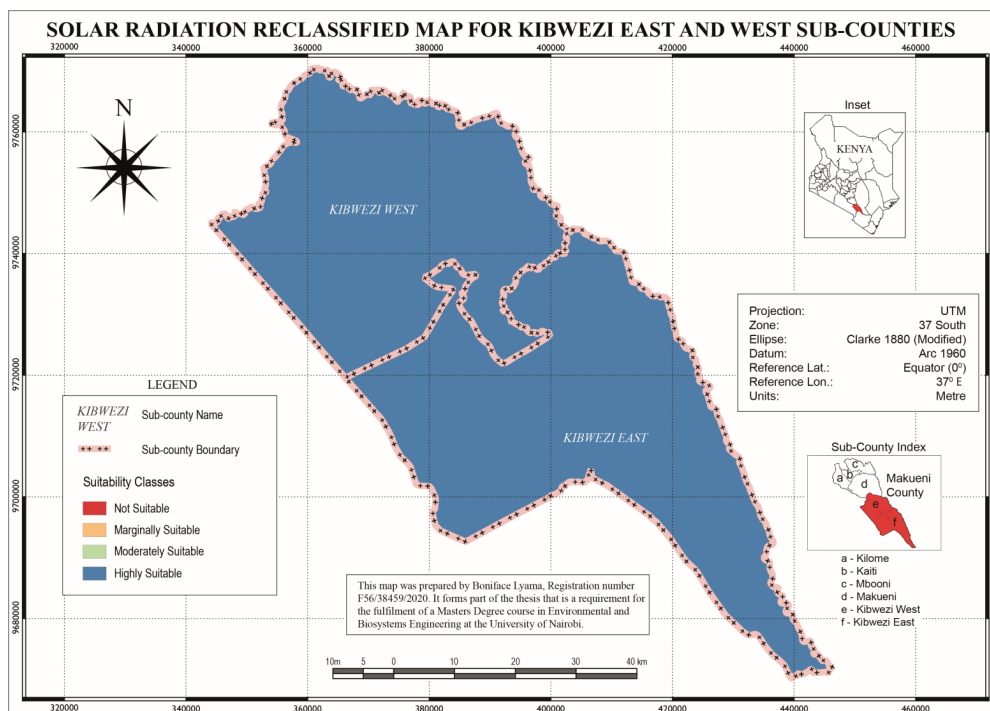
## Appendix 13: Land Use and Land Cover Map



