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Faculty of Engineering

DEPARTMENT OF GEOSPATIAL AND SPACE TECHNOLOGY

Using GIS for Site Suitability Analysis for Siting a Radio Telescope in Kenya

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Declaration

I, Ochieng Francis Omondi, hereby declare that this project report is my original work. To the best of my knowledge, the work presented herein has not been presented for a project in any other university.

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Name of Student	**Signature**	**Date**

This project report has been submitted for examination with my approval as the University supervisor.

Dr.-Ing. S.M. Musyoka	…………………………	22·08·2022
Name of Supervisor	**Signature**	**Date**

Abstract

Radio sources in the outer space emit radio signals which travel to the earth. Even though the radio signals are very weak, they are able to reach the earth's surface because they can penetrate dust in the atmosphere. However, because of constant man-made radio frequency interference, it is a challenge to detect them from any location. This is the reason why sites hosting radio telescopes are carefully chosen. Multiple-Attribute Decision Making (MADM) process of GIS based Multi-Criteria Decision Analysis (MCDA) was employed in the search for suitable sites. These sites are distributed across eighteen counties which are: Turkana, Marsabit, Mandera, Wajir, Isiolo, Samburu, West Pokot, Trans Nzoia, Bungoma, Baringo, Laikipia, Meru, Nakuru, Tana River, Narok, Kajiado, Nyeri, and Nyandarua counties. It is important to note that some suitable areas especially in counties that are along Kenya's boarder may not be suitable because of national security reasons, and varying anthropogenic conditions amongst neighbouring states. However, this reality was not factored in in this study which is recommended as an area for further research.

Whereas there are proposals from radio astronomy enthusiasts in Kenya to have Longonot Earth Station refurbished to a radio astronomy site as was with Ghana Radio Astronomy Observatory (GRAO), it is important to note that the defunct earth station currently suffers from higher RFI caused by increasing human settlement around the station as a result of the construction and operationalization of the Naivasha Inland Container Depot amongst other critical national infrastructure in the surrounding area. This study clearly shows that GIS can be applied in a MCDA to perform site suitability analysis in radio astronomy. It is recommended that further RFI, wind gradient, atmospheric dust, precipitable water vapour, and site suitability analysis be conducted in each suitable county.

Dedication

To the Ochieng's family.

Acknowledgement

I thank my parents and siblings for their tremendous support in this journey. Sincere gratitude to the Chair, teaching and non-teaching staff of the Department of Geospatial and Space Technology for being supportive throughout my study period at the University of Nairobi.

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List of Abbreviations

AHP	Analytic Hierarchy Process
ALMA	Atacama Large Millimeter/sub-millimeter Array
AVN	African Very Long Baseline Interferometry Network
CAK	Communications Authority of Kenya
CT	Computed Tomography
DARA	Development in Africa with Radio Astronomy
DEM	Digital Elevation Model
ESA	European Space Agency
ESSS	Earth Exploration Satellites Service
FAO	Food and Agricultural Organization
FAST	Five-hundred-meter-Aperture Spherical Telescope
GIS	Geographic Information System
GRAO	Ghana Radio Astronomy Observatory
GSSTI	Ghana Space Science and Technology Institute
ICD	Inland Container Depot
INISSE	International Institute for Space Sciences and Electronics
KETRACO	Kenya Electricity Transmission Company
KIRO	Kenya International Radio Observatory
KPLC	Kenya Power and Lighting Company
KSA	Kenya Space Agency
LEOP	Launch and Early Orbit Phase
LOFAR	Low Frequency Array
LULC	Land Use Land Cover
MADM	Multiple-Attribute Decision Making
MCDA	Multi- Criteria Decision Analysis
MCE	Multiple- Criteria Evaluation
NASA	National Administration Space Agency
NRAO	National Radio Astronomy Observatory
PWV	Precipitable Water Vapor
RCMRD	Regional Centre for Mapping of Resources for Development
RFI	Radio Frequency Interference
RQZ	Radio Quiet Zone

SKA	Square Kilometer Array
VLBI	Very Large Baseline Interferometry
VSAT	Very Small Aperture Terminal

CHAPTER 1: INTRODUCTION

1.1 Background

Nearly all astronomical objects in space emit radio signals. Those that emit stronger radio signals that enable them to be studied using radio telescopes are pulsars, nebulas, quasars and radio galaxies (Umar et. al. 2014).

Africa is increasingly becoming a blue-eye boy of the world in space activities, and specifically; radio astronomy. Africa is part of the Square Kilometer Array (SKA) project which is "an international effort in building the world's largest radio telescope with over a square kilometer of collecting area" (SKAO, 2022). SKA is a ground-based centimeter-wave radio telescope array. Its collecting area is10^6 square meters with baselines of up to 3000 kilometers (International Telecommunications Union, 2013), operating at frequency ranges of 100 MHz to 25 GHz (International Telecommunications Union, 2013), which relates to increased sensitivity factor of 100 greater than that of existing centimeter-wave radio telescopes. Such sensitivity will revolutionize the study of objects and phenomena which at the moment are undetectable at centimeter wavelength (National Research Council, 2001). It will also boost the study of the first structures and luminous objects that formed during the birth of the modern universe (National Research Council, 2001). South Africa's Karoo desert for instance, is hosting the nucleus of the high and mid frequency SKA dishes with an ultimate extension to Kenya and other seven African countries. The desert was selected because of sufficient scientific and technical reasons: atmospheric clarity and radio quietness. The project's other co-host is Western Australia's Murchison Shire, which is currently hosting the low-frequency antennas (SKAO, 2022).

Kenya has two major sites that are dedicated to space activities: Longonot Earth station in Nakuru County and Luigi Broglio Space Centre in Malindi, Kilifi County. Longonot Earth Station is under the management of Kenya Space Agency (KSA) which is mandated to "promote and coordinate space related activities in Kenya (Kenya Space Agency, 2022) whilst Luigi Broglio Space Centre is under a tripartite agreement between the Governments of Kenya and Italy (Kenya Space Agency, 2022).

The Longonot Earth Station is set in Kedong' valley which lies between Mt. Longonot, Mt. Suswa and the Kijabe escarpment. Kenya Port Authority's (KPA) Inland Container Depot (ICD) is also found in this area. It is located four kilometers, south-west of the Longonot teleport. The earth station was established in 1970 (Geography of Kenya, 2020). It aimed at connecting East Africa with the world via satellite technology. The first phase of the facility connected Kenya, Uganda and Tanzania to the world via the Atlantic Ocean. It was owned by the defunct East Africa Post and Telecommunications. Being that Kenya is strategically located along the Equator, this enabled it to host telecommunications infrastructure that enabled communication with satellites in both the northern and southern hemisphere (Geography of Kenya, 2020).

Kenya had earmarked the 32 meter Longonot dish for conversion to a radio telescope before the SKA. With its conversion, the radio telescope is expected to be part of a continental wide network of radio telescopes called the African Very Long Baseline Interferometry Network (AVN) (Technical University of Kenya, 2022), with Professor Paul Baki of the School of Physics and Earth Sciences at Technical University of Kenya taking lead. However, it is worrying to note that the teleport has been vandalized (Osoro, 2020) with telecommunication companies setting up their masts next to the facility.

Malindi town in Kilifi County hosts the Luigi Broglio Space Centre which was established in 1962 through a collaboration between Italy and the Government of Kenya. The Malindi site was most probable since it has the combination of being on the East Coast of the continent, and it also lies on the Equator. Its location in Unguana Bay in Ngomeni Village in Magarini makes the site a perfect location for launching and tracking equatorial rockets and satellites. Further, the area possesses unique magnetic anomalies, thus making it the most suited place for carrying out tests that would otherwise be affected by the earths' magnetic fields. (Kimani, 2017). Since its establishment, the Luigi Broglio Space Centre, has recorded 20 successful rocket launches. The notable recent activity at the station was the picking of the first signals from James Webb Space Telescope operated by National Administration Space Agency (NASA) while on its 1.5-million-kilometer journey to its destination in the outer space (Kinyanjui, 2021). This is an example of a Tripartite activity where the station offers support for European Space Agency (ESA) in rocket launches from Kourou, French Guyana. The space station also offers support to Kenya's national programs in Telemetry Tracking and Control of Satellites (AGILE, SWIFT, NuSTAR) and Third-Party Support for Chinese Missions (Shenzou and Tiangong) and Kongsberg Satellite Services ASNARO Launch and Early Orbit Phase (LEOP). The site is also being used as a data acquisition site for remotely sensed data for ASI- COSMOS, SkyMed, NASA, NOAA, ESA and CBERS, (Kimani, 2017).

As discussed above, it is evident that a new site be selected for setting up a radio telescope in Kenya. For instance, the Longonot station is not radio quiet and the Luigi Broglio Space Centre suffers from atmospheric noise because of its coastal location. This study aims at applying Geographic Information System (GIS) technology as the main decision-making tool for finding potential sites for siting a radio telescope as a base study for setting up future radio observatories in Kenya.

Data layers used in this study for site selection are classified into two groups: anthropogenic and geographic datasets. Anthropogenic datasets are: cell-tower data, and Kenya's national electricity grid data. Geographic datasets are: rainfall, Land Use Land Cover (LULC), wind speed, and Digital Elevation Model (DEM).

1.2 Problem Statement

The antennas at the Longonot Earth Station were primarily used for telecommunication purposes. The advent of Very Small Aperture Terminal (VSAT) satellites whose dish-like type are much smaller than the teleport's antennas rendered Longonot Earth Station moribund (Oduo, 2020). This abandonment has led to vandalism of the metal parts of the antennas and other infrastructure at the station. Furthermore, there are proposals from space and astronomy enthusiasts in Kenya to convert the site to a radio astronomy research centre, with Kenya Space Agency taking lead. However, it is not established by use of geospatial methods whether the Longonot Earth Station, presently, is suitable for hosting a radio telescope.

Additionally, Kenya is also a member of the SKA project which aims at having the longest baseline of telescopes for astronomical observations. It is against these backdrops that it is imperative that a suitable site(s) for siting a radio telescope in Kenya be identified. The purpose of this study, therefore, is to identify suitable area(s) for siting a radio telescope in Kenya using GIS.

1.3 Objectives

1.3.1 Main Objective

The main objective of this study is to demonstrate how GIS can be applied in a multi-criterion suitability analysis for siting of a radio telescope in Kenya.

1.3.2 Specific Objectives

a) To establish the criteria for siting a radio telescope
b) To collect relevant geospatial data for the study
c) To generate suitability maps showing optimal areas for siting a radio telescope in Kenya

1.4 Justification for the study

Radio signals from celestial sources are very weak by the time they reach the earth since they travel long distances from the outer space. With increased Radio Frequency Interference (RFI) from man, radio astronomy studies continue to face critical problems. The Communications Authority of Kenya in its Fourth Quarter Sector Statistics Report for the Financial Year 2019/20 notes that, as at June 30th 2021, mobile subscriptions in Kenya were at 64.4 million as compared to 57.0 million as at June 30th 2020. This translates to mobile (SIM) penetration of 132.2 percent as at June 30th 2021 when compared to 119.9% penetration as at June 30th 2020 (Communications Authority of Kenya, 2021). This is a critical indicator that RFI interference in the country is on the rise since. It is therefore imperative that a radio quiet area that also meets minimum geographic conditions be selected for siting a radio telescope in Kenya.

1.5 The Scope of Work

The scope of work for this study included a reconnaissance mission to Longonot Earth Station and Luigi Broglio Space Centre, elimination of built-up areas, mountains, and critical infrastructure zones from land-use-land-cover dataset. The pre-visit to Longonot Earth Station and Luigi Broglio Space Centre was done from 24th to 30th April, 2022. The aim of the pre-visit was to familiarize with the current locations where space activities have been dedicated to and to seek data collection permission from authorities mandated with the management of the sites before carrying out the research.

The reconnaissance mission was followed by primary data collection from the space stations and secondary collection and collation of data from relevant authorities including Kenya Power and Lighting Company (KPLC), Kenya Electricity Transmission Company (KETRACO) Communications Authority of Kenya (CAK), Kenya Meteorological Department, and Kenya Space Agency (KSA).

The collected data was analyzed, and the results interpreted, and conclusions drawn. Vector and raster datasets were integrated in a GIS environment; ArcGIS 10.8 was used for processing to determine the suitable sites for siting a radio telescope.

CHAPTER 2: LITERATURE REVIEW

The discussions in this chapter focus on radio astronomy and GIS. The sub-sections of this chapter discuss: 1) Radio astronomy and Radio Telescopes; 2) Factors affecting radio observations; 3) Benefits of Radio Astronomy; 4) Trends in Radio Astronomy; 5) Radio Astronomy efforts in Kenya; and 6) GIS.

2.1 Radio Astronomy and Radio Telescopes

Astronomy is the "study of the objects that lie beyond our planet Earth and the processes by which these objects interact with one another" (Fraknoi, Morrison and Wolff, 2016). Radio astronomy on the other hand is the study of natural radio waves from celestial sources in the depths of space (Verschuur, 2015; Condon and Ransom, 2016).

Astronomy is argued to be the oldest of all the sciences (Morison, 2008). What distinguishes astronomy from all the other sciences is the impossibility of conducting astronomical experimental tests in the laboratory. Instead, an astronomer observes only what is seen in the universe and checks whether these observations align with theories that have been set forth. The existence of extreme states of matter in the universe that cannot be created on earth allows astronomers to test key scientific theories such as the Theory of General Relativity by Albert Einstein (Morison, 2008).

For the longest time, humans depended on the evidence presented by the senses to have a picture of the universe, that is, all observations were in the visible part of the electromagnetic spectrum (Kraus, 2005;), optical astronomy. With advancements in wonder and the desire to see the universe deeper and clearer, telescopes were invented. It is Galileo Galilei who pioneered modern scientific concepts of observation, experimentation, hypothesis testing through careful quantitative measurements (Fraknoi, et al., 2016). It is in the last seven decades that astronomical observations started to be made in the radio wavelength, thus creating a branch of astronomy called radio astronomy (Kraus, 2005).

Radio astronomy involves observation of the universe on the radio band of the electromagnetic spectrum. This is because, most of the celestial objects that do not emit light, emit radio waves (Lockman, 2017). These observations can be done from the ground or space by use of radio telescopes which are special devices designed to receive radio signals emitted by extraterrestrial sources from space.

Ground-based radio telescopes can exist in singularity or in an array. An example of a ground-based telescope in singularity is the Five-hundred-meter-Aperture Spherical Telescope (FAST) in Guizhou province in China (see Figure 1). An example of an array of radio telescopes is SKA (see Figure 2) while RadioAstron (see Figure 3) is an example of a space-based radio telescope.

Figure 1: *An aerial image of FAST Telescope in China*

Source: www.nature.com

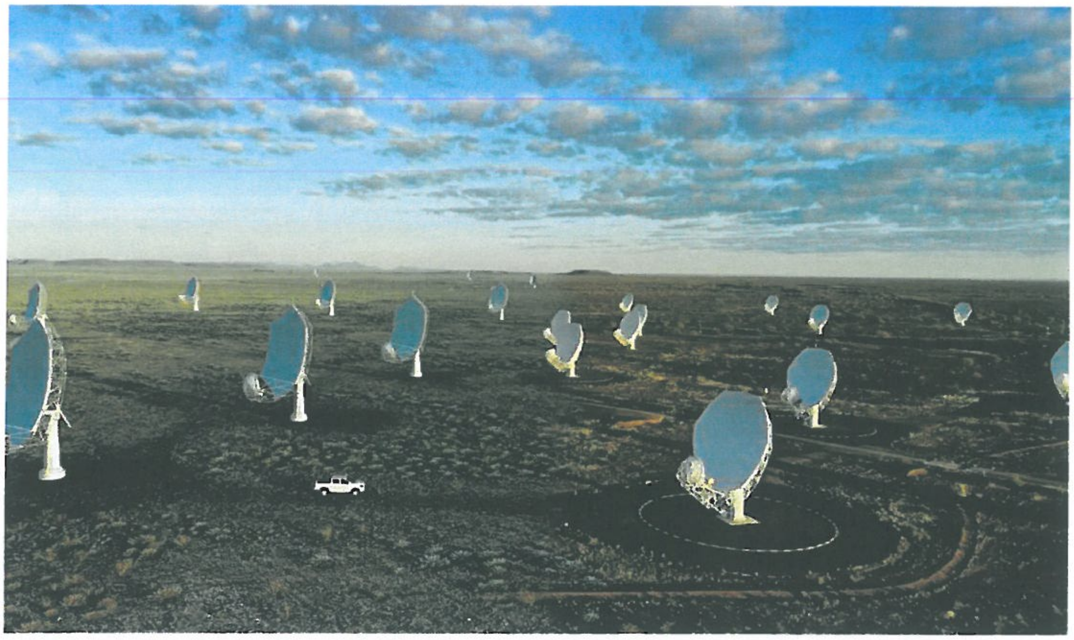

Figure 2: *An array of radio telescopes of the SKA Project.*

Source: *www.skatetelscope.org*

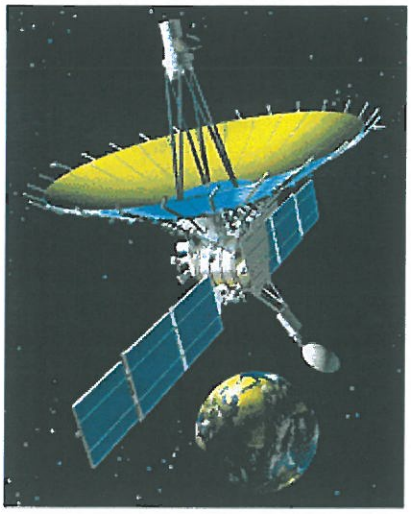

Figure 3: *Front view of RadioAstron space telescope*

Source: *www.asc.rssi.ru/*

Lockman (2017) identifies two main reasons behind the study of radio waves from celestial sources:

i. To accommodate celestial sources, for example, pulsars, that release radio waves but do not release or reflect light. Pulsars are remnants of an explosion of a star or stars when they die

ii. Radio waves can pass through the dust that is in the interstellar space as compared to light

The earth's atmosphere is transparent to both light and radio signals, thus making it possible to do radio observation from the earth's surface (Lockman, 2017). However, it is important to note that cosmic radio signals reaching the earth's atmosphere competes with radio waves produced by radio and TV transmitters, FM, satellite, radar and cell phones. This demands use of powerful radio telescopes to detect the faint radio signals from celestial sources which contain deep insights into the early universe. These telescopes are often located in remote locations far away from urban centers which relate to minimized man-made radio frequency interference (Lockman, 2017).

There is a difference in visual and radio images of celestial bodies (see Figures 4 & 5).

Figure 4a: *Image of planet Jupiter in Visible light*
Source: (Lockman, 2017).

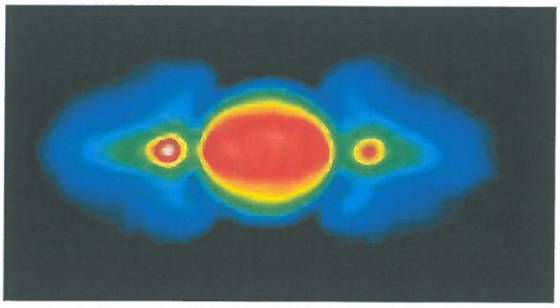

Figure 4b: *Radio Image of planet, Jupiter*
Source: (Lockman, 2017).

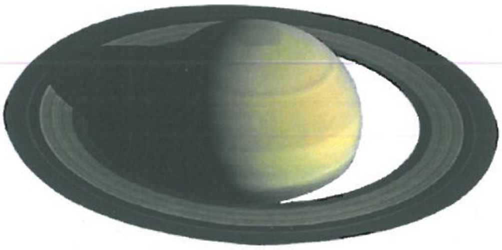

Figure 5a: *Image of planet Jupiter in Visible light*
Source: (Lockman, 2017).

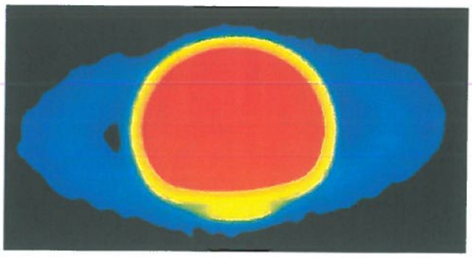

Figure 5b: *Radio Image of planet, Jupiter*
Source: (Lockman, 2017).

As shown in Figures 4a, 4b, 5a and 5b above, radio signals are colored to depict their intensity; red shows high intensity and dark blue shows the faintest intensity (Lockman, 2017).

In radio telescopes, the size of the telescope's aperture is of more importance than the depth or shape of a radio telescope since it affects the amount of radio waves that is collected (Lockman, 2017). Aperture size can be simply explained as the opening of the radio telescope's aperture.

The intensity of radio waves is the "power of radio waves that pass through an aperture of 1 square meter in 1 second in a bandwidth of 1 hertz" (Lockman, 2017). The intensity is measured in Janskys, named after Karl G. Jansky who was the first person to discover radio signals from space.

The intensity of radio signals is measured as:

$$1 \text{ Jansky} = 10^{-26} \text{ Watts/square meter/ hertz}$$

As seen above, that is a very small amount of energy in comparison to a standard cell phone which emits a radio signal of about 5×10^{15} Janskys which is stronger than a radio signal from a bright quasar. Currently, celestial objects are producing radio signals that are in millijanskys and microjanskys; the radio signals are a million times weaker than a jansky (Lockman, 2017).

To enable detection of such faint radio signals, it means that, the aperture of a radio telescope should be wide enough to a tune of several square meters (Lockman, 2017).

2.2 Factors affecting radio observations

The best site for hosting a radio observatory is one that has very low precipitable water vapor (PWV) and minimal Radio Frequency Interference (RFI); Radio Quiet Zone (RQZ) (Witt, *et. al.*, 2016). RFI interference can be caused by geomagnetic effects on ground systems and cell towers and TV & radio transmitters amongst other man-made sources as expounded below.

a) Geomagnetic effects on ground systems

Changes in the earth's magnetic field is caused by changes in velocity and density of solar winds. These changes generate an electric current on power lines, pipelines, and telephone cables. The generated electric current can be picked by a radio telescope as a signal, thus lowering the quality of the telescope's results (International Telecommunications Union, 2013).

b) Cell towers and TV & Radio transmitters because they cause RFI
c) Rainfall / precipitation reduces radio propagation. Water in the atmosphere affects radio penetration by either reflecting, refracting or attenuating radio signals (Masong and Pobre, 2017).

A radio quiet zone is defined as "any recognized geographic area within which the usual spectrum management procedures are modified for the specific purpose of reducing or avoiding interference to radio telescopes, to optimize the environment in which radio observations are carried" (International Telecommunications Union, 2013).

It is important to note that most restrictions that are implemented in RQZ do not include transmissions from air or satellites. This is because, radio interference that emanates from moving objects, specifically aeronautical sources, are usually for a short time such that, by the time the interference is detected, the source causing the interference will be out of the observable region the radio telescope is observing (International Telecommunications Union, 2013).

With all these restrictions, a RQZ implies coexistence with a range of man-made devices but not the total absence of radio transmissions. This means that a RQZ is a buffer zone that "allows for the implementation of mechanisms to protect radio astronomy observations from detrimental RFI, through effective mitigation strategies and regulation of radio frequency transmitters" (International Telecommunications Union, 2013).

Where possible, no-fly zones above radio observatories should be gazetted to minimize significant interference to radio observations by aircrafts (International Telecommunications Union, 2013).

The Communications Authority of Kenya (CAK) is the body mandated with frequency allocation in Kenya. As published in CAK national frequency allocation table 2020 report, radio astronomy service in Kenya has been allocated 150.05-153.0 MHz. Frequency bands of 1660.5 – 1668.4 MHz have also been allocated to K131 radio astronomy and passive space research with zero emissions (Communications Authority of Kenya, 2020).

Further, a radio observatory should be set in locations that are far from heavily populated areas and in areas that offer natural shielding. Valleys are highly recommended because they offer natural shielding from far away TV & radio transmitters especially if the transmitters operate within the frequency range of radio telescopes. Also, a transmitter can be allowed in a RQZ as long as the received signal does not exceed a specified interference threshold, that is, the set frequency range in the RQZ (International Telecommunications Union, 2013).

When allocating frequencies, it is important to ensure that the frequency range allocated to operations of RQZ be in line with the protected operations of astronomical instruments within it.

The impact of RFI on Radio Astronomy Observations

a) RFI increases the signal to noise levels
b) Excessive RFI can also destroy the receivers of a radio telescope

Having discussed these important factors affecting radio transmissions, the next section discusses the benefits of radio astronomy.

2.3 Benefits of Radio Astronomy

Radio astronomy has birthed a lot of useful technologies today, thanks to advancements in its receiver and digital technology. Some of the benefits of research in radio astronomy, which have been incorporated in various applications, are discussed below.

a) Telecommunications

Radio astronomy technology has been applied in telecommunications' receiver systems and antenna technology.

In receiver systems, unique requirements of radio astronomy necessitated the development of parametric amplifiers, HEMT amplifiers and SIS Mixers which made receiver systems to operate at very wide bandwidths and extremely low temperatures like 2 kelvins (International Telecommunications Union, 2013). These technologies have been incorporated in most of deep space telecommunication systems which have enabled their onboard oscillators to be synchronized in time at sub-picosecond levels by standards of atomic frequency. These guidelines are being used as the main backbone for both terrestrial and space navigation time-keeping systems (International Telecommunications Union, 2013).

Satellite transmitters use circularly polarized feed horns to transmit polarizations via one feed horn thus huge savings in both package mass and space. This was inspired by radio astronomers who were the pioneers of the use of circularly polarized feed horns (International Telecommunications Union, 2013).

b) Interferometric technology

Interferometry was developed by radio astronomers to obtain increased angular resolution and imaging techniques which were later applied in the production of digitized single-pixel surveys of the sky. Interferometry is currently being applied in remote sensing, fiber optics, quantum mechanics, oceanography, optical metrology, seismology, nuclear & particle physics, plasma physics and engineering metrology (International Telecommunications Union, 2013).

For radio images to be useful, instrumental and environmental noise must be removed from them. The techniques involved for such were developed by radio astronomers. The techniques are currently being applied in terrestrial and satellite-based studies of the heavens and the earth by Earth Exploration Satellites Service (ESSS) (International Telecommunications Union, 2013).

c) Wi-Fi Applications

The efficiency of Wi-Fi technology is attributed to radio astronomy. Radio astronomers were able to develop signal processing techniques that overcame reflections from the atmosphere. This was then applied in reducing echo signals in receivers after the arrival of transmission signals in wireless networking devices (International Telecommunications Union, 2013).

d) Computing technology

FORTH programming language is used to write code for most satellite tracking software and controlling telescopes in observatories. The language was first developed at the USA's National Radio Astronomy Observatory (NRAO) in the early 1970s to control and process data from one of the NRAO telescopes (International Telecommunications Union, 2013).

e) Medical technology

Computed Tomography (CT) scanning is a medical imaging technique where computers are used to create a 3D image of an internal body organ or object by merging series of 2D X-ray images taken around a single axis of rotation. This technique borrows from mathematical techniques that were developed by radio astronomers in reconstructing 2D images from 1D images, and reconstructing 3D images from 2D images (International Telecommunications Union, 2013).

Observing distant cosmic sources on radio wavelength is basically measuring the temperatures of these sources. This technique is being applied in conducting non-invasive measurements of temperature of human tissues (International Telecommunications Union, 2013).

f) Geodesy

Using celestial sources as reference points has enabled the terrestrial Very Large Baseline Interferometry (VLBI) to have enabled accurate measurements of continental drifts; the slippage of tectonic plates at fault lines. These measurements are being used to accurately predict earthquakes. Coupled with Doppler tracking, these measurements are being used in high-precision space-navigation missions within our Solar system (International Telecommunications Union, 2013).