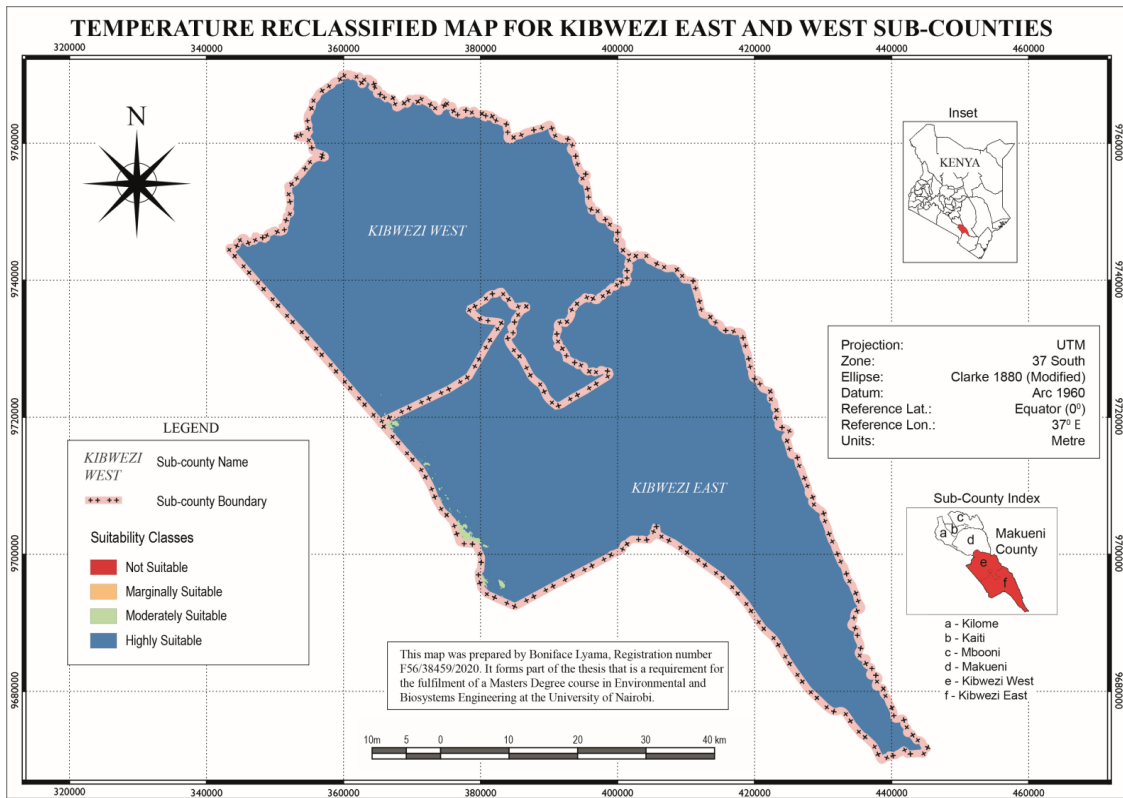
## Appendix 14: Road Access Map



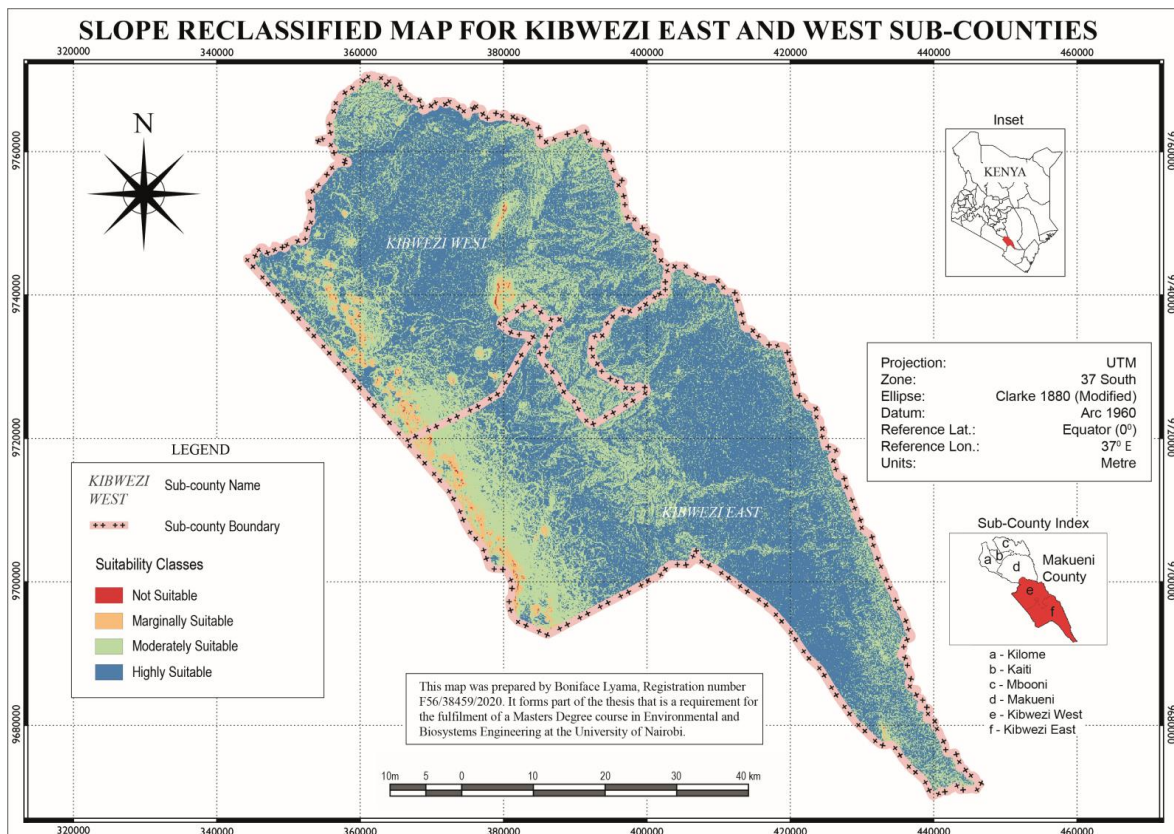
## Appendix 15: Reclassified Solar Radiation Map



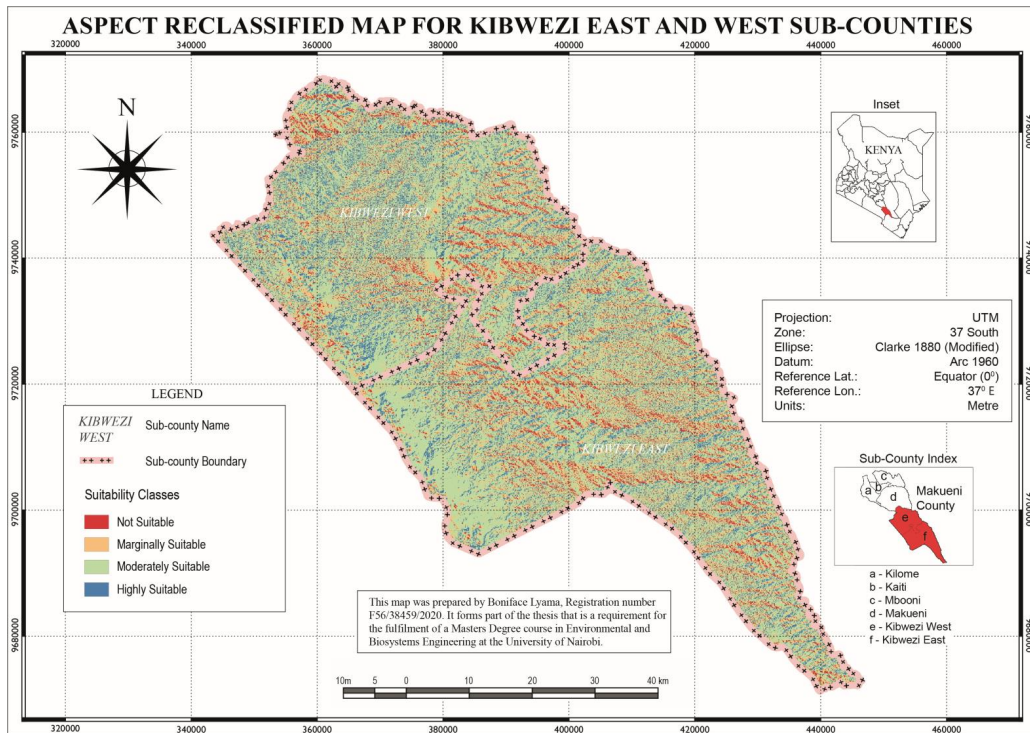
## Appendix 16: Reclassified Temperature Map