2.4 Trends in Radio Astronomy

Radio astronomy has experienced exponential growth in the last five decades. Notable trends are geared towards constructing telescopes with even higher sensitivities at all frequencies (International Telecommunications Union, 2013).

Bigger telescopes with larger collecting areas with expanded operational bandwidths are being constructed because most receivers are approaching their quantum limits at many frequencies. (International Telecommunications Union, 2013).

Another trend is seen in the upgrading of existing telescopes and parabolic satellite antennas to fit broadband receivers operating from 1 to 8 GHz for use in spectral line observations. An example of this upgrading is the Ghana Radio Astronomy Observatory in Kutunse, Ghana.

Lastly, there are international efforts in constructing new-generation radio telescopes, that is, interferometer networks. These networks include the SKA project, Low Frequency Array (LOFAR) in The Netherlands and the Atacama Large Millimeter/submillimeter Array (ALMA).

Besides the international efforts, Kenya has made some efforts in radio astronomy as expounded on in the next section.

2.5 Radio Astronomy efforts in Kenya

Kenya has not been left behind towards in tapping the power of radio astronomy for her development. Key efforts in radio astronomy are:

a) University Training
b) Kenya International Radio Observatory (KIRO)
c) Development in Africa with Radio Astronomy (DARA) programme

2.5.1 University Training

The University of Nairobi, Technical University of Kenya and Kenyatta University are currently offering degree programs in Astronomy and Astrophysics.

The Technical University of Kenya and the University of Nairobi are offering masters and Doctoral programs in Astronomy.

Such training has increased the local capacity in astronomical studies, thus making Kenya prepared for astronomical activities like the SKA.

2.5.2 Kenya International Radio Observatory

The proposal to construct KIRO was brought forth in 2005 by J.O. Malo of the University of Nairobi, Kenya. The observatory was to be constructed by International Institute for Space Sciences and Electronics (INISSE) through collaborative multinational effort, a proposal by a consortium of Indian, Kenyan and Nigerian scientists back in the 1980s. In the proposal to construct INISSE, a Giant Equatorial Radio Telescope (GERT) was also proposed for construction at a site that is close to the earth's equator (Malo and Thide, 2005).

The INISSE institute was to develop programs in radio astronomy and space sciences to catalyze collaboration amongst developing countries in space applications and electronics.

The site proposed was to be along the geomagnetic equator in northern Kenya. The area was proposed because of its remoteness, that is to say, the area at that time did not have TV and radio transmitters, and ground-based radar stations (Malo and Thide, 2005).

KIRO was proposed to be a preferred site for lunar occultation and for studying interplanetary scintillations, and pulsars.

2.5.3 Development in Africa with Radio Astronomy (DARA) programme

The DARA project is a concerted venture between the UK, South Africa and African partner nations including Kenya that "aims to provide development, education, training and career advice to Africans through radio astronomy and related technical disciplines" (Hoare, 2018, p.506). The DARA project has got funding of about £4 million from the Newton Fund for training a first generation of radio astronomers in each of the AVN partner countries (Hoare, 2018).

The program has basic training and advanced training program for its trainees. The basic training program is in radio astronomy in Botswana, Ghana, Kenya, Madagascar, Mozambique, Namibia and Zambia. In Kenya, the program's host institute is the Technical University of Kenya (Hoare, 2018; Technical University of Kenya, 2022). The programme is delivered over eight intensive weeks of contact time spread out over a year. In addition to an introduction to astrophysics, the trainees get practical training either at Hartebeesthoek Radio Astronomy Observatory in South Africa, or at the newly commissioned 32-meter radio telescope in Ghana at Ghana Space Science and Technology Institute (GSSTI) in Accra, Ghana (Hoare, 2018, p. 506).

On completion of basic training, trainees are awarded certificates of completion which they can use to apply for an advanced training programme in radio astronomy at Masters or PhD level, or even use their new skills to aid in the development of related high-tech industries in the AVN Countries (DARA Project, no date; Hoare, 2018).

2.6 Geographic Information System

GIS is a spatial system that creates, manages, analyzes, and maps all types of data (ESRI, 2022). It is also a system of hardware, software and procedures that have been designed to support the capture, management, manipulation, analysis and display of spatially referenced data for solving complex planning and management problems (Mukti, et. Al., 2005). It combines graphic data in the form of maps with additional data in the form of tables (Wehrmann, 2009).

GIS has the capability of manipulating and visually displaying numerous data types for easy comprehension. It continues to be widely used as a decision support system in the public and private sectors (Wehrmann, 2009). In addition, GIS has proved to be a useful tool for any planning and decision-making that involves spatial issues like finding the right location (Wehrmann, 2009).

2.7 Multi-Criteria Decision Analysis

Multi- Criteria Decision Analysis (MCDA) is as '*a collection of formal approaches which seeks to take explicit amount of key factors in helping individuals or groups explore decisions that matter*' (Belton and Stewart 2002, 2).

MCDA methods have been applied in solving spatial problems by combining them with GIS (Carver, 1991; Malczewski, 2006). MCDA is effective in that it accommodates a number of options between mathematical programming for finding optimal solutions and heuristic methods for finding satisfactory solutions that are closer to the best solution (Greene, et.al., 2011)

Where the goal is a single objective, for example recommending a suitable location for a school, the focus is always on developing relevant criteria or collating factors with measurable attributes in a process called multiple- criteria evaluation (MCE) or multiple-attribute decision making (MADM) (Jankowski, 1995; Malczewski 1999). MADM employs non-compensatory aggregation methods; they are easier to understand and apply. However, they require inclusion or exclusion of alternatives based on hard cut-offs. The methods are discussed below.

1. Conjunctive- Alternatives are accepted as long as they meet the set cut-off value on each criteria i.e. binary overlay (Jankowski, 1995; McHarg, 1969. Several data layers are combined using the intersection operation (logical AND) (Greene, et.al., 2011).

2. Disjunctive- Only alternatives that meet a cut-off value on at least one criterion are accepted (Hwang and Yoon, 1981). Also employed using binary overlay but data layers are combined using the union (logical OR) operator.
3. Lexicographic- Here, the criteria set is ordered or ranked, and then elimination is done by comparing alternatives against the highest ranked criterion then the second highest ranked criterion etc (Carver, 1991).
4. Elimination by aspects- Here, a lexicographic approach is combined with the conjunctive method for each criterion (Malczewski, 1999).
5. Dominance- Here, dominant alternatives that rank as high as every other alternative on every criterion are selected (Jankowski, 1995).

GIS Based MCDA

The motivation behind incorporating GIS in MCDA is to supplement the traditional 'where' question with the 'what' question (Malczewski, 1999). GIS based MCDA makes it easier to calculate and spatially analyse criteria like distance, travel time and slope (Greene, et.al., 2011). As Greene, et.al. (2011) notes, there is need for more research in GIS- based MCDA.

ESRI's ArcGIS suite of products offers various tools that are essential in implementing MCDA in GIS without requiring further programming (Greene, et.al., 2011). Some of the tools are weighting overlay and map algebra.

Many factors are always considered in land suitability analysis because of enormous amounts of data that is involved. Analytical Hierarchy Process (AHP) is a technique that guides in making proper decisions in land suitability analysis in site selection activities (Mendoza, 1997).

AHP follows a distinct six step procedure as listed below (Lee, et. al., 2008).

a) Definition of unstructured problem
b) Development of AHP hierarchy
c) Pairwise comparison
d) Estimation of relative weights
e) Consistency checking

f) Obtaining overall rating based on aggregation of relative weights of decision elements

2.8 Jurisdictions where GIS has been Applied in siting radio telescope

There are limited studies in radio astronomy because of man-made RFI. It is therefore imperative that RFI mapping be conducted in radio astronomy site selection, (Umar, et. al., 2014). GIS has been used as a tool in mapping RFI since it aids in finding and monitoring spectrum occupancy in identifying and recognizing the most intense sources of interference especially from terrestrial transmitters. GIS MCDA has been used in various jurisdictions and a select of them, which are Peninsular of Malaysia, The Philippines and Turkey. In all the mentioned jurisdictions, AHP process was also employed.

In the Peninsular of Malaysia, anthropogenic data sets used are population density and road network while the geographic datasets used are contour shielding and rainfall data was used (Umar, et. al. 2014). Population density and distance to road network offered an indication of man-made RFI in the study. In the Philippines, population density, road network, climatic conditions and contour shielding datasets were employed (Masong, 2017). In Turkey, wind speed and direction, cloudiness, temperature, relative humidity, evaporation, number of days with thunderstorm, storm and hail and lastly rainfall data was used in finding candidate sites for a radio observatory (Küçük, et. al., 2012).

CHAPTER 3: MATERIALS AND METHODS

3.1 Study area

Kenya was the study area. It is geographically located in East Africa next to the Indian Ocean coast between Somalia and Tanzania. Its total area is 582,650.2 square kilometers. Figure 7 shows the study area which is Kenya.

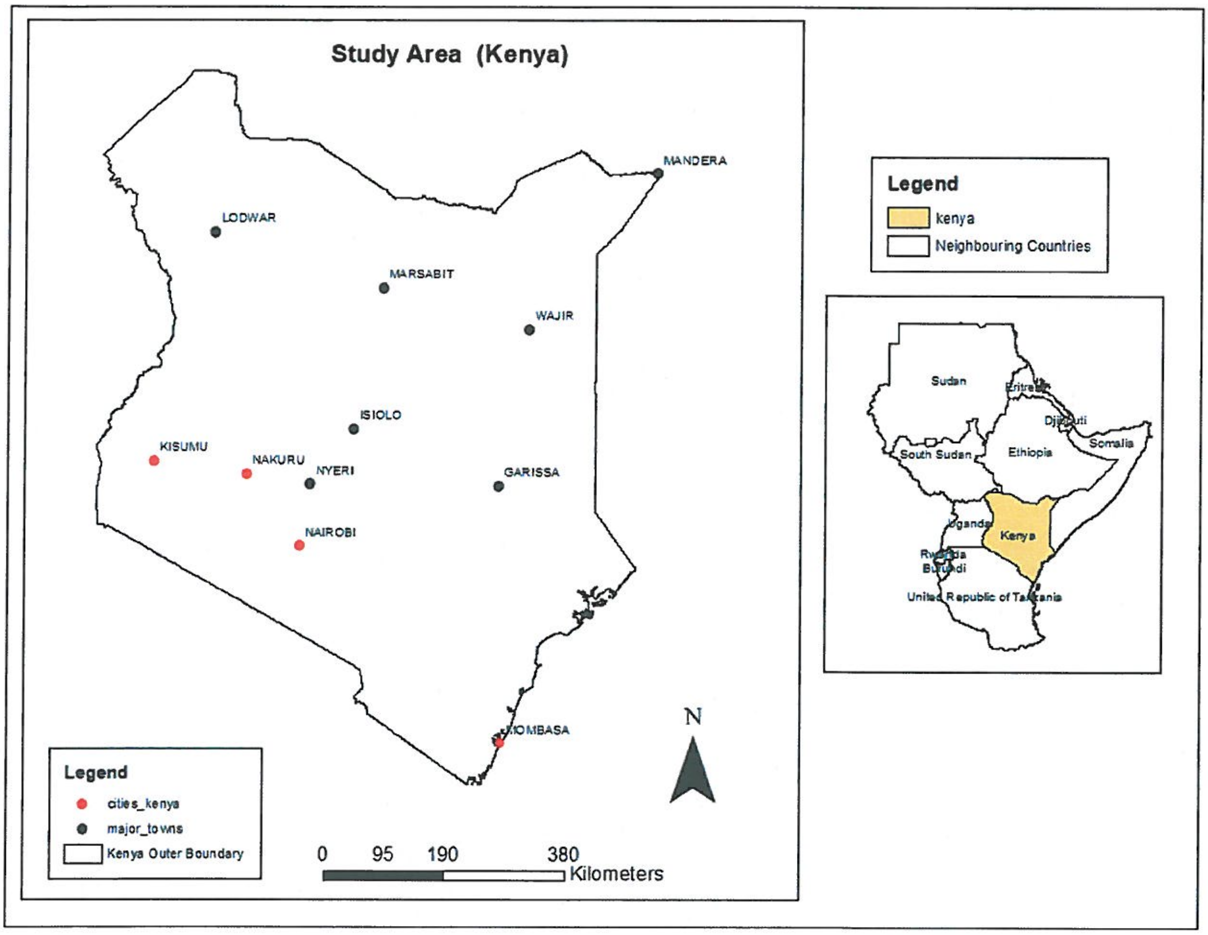

***Figure 6:** Study Area*

***Source:** Author*

3.2 Classification of datasets and the tool of study

The data layers used for site selection in this study were classified into two groups: anthropogenic and geographic datasets. Anthropogenic datasets are: cell-tower data and national electricity grid data. Geographic datasets are: rainfall, LULC, wind speed, and DEM. ArcGIS 10.8 software was used for analysis. The MADM process of MCDA was employed in this study because the specific objectives of the study are not in conflict with each other.

3.3 Sources of Data

Various data for the study were sourced from various agencies and from authoritative online sources as shown in Table 1.

Table 1: Sources of Data

NO.	DATASET	SOURCE	DATA RECENCY (YEARS)
1	DEM	Unites States Geological Survey (https://earthexplorer.usgs.gov/	2022
2	Rainfall	Kenya Meteorological department; The Ministry of Environment and Forestry	2021
3	Cell Tower	CAK	2019
4	Electricity	KPLC & KETRACO	2021
5	LULC	Regional Centre for Mapping of Resources for Development (RCMRD) Portal http://www.geoportal.rcmrd.org/layers/server%3Akenya_sentinel2_lulc2016	2016
6	Wind speed	Kenya Meteorological department; The Ministry of Environment and Forestry	2020

3.4 Threshold setting

Equal interval method was used to reclassify all the data sets.

3.4.1 Wind speed

Higher wind magnitude interferes with the efficiency of a radio telescope in pointing stability and accurate tracking of radio sources. Areas that experience low wind speeds are highly recommended for siting radio telescopes.