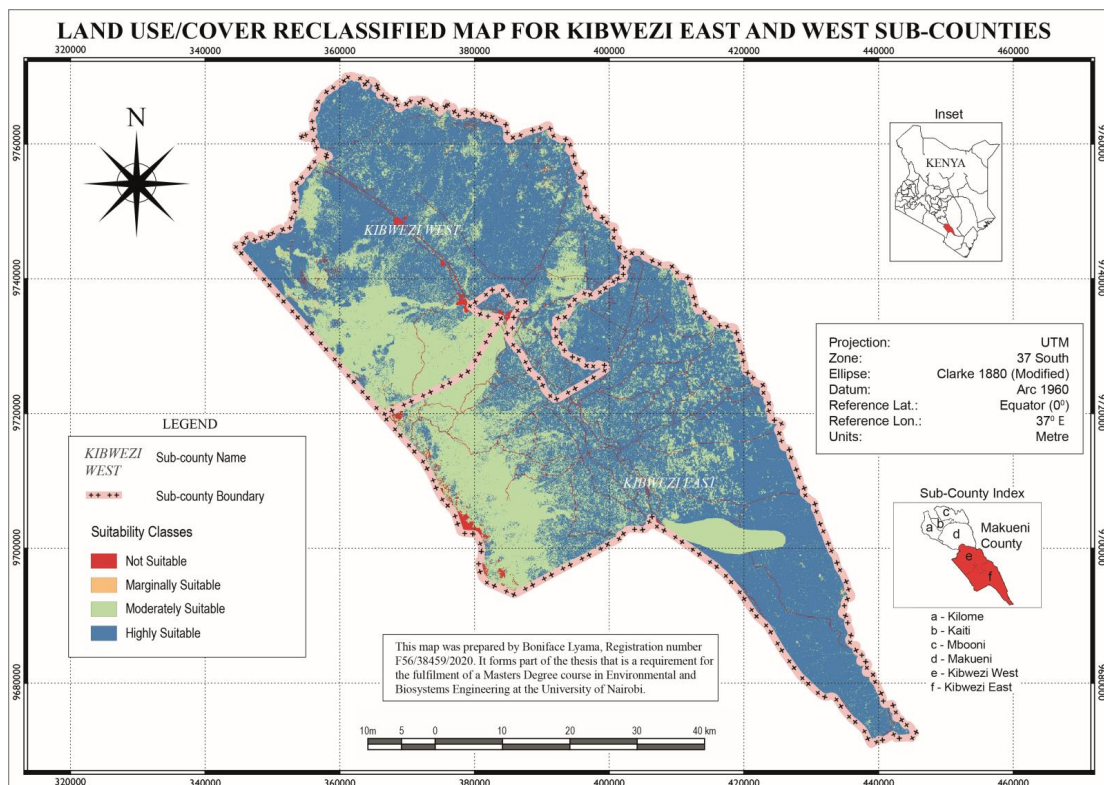
## Appendix 17: Reclassified Slope Map



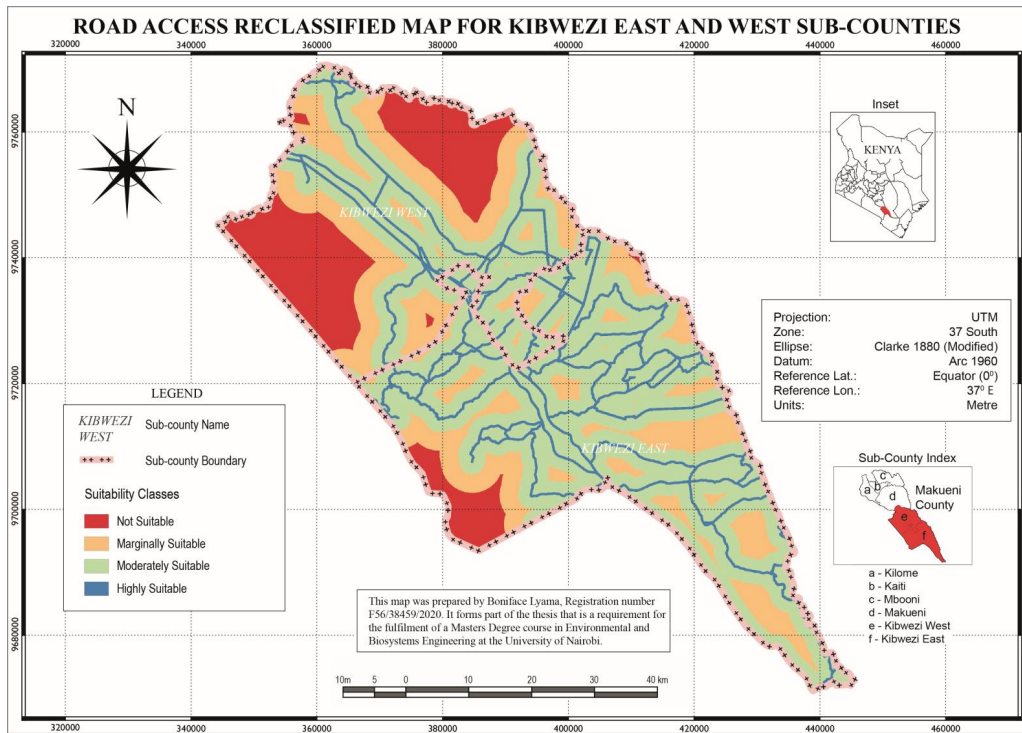
## Appendix 18: Reclassified Aspect Map



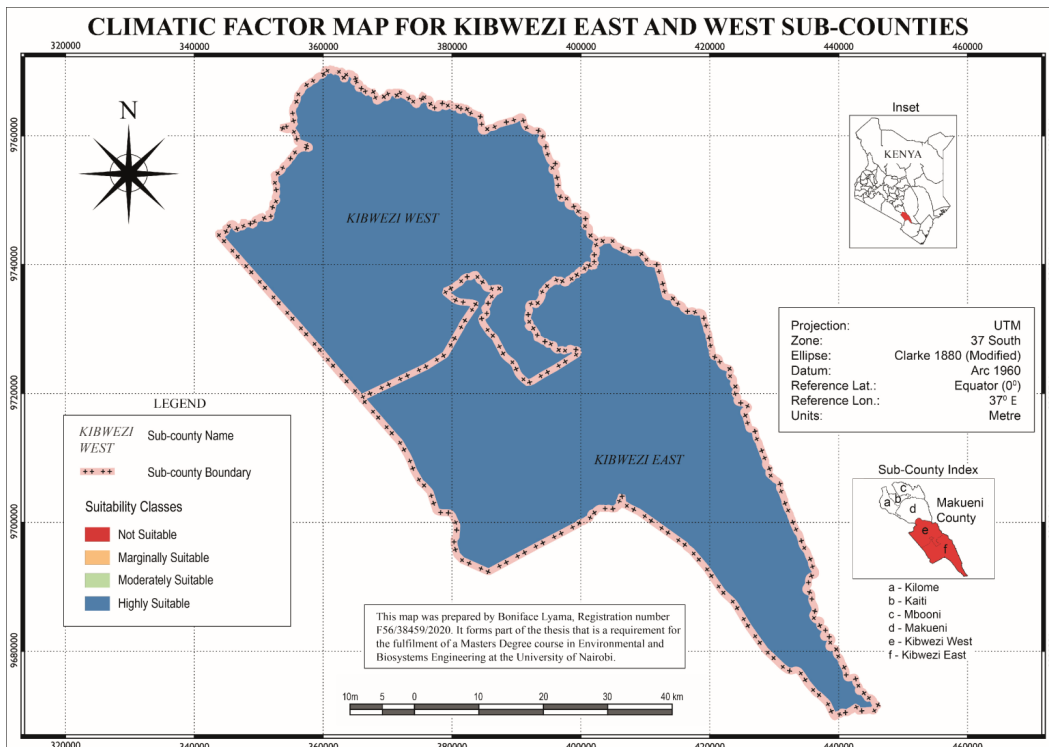
## Appendix 19: Reclassified LULC Map



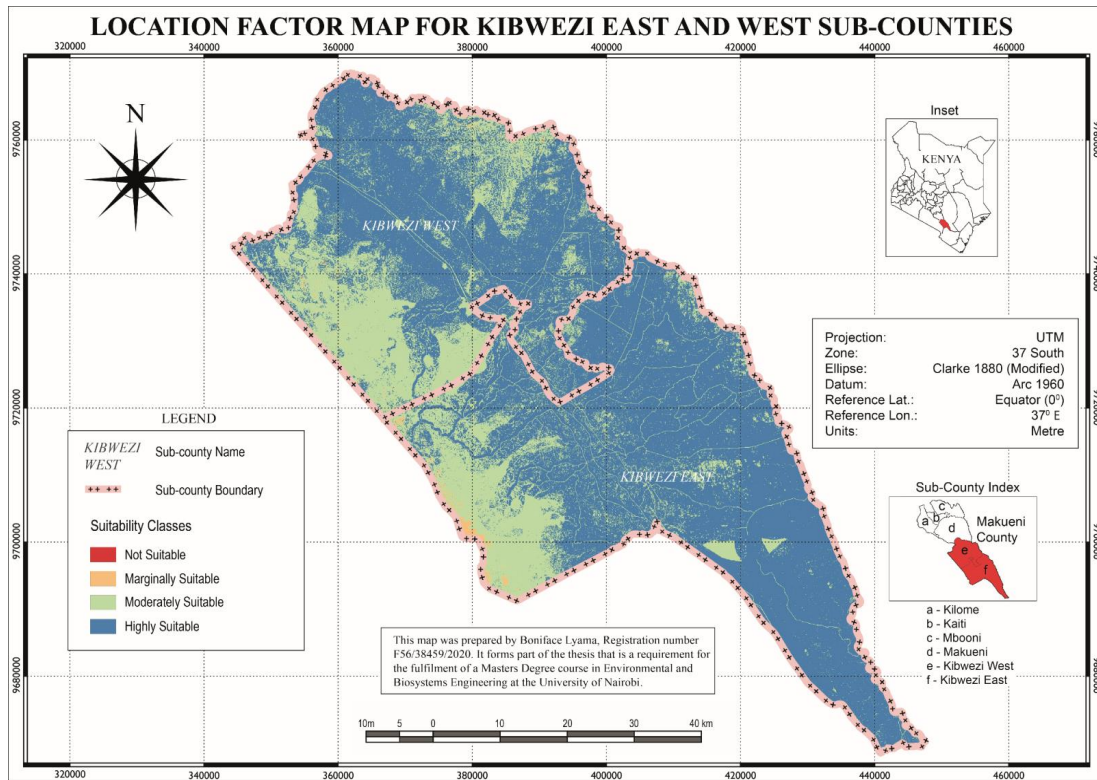
## Appendix 20: Reclassified Road Access Map