North eastern parts of Kenya as well as the coastal region experience the highest wind speeds which are greater than 4.0 meters per second, (Oludhe, 2008). Marsabit county, for instance, experienced frequent wind speeds of between 10.0 – 11.0 meters per second which blew more than 60 percent in the year 2000 (Oludhe, 2008). Based on Kenya's wind speed profile, regions that experience wind speeds of up to 4.5 meters per second are recommended. The wind data used for the study had a resolution of 200 meters. Figure 7 shows the reclassification of Kenya's wind speed data. Figure 10 shows Kenya's wind profile.

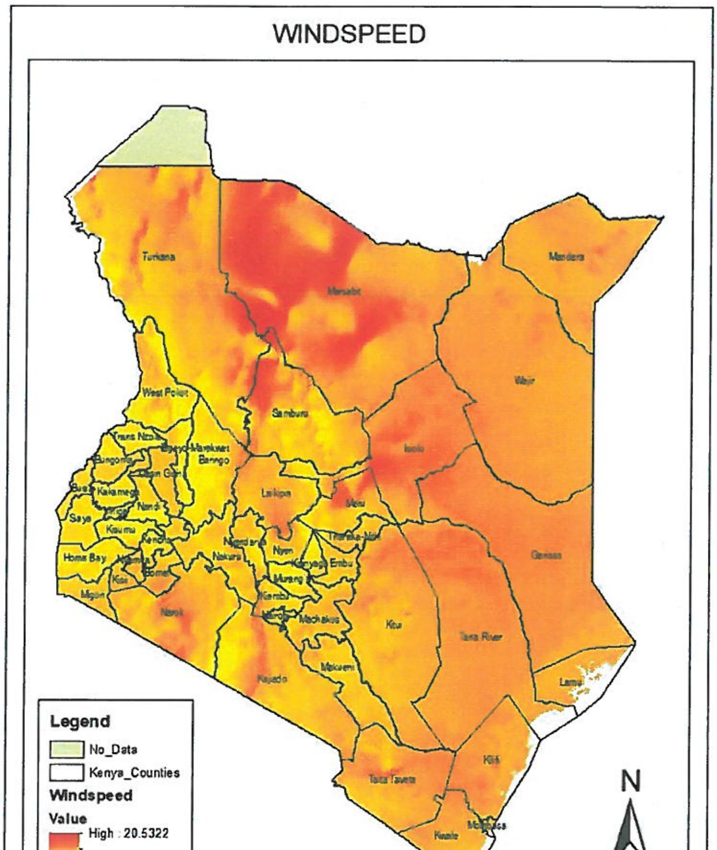

Figure 7: Kenya Wind speed Profile

***Source:** Author*

3.4.2 Electricity Power Lines

Euclidean distance from the power lines was calculated so as to find locations that are away from the existing power lines. The results were then reclassified where maximum distance from the power line was set to 100 meters. Areas that are farthest from the national grid lines (500hVDC, 400kV, 220kV, 132kV) were the most preferred and areas that close to the power lines were the least preferred.

KPLC has developed various way-leave traces for different circuits as shown in the Table 2.

***Table 2:** KPLC Wayleave Trace*

No.	**Circuit**	**Distance (meters)**
1	11/33Kv Single Circuit	10
2	66Kv Single Circuit	10
3	132Kv Single Circuit	30
4	220Kv Single Circuit	40
5	66kV double circuit on single structure	20
6	132kV double circuit on single tower	40
7	220kV double circuit on single tower	40
8	66kV two circuits running in parallel	30
9	220kV two circuits running in parallel	60
10	132Kv two circuits running in parallel	60

KETRACO has set an average of 25 to 180 feet as corridors where electric utilities can pass through on private property as way-leaves. However, it notes that the set distances as averages but not limits as some way-leaves can be wider depending on survey reports of way-leave areas. Figure 8 shows Kenya's national electricity grid network with voltage carried by respective lines.

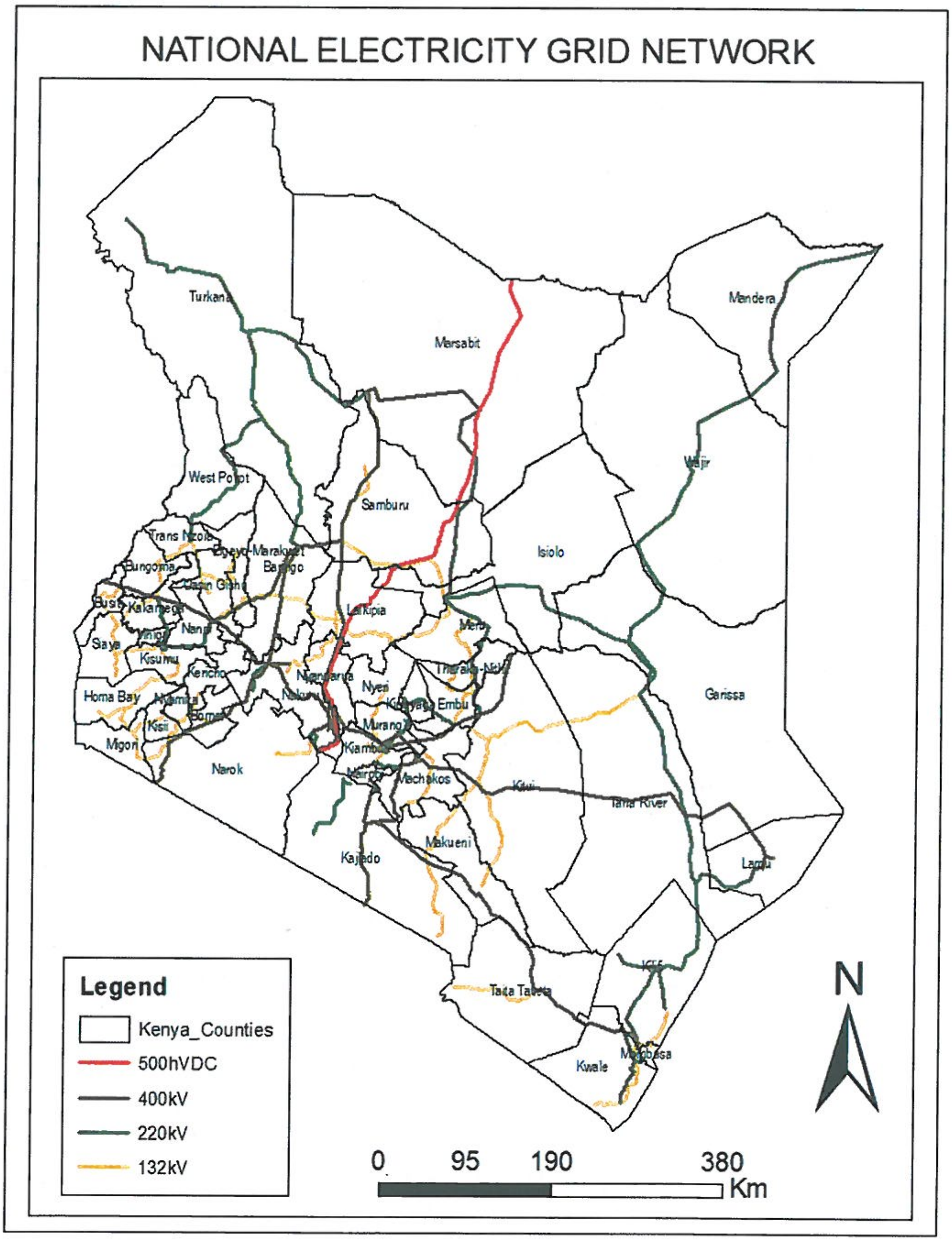

Figure 8: Kenya National Electricity Grid Network
Source: Author

3.4.3 Rainfall

Almost half of Kenya is arid and semi-arid. Kenya's central region enjoys higher precipitation as compared to northern Kenya. Figure 9 shows rainfall distribution in Kenya.

The rainfall data was for the year 2020 and it was in raster format. It was sourced from the Kenya Meteorological Department. On acquisition, the raw data had a resolution of 0.3 meters. The data set was then re-projected to a resolution of 3500 meters, WGS 1984 projected coordinate system. Areas that receive annual rainfall of 800 millimeters and below were preferred because the raindrops causes radio signals to be scattered and with a slight increase in atmospheric temperature, the radio signals get absorbed because of the increase in molecular energy in water molecules (Umar et.al., 2015).

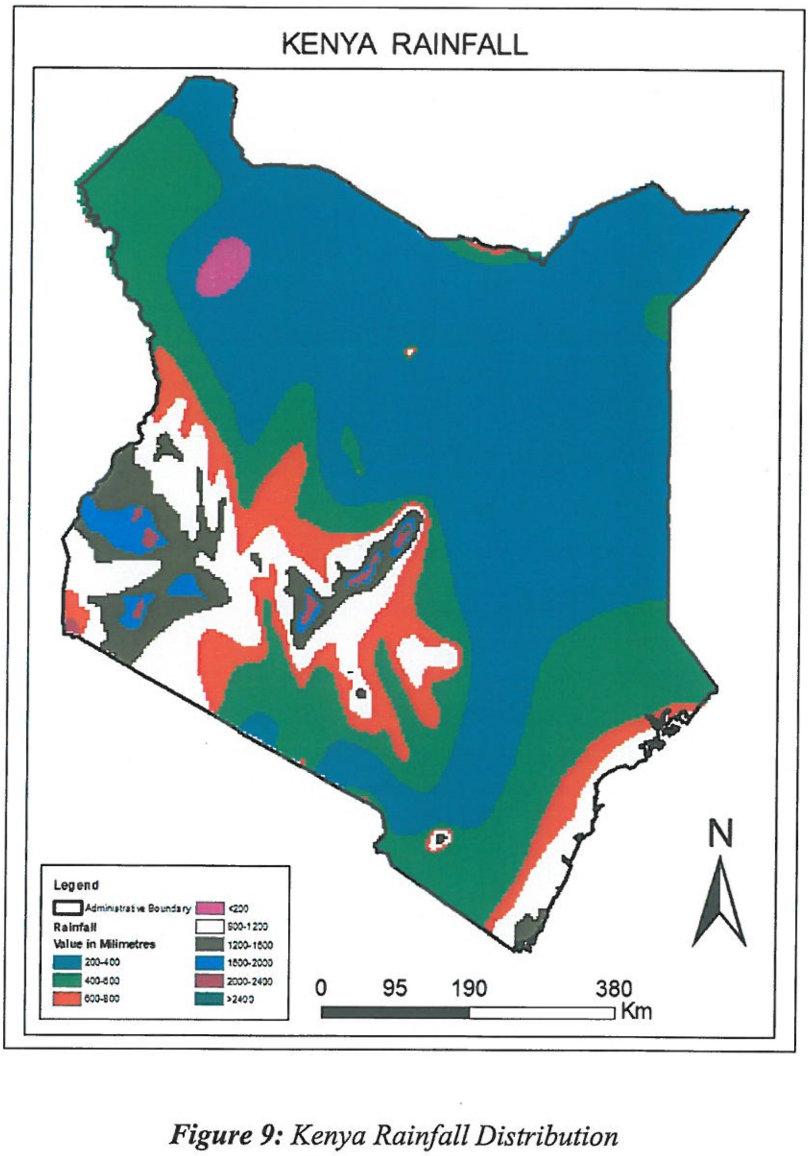

Figure 9: Kenya Rainfall Distribution
***Source:** Author*

3.4.4 Cell Towers

Cell towers are an indication of RFI since telecommunication companies only erect cell towers to serve populace areas hence no need for population distribution dataset. Euclidean distance from the cell towers was calculated before reclassification. A maximum distance of 1000 meters was set from the cell towers because the aim was to find locations that are away from existing cell towers. Figure 10 shows the distribution of cell towers in Kenya as at 2017.

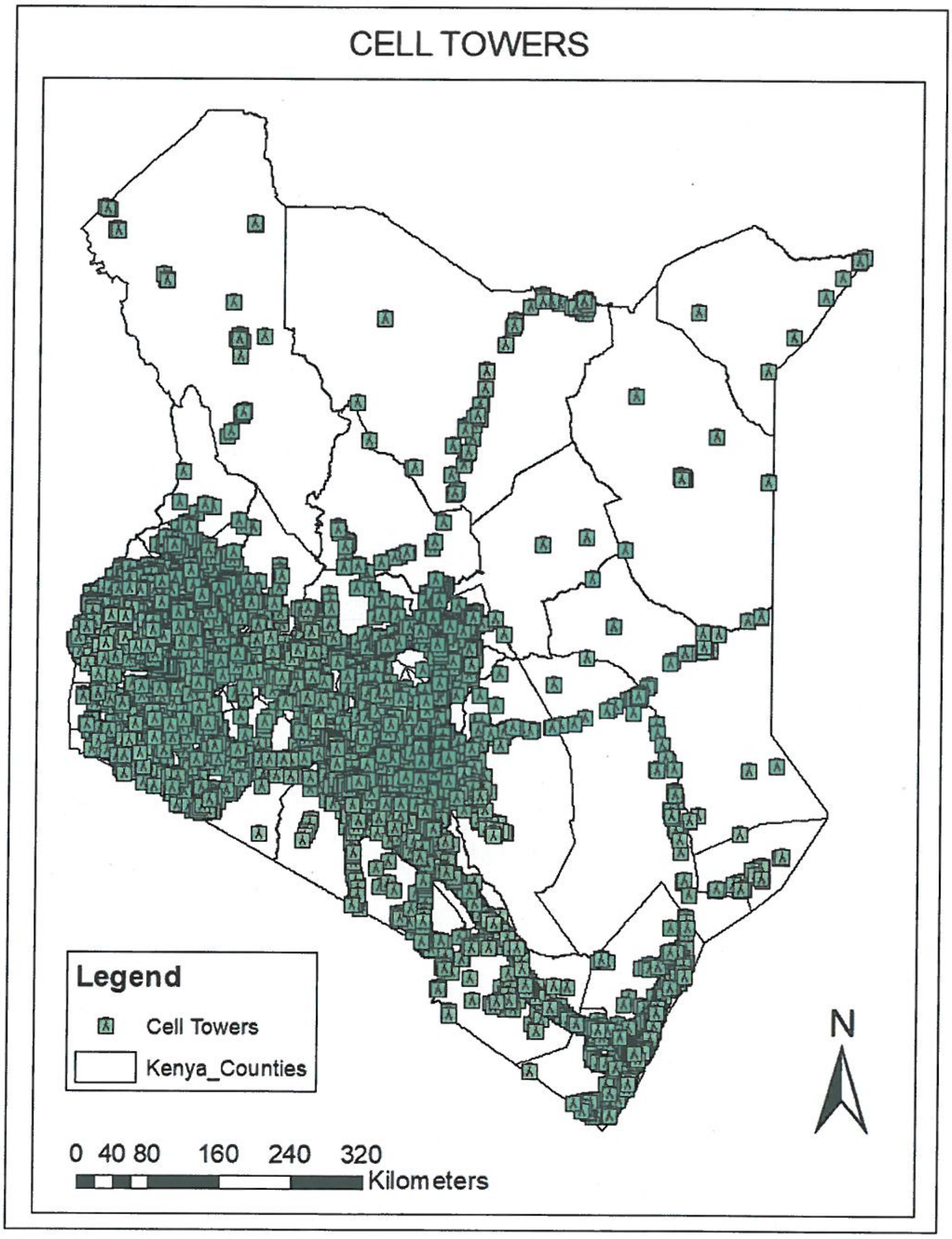

***Figure 10:** Kenya Cell Towers*
***Source:** Author*

3.4.5 Digital Elevation Model

DEM data gives Kenya's contour information and further guide areas that enjoy natural contour shielding from ground interference, (Umar, et. al. 2014). Kenya is generally a mountainous country with almost two thirds of the state lying at an altitude that is higher than 1500 meters above sea level. The Great Rift Valley that passes through Kenya is the most dominant topographic feature, (Graham, et.al. 2016).