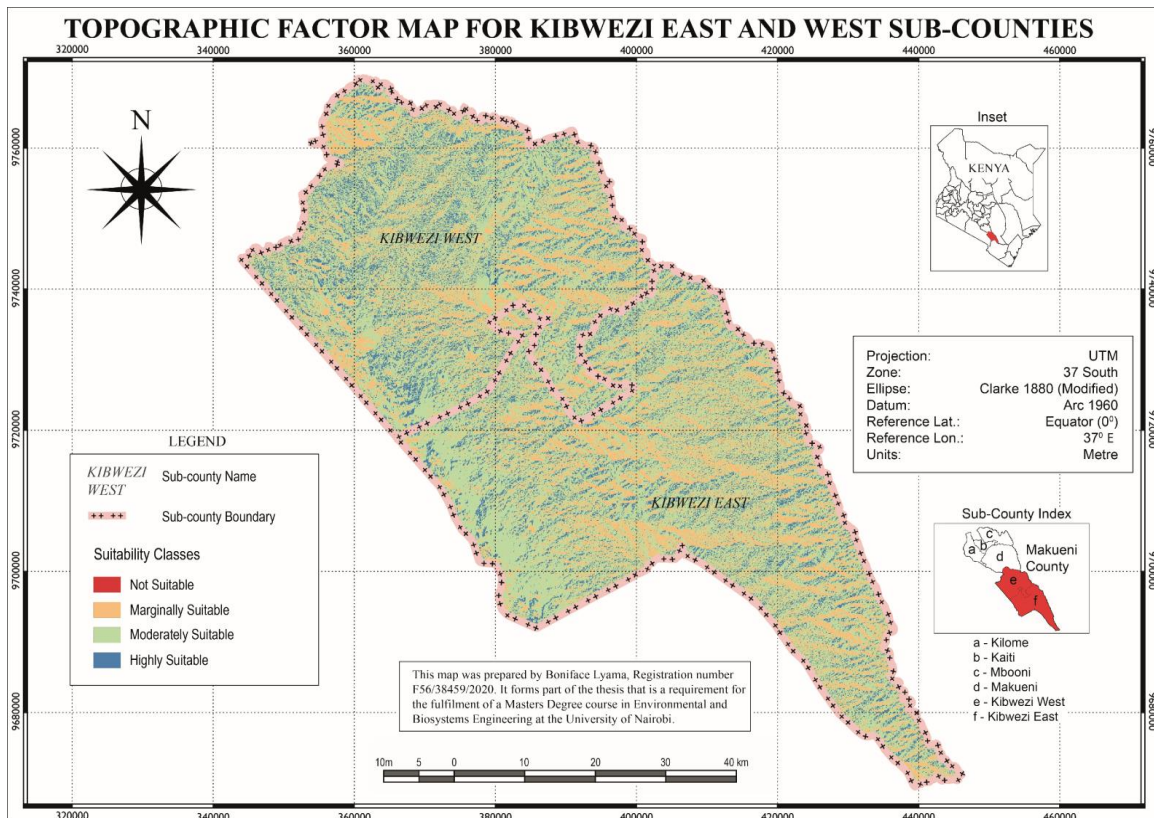
## Appendix 21: Climatic Factor Map



## Appendix 22: Locational Factor Map

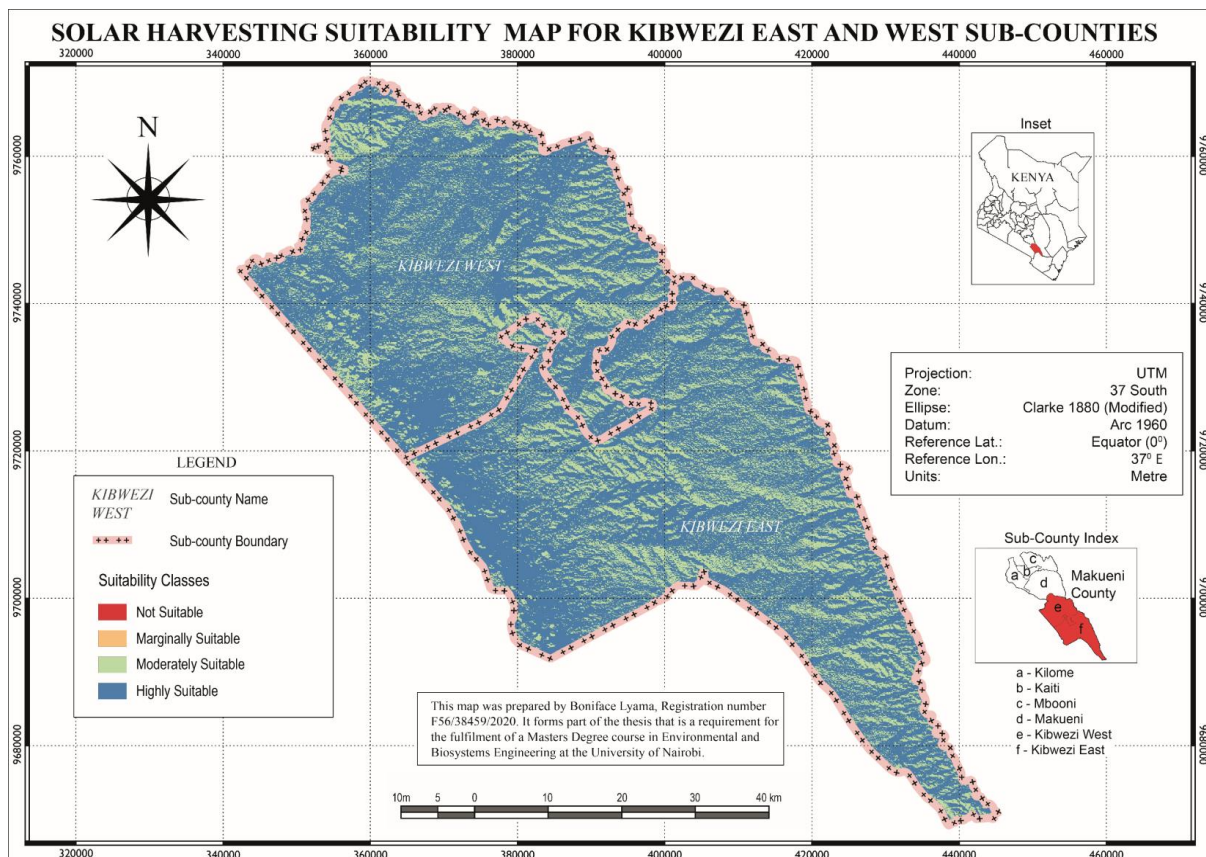


## Appendix 23: Topographical Factor Map






## Appendix 24: Final Suitability Map



# PLAGIARISM REPORT

11/29/23, 9:30 AM

Turnitin - Originality Report - Modelling suitability for solar harvesting

<p><b>Turnitin Originality Report</b></p> <p>Processed on: 29-Nov-2023 09:15 EAT          ID: 2241722988          Word Count: 14156          Submitted: 1</p> <p>Modelling suitability for solar harvesting By          Boniface Lyama</p>		 <p><b>29 Nov 2023</b></p>	
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<p>&lt; 1% match (Internet from 21-Jun-2023)  <a href="http://erepository.uonbi.ac.ke:8080/bitstream/handle/11295/162622/Sajome%20Wambui%20Kinjira-Dissertation.pdf?isAllowed=y&amp;sequence=1">http://erepository.uonbi.ac.ke:8080/bitstream/handle/11295/162622/Sajome%20Wambui%20Kinjira-Dissertation.pdf?isAllowed=y&amp;sequence=1</a></p>	
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