The DEM data was used to generate the slope of the study area. Low altitude areas that also enjoy natural contour shielding were the most preferred as compared to high altitude areas. Figure 11 shows Kenya's elevation profile.

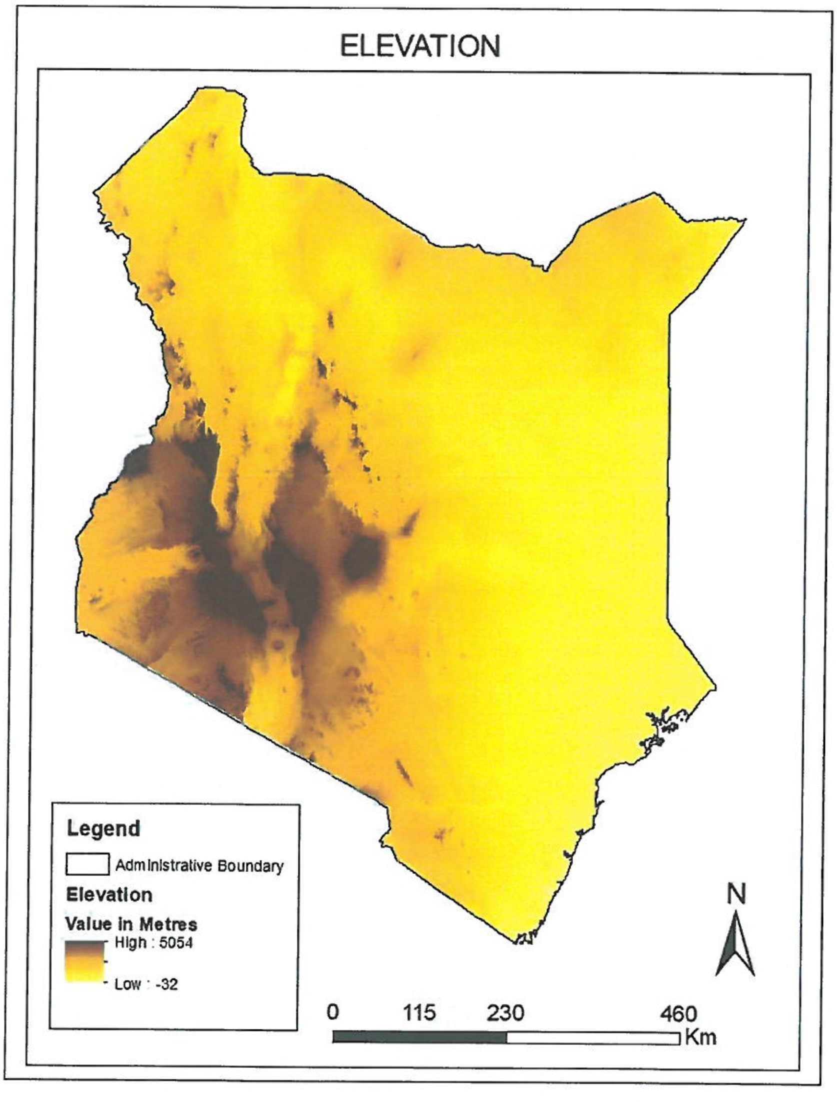

Figure 11: Kenya Elevation

Source: *Author*

3.4.6 Land Use Land Cover

The dataset used had nine classes as listed below: Tree cover areas, shrub cover areas, grassland, cropland, vegetation aquatic or regularly flooded, lichen mosses/ sparse vegetation, bare areas, built-up areas and open water.

Built up areas, tree cover areas, cropland, vegetation aquatic or regularly flooded, and lichen mosses/ sparse vegetation are the least preferred. Bare areas, shrub cover areas, and grass lands are preferred because of very minimal cost in relocating existing infrastructure to pave ground for hosting a radio telescope. Figure 12 shows the various land uses and land covers in Kenya.

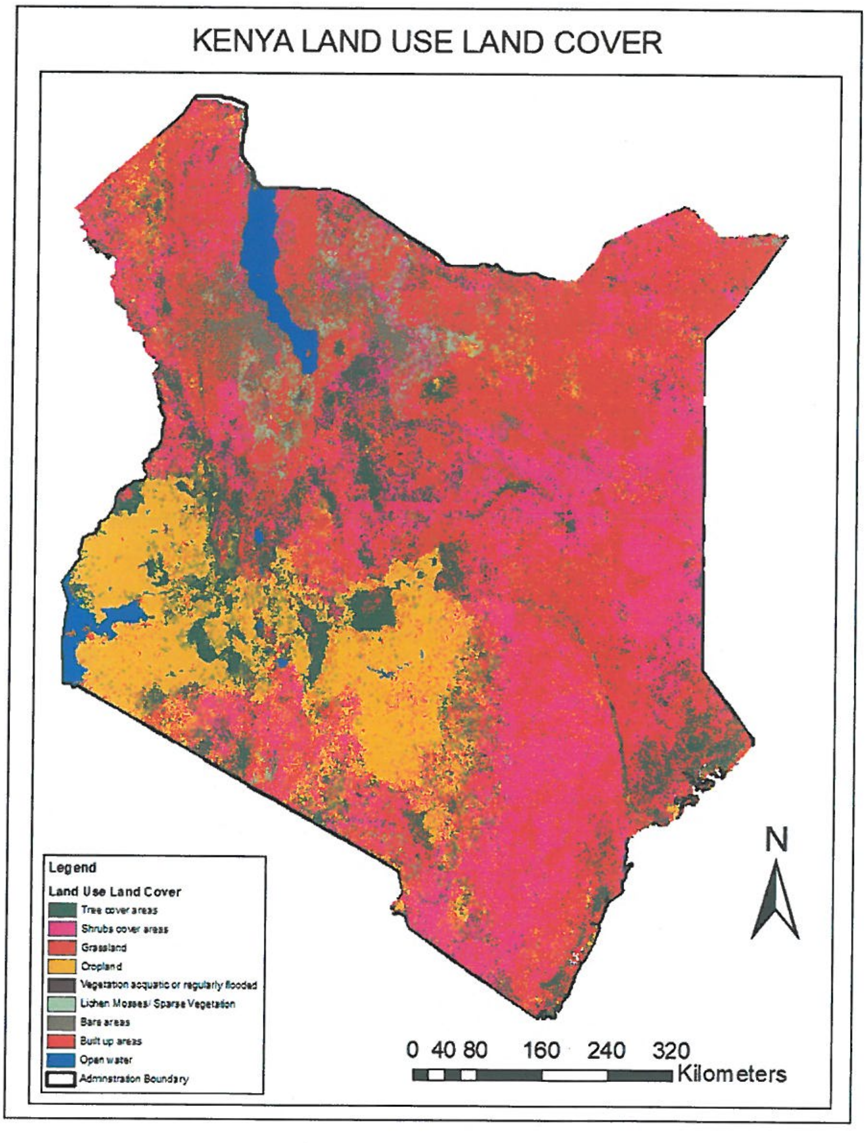

Figure 12: Kenya Land Use Land Cover

***Source:** Author*

3.5 Steps for finding suitable locations

A three-step procedure was followed in finding suitable locations for siting a radio telescope in Kenya.

i) Determination of threshold value for each parameter by consultation from industry expert; radio astronomer
ii) Data combination to produce maps for each parameter
iii) Carrying out MCDA

Figure 13 shows the step-by-step methodology that was followed in finding suitable locations for siting a radio telescope in Kenya.

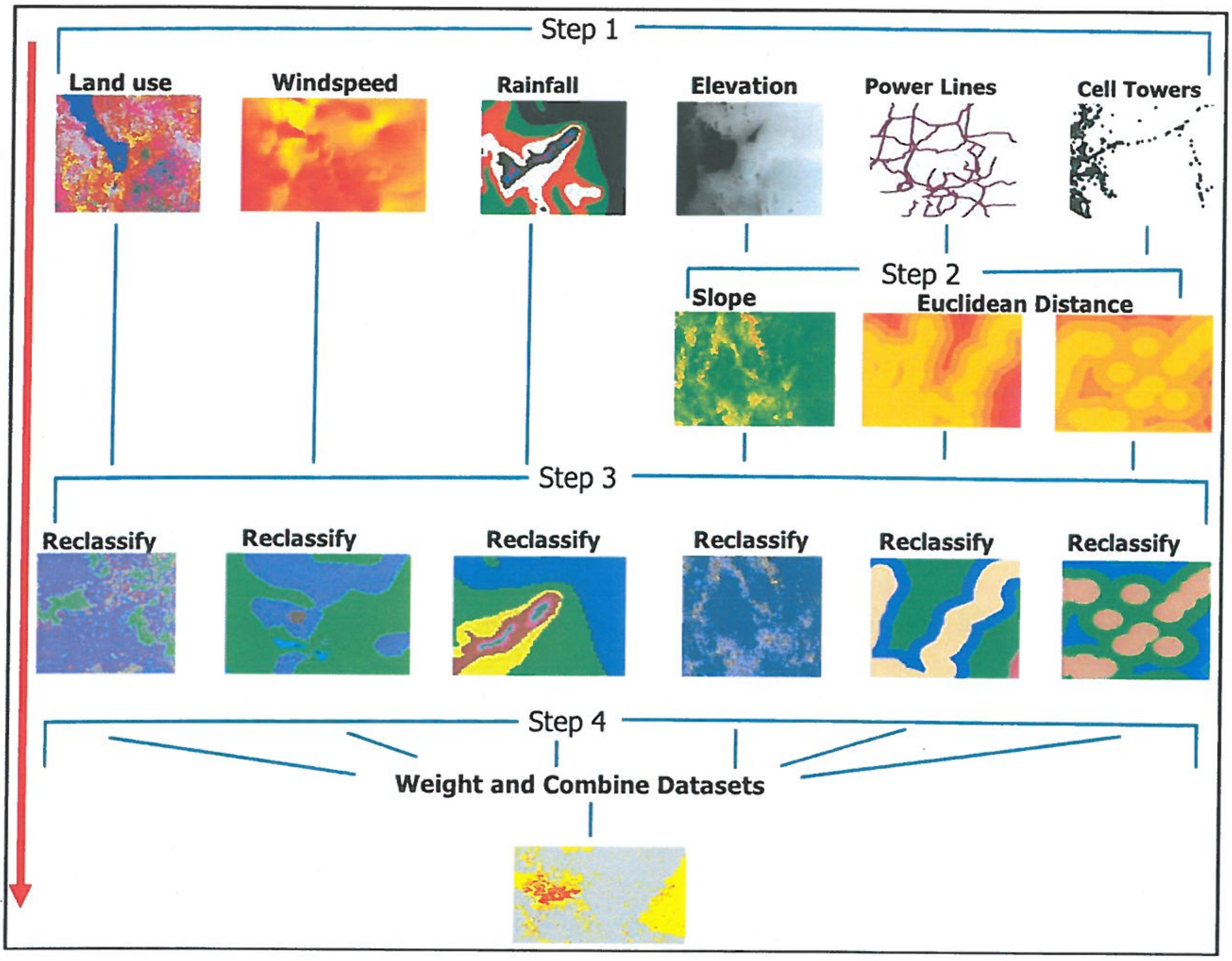

Figure 13: Step-by-step Methodology

***Source:** Author*

Figure 14 shows the schematic representation of the methodology employed in the study.

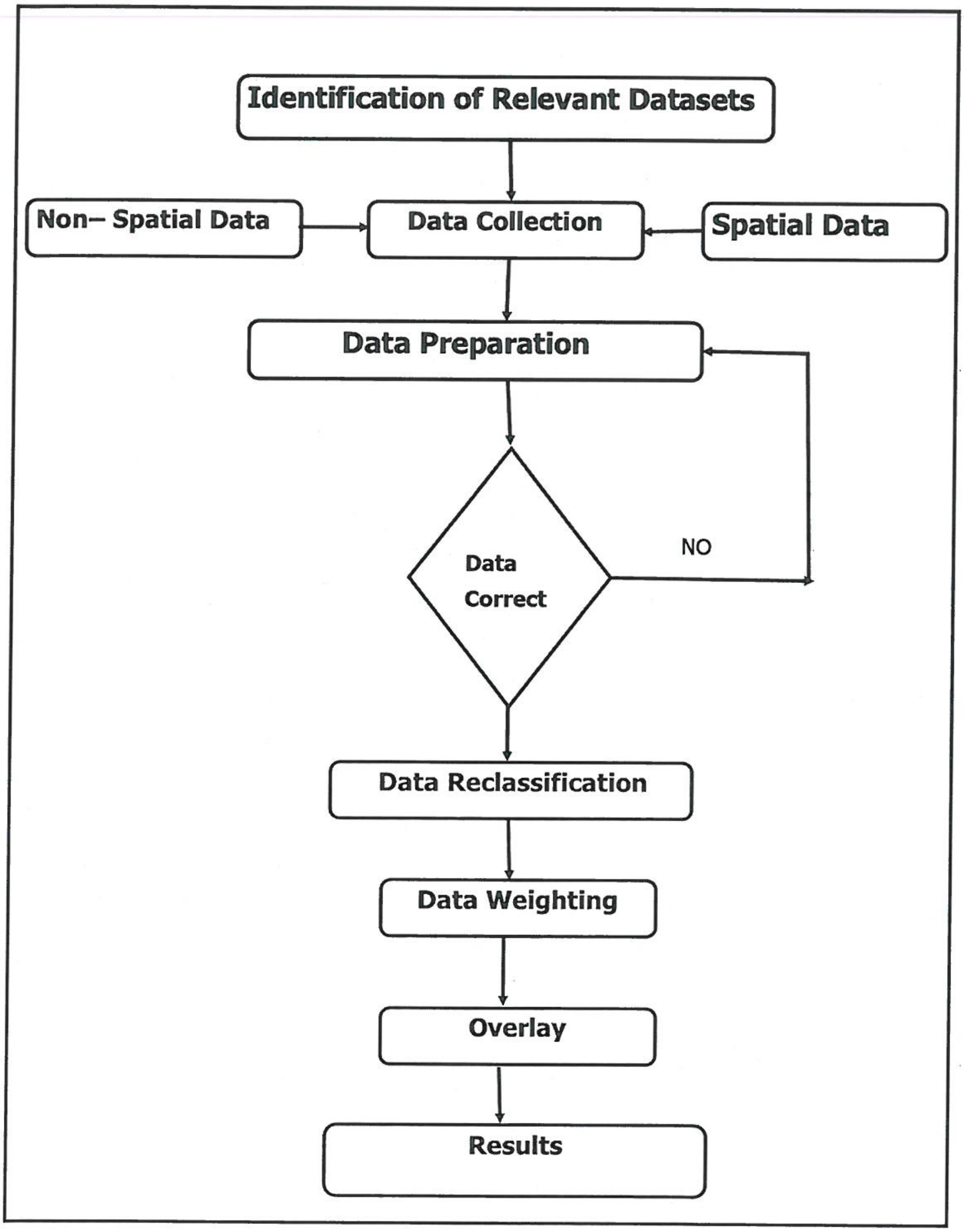

Figure 14: *Schematic Representation of the Methodology*

Source: *Author*

Figure 15 shows the ArcGIS model used to find suitable locations for siting a radio telescope in Kenya.

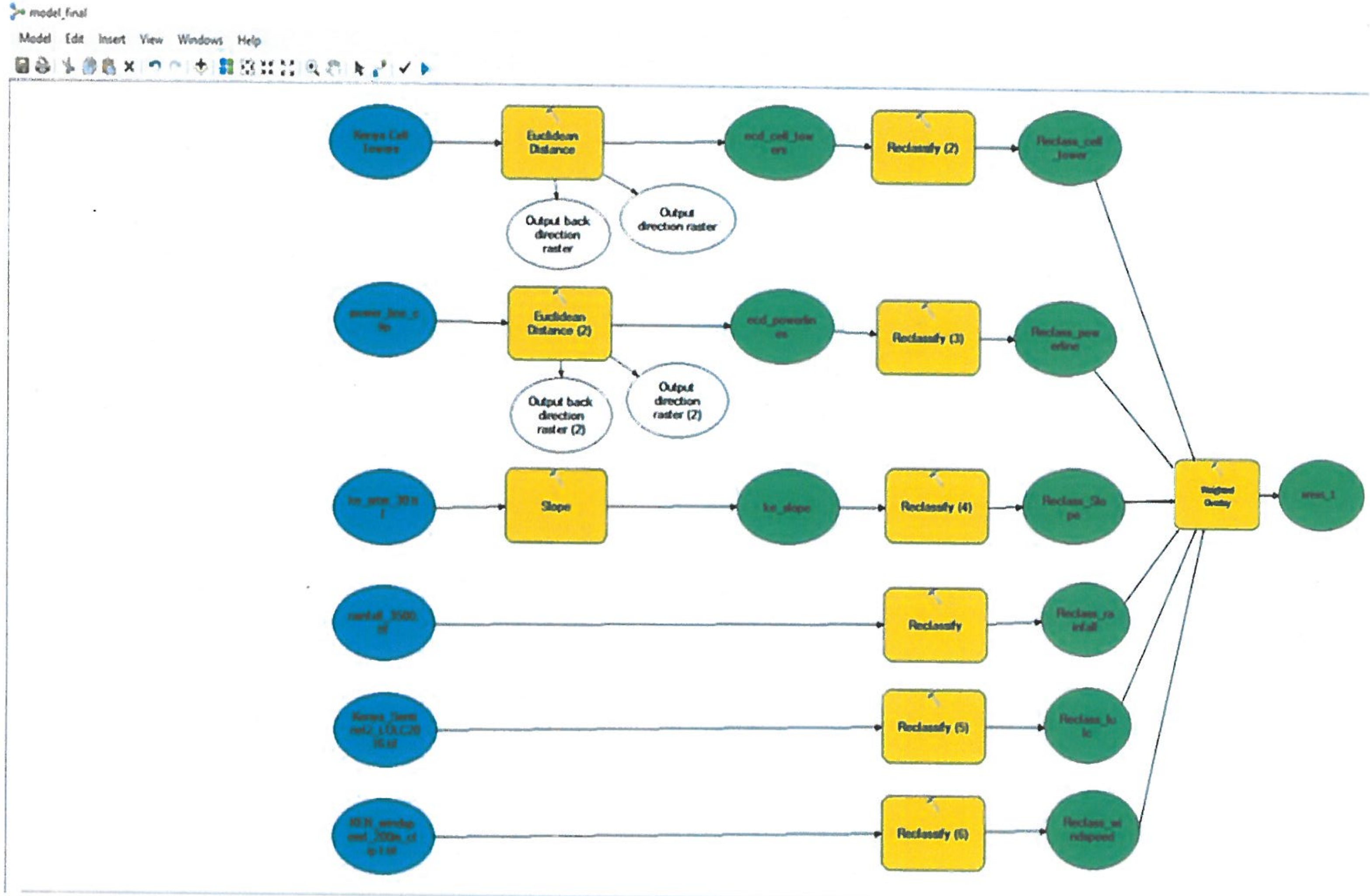

Figure 15: *ArcGIS Model of the Study*

Source: *Author*

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Data Preprocessing

i) Results for the Euclidean distances

a) Cell towers

Figure 16 shows the Euclidean distances from each cell towers in Kenya.

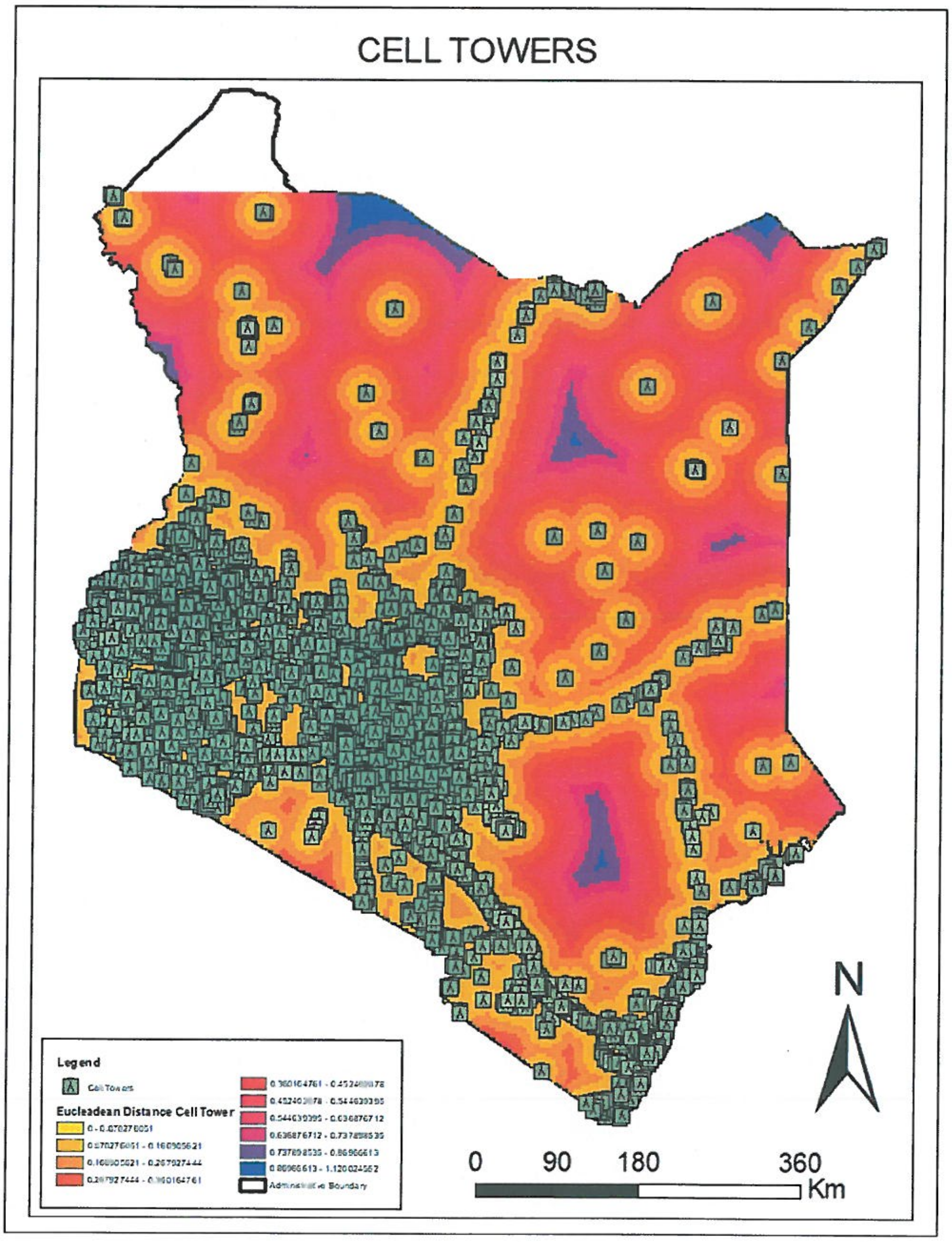

Figure 16: Cell Towers Euclidean Distance

Source: Author

b) Electricity grid lines

The maximum Euclidean distance from the power lines was set at 100 metres. Figure 17 shows the Euclidean distances from each main grid power line in Kenya.

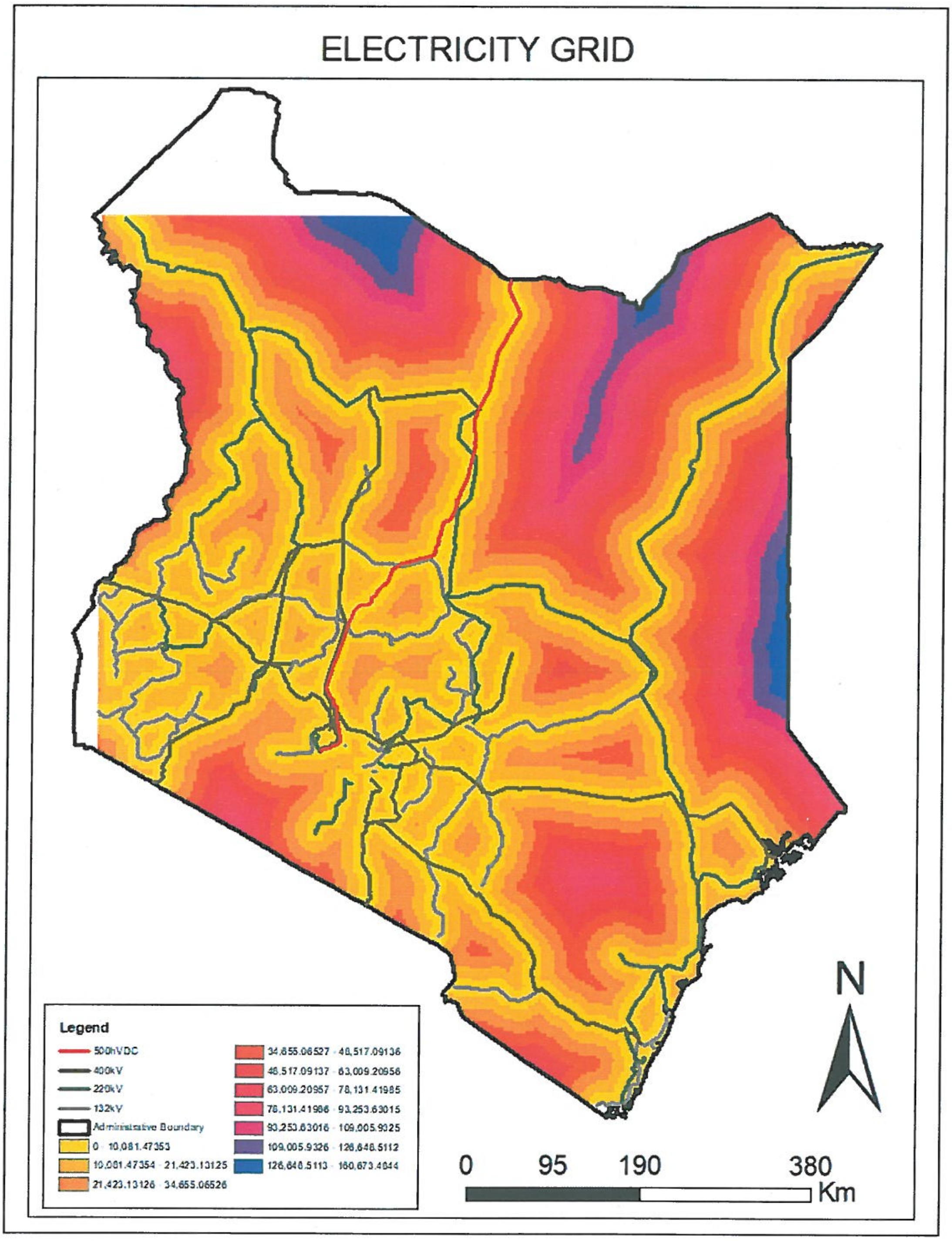

Figure 17: Electricity Euclidean Distance
***Source:** Author*

ii) Slope

Planar method was used to generate Kenya's slope. Figure 18 shows Kenya's slope profile degrees.

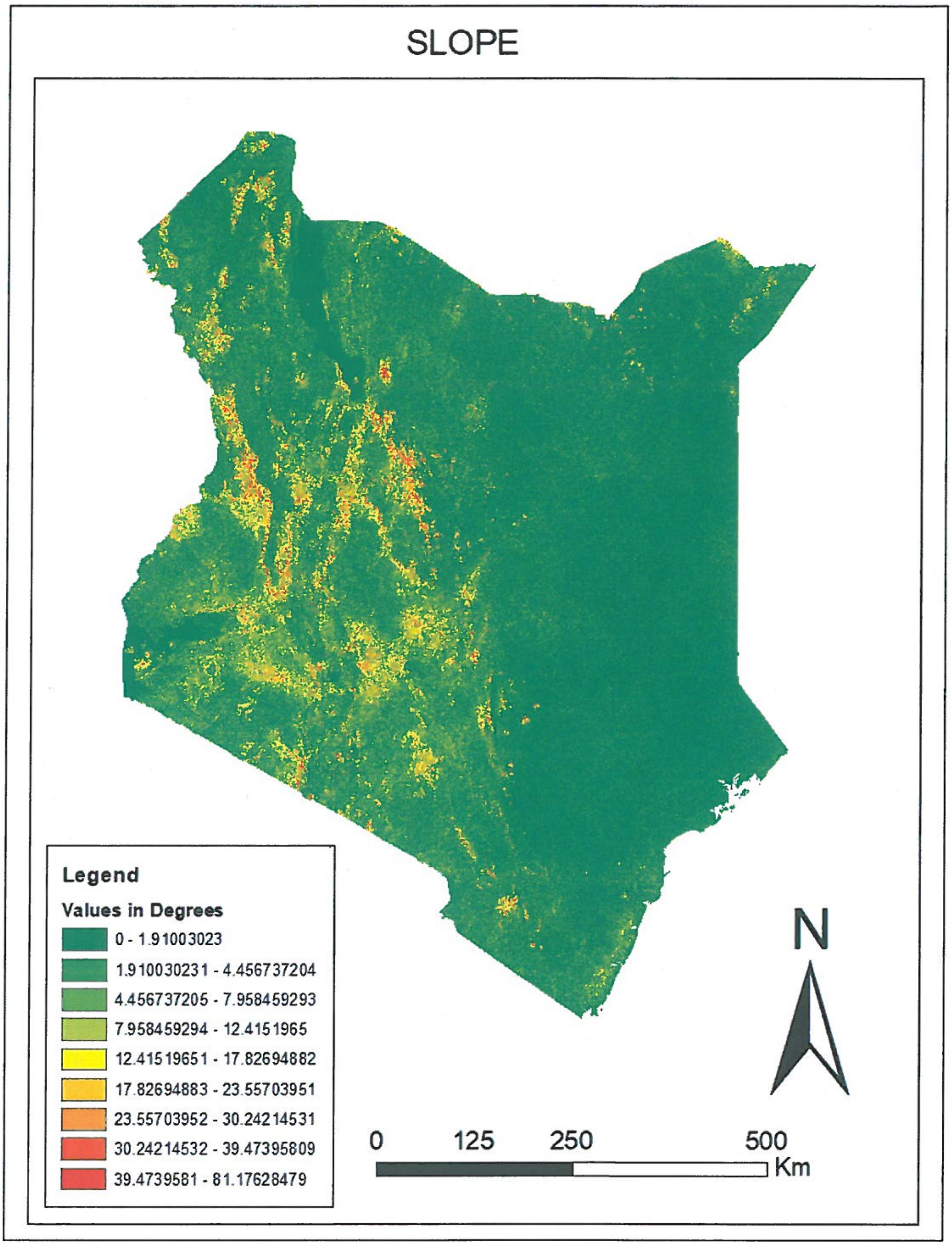

***Figure 18:** Kenya Slope*
***Source:** Author*

4.2 Results for Reclassified Data

The datasets were then reclassified as guided by the Food and Agricultural Organization (FAO) and also implemented by Saaty (1980) in his famous AHP method. Sites were ranked as S1, S2, S3 and NS which represented classes 1, 2, 3 and 4 respectively in the reclassification stage. S1, S2, S3 and NS were used to imply most suitable, moderately suitable, marginally suitable and not suitable respectively.

a) Wind speed

Figure 19 shows the Kenya's wind speed suitability map.

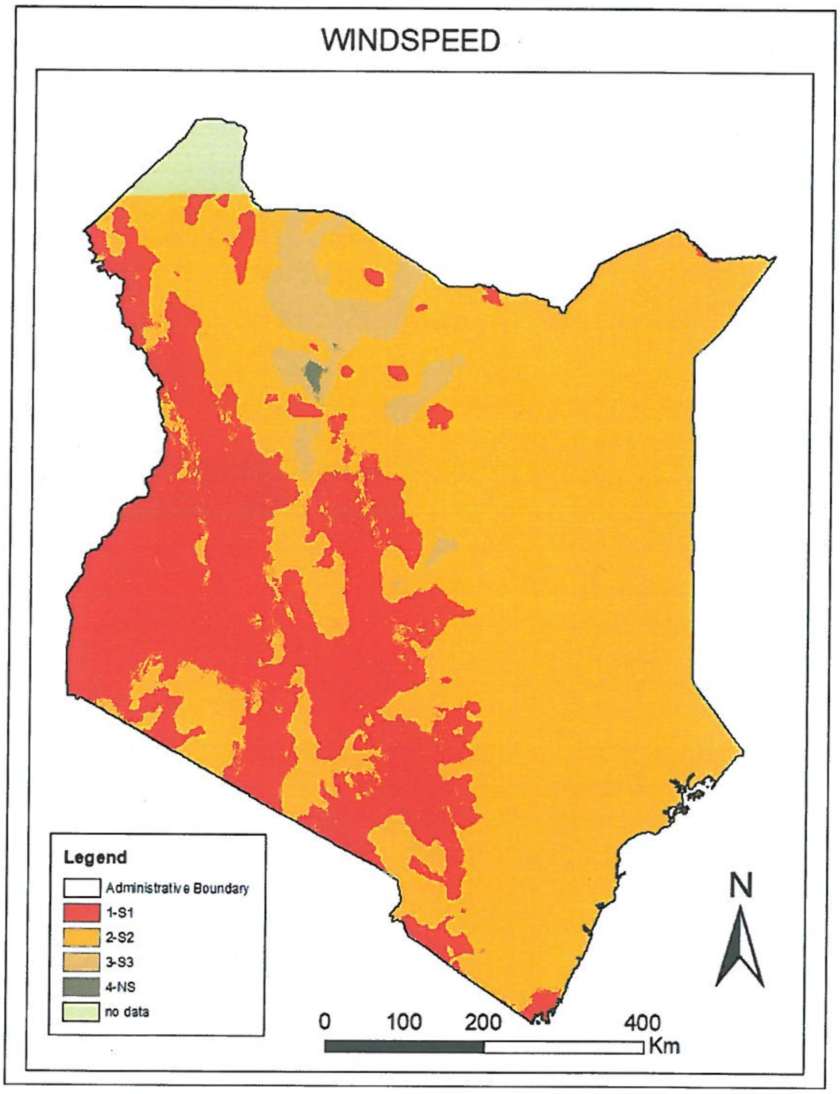

Figure 19: Kenya Wind speed suitability map
Source: Author

b) Cell towers

Figure 20 shows the Kenya's cell towers suitability map.

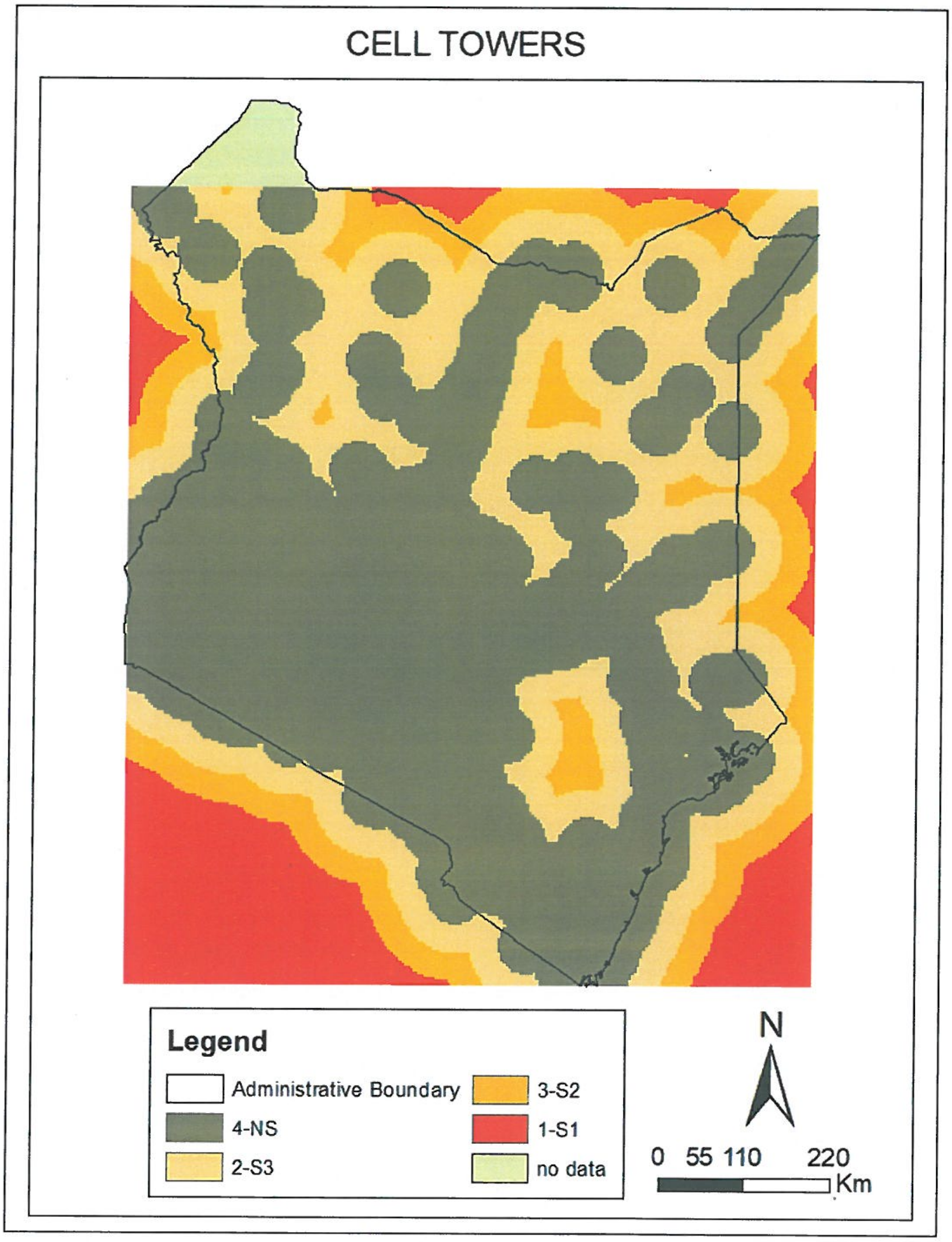

Figure 20: *Kenya Cell Towers Suitability Map*
Source: *Author*

c) Electricity grid

Figure 21 shows the Kenya's national electricity grid suitability map.

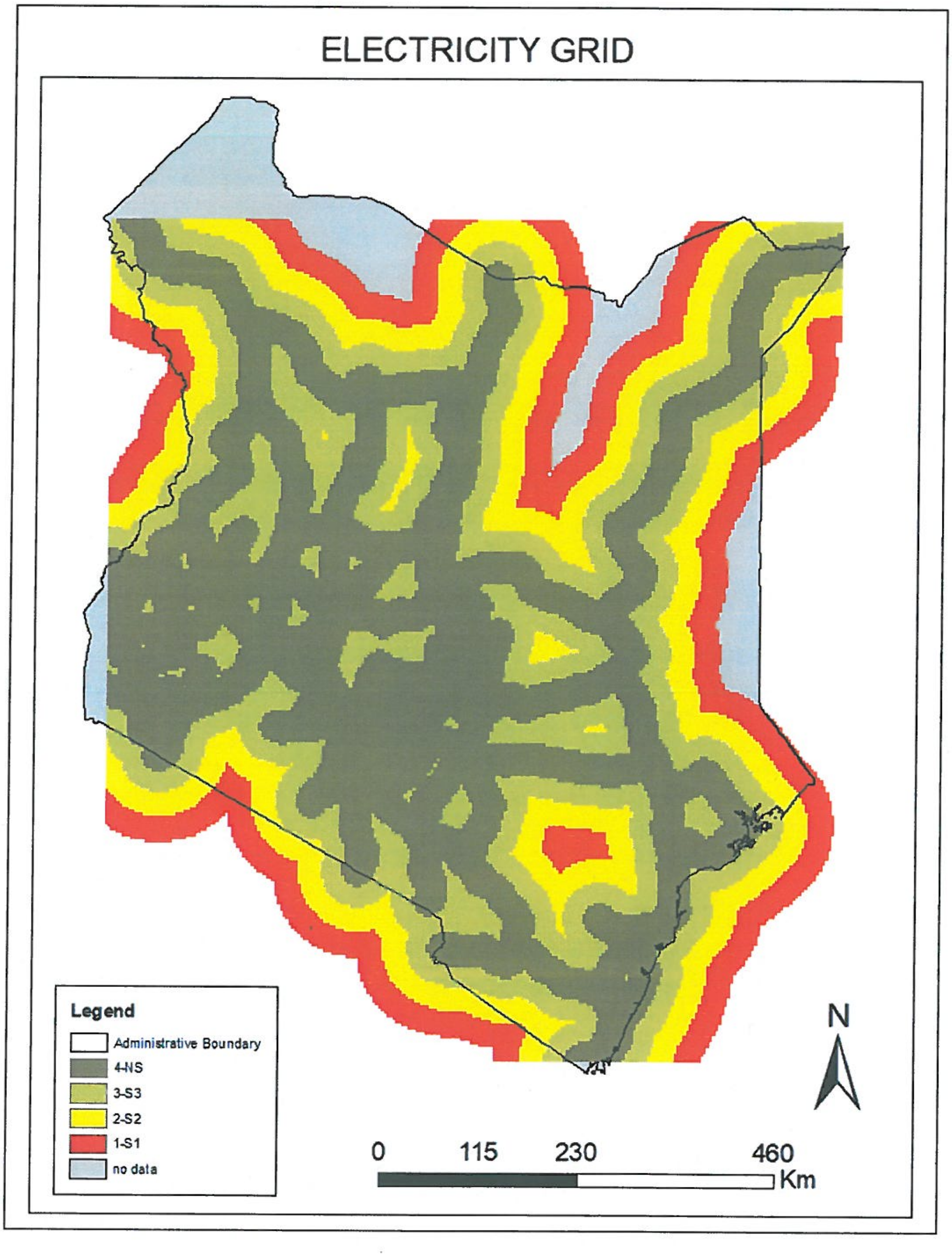

Figure 21: *Kenya National Electricity Grid Suitability Map*
Source: *Author*

d) Slope Suitability

Figure 22 shows the Kenya's slope suitability profile after reclassification.

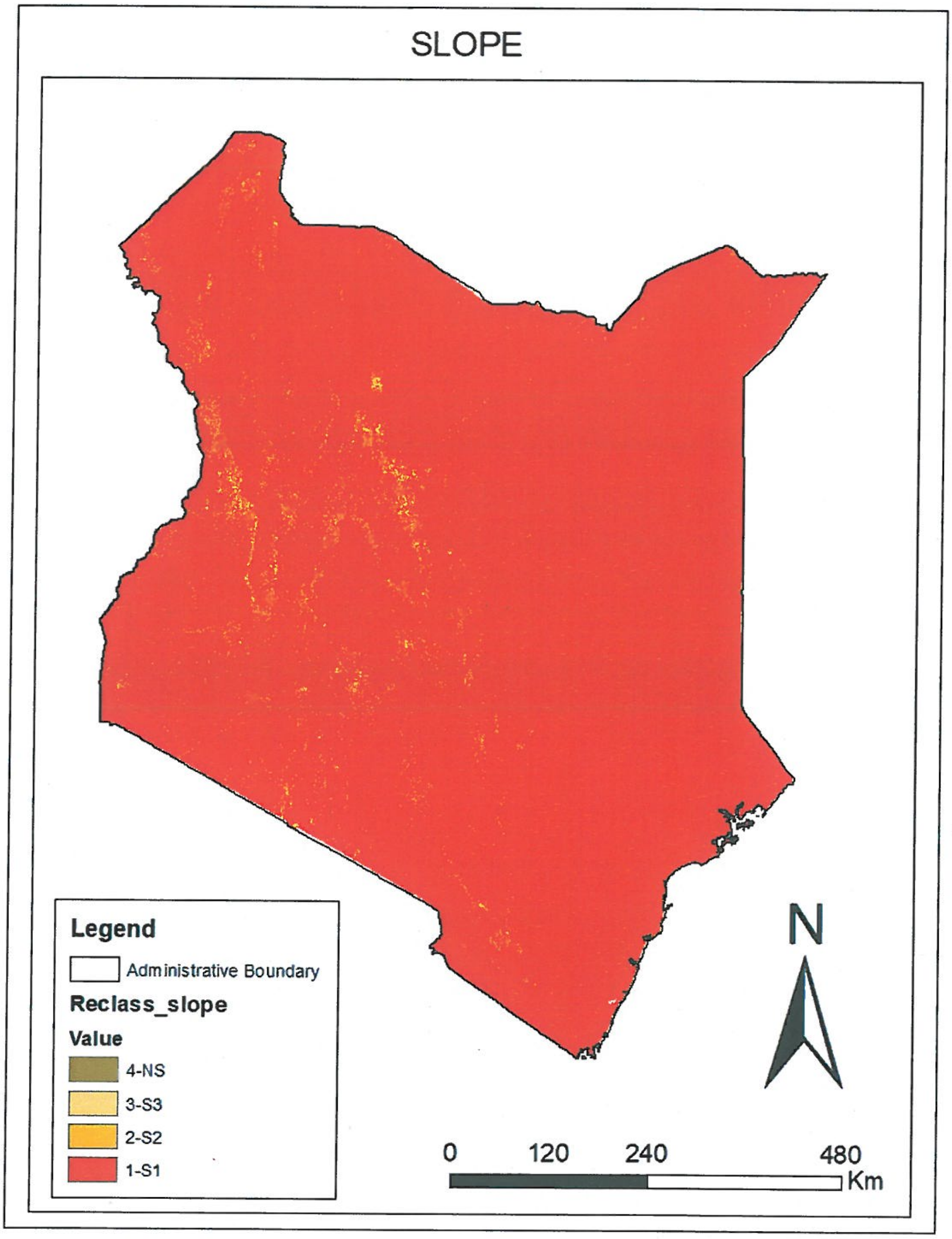

Figure 22: Kenya Slope Suitability Map
***Source:** Author*

e) Rainfall

Figure 23 shows the Kenya's rainfall profile after reclassification.

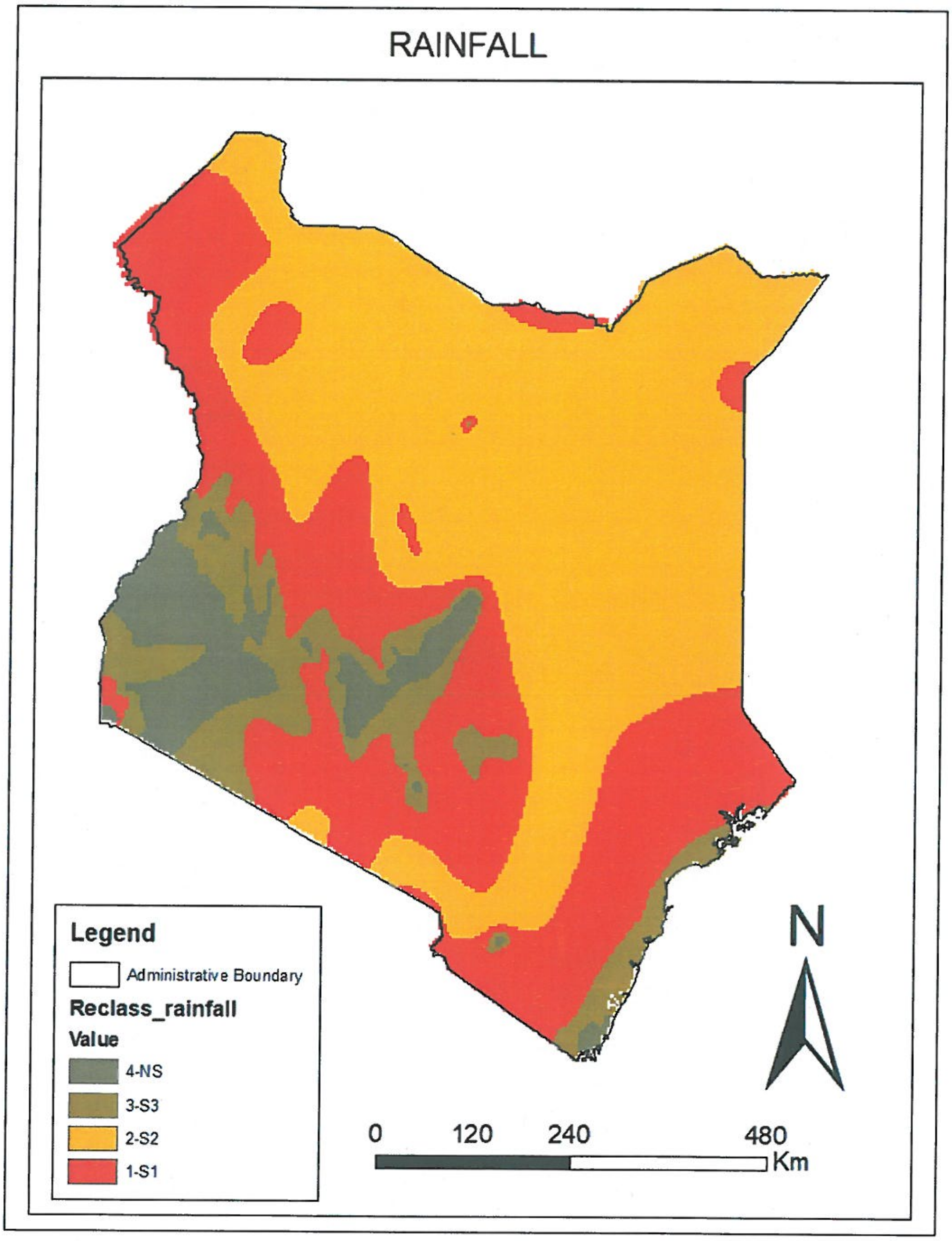

Figure 23: Kenya Rainfall Suitability Map
Source: Author

f) Land Use Land Cover

Figure 24 shows the Kenya's land use land cover profile after reclassification.

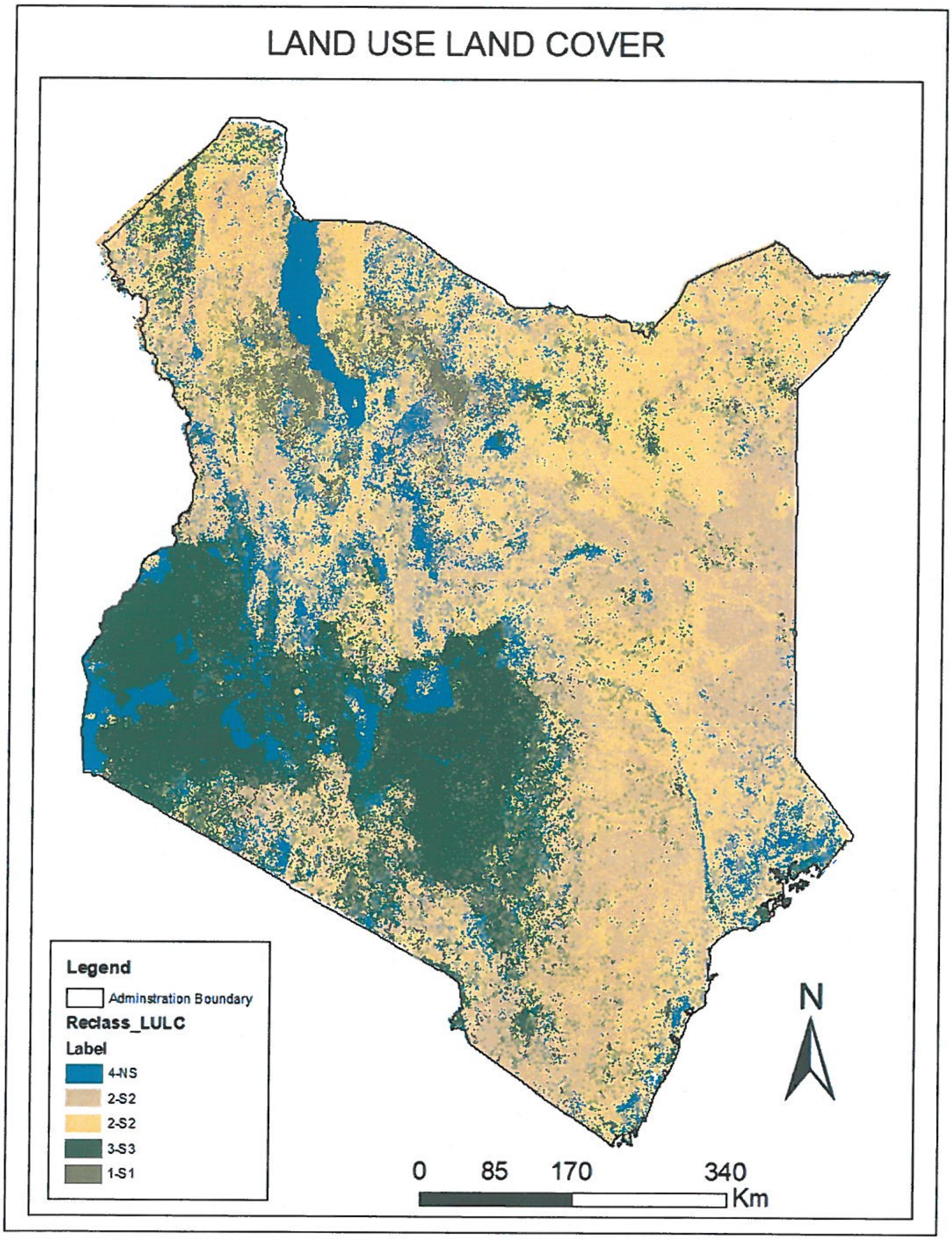

Figure 24: Kenya Land Use Land Cover Reclassified
Source: Author

4.3 Suitability Map

Datasets Weighting

AHP method was used in the overall weighting criteria. The reclassified raster datasets, which are suitability maps for respective datasets, were weighted and different weights assigned to each one of them based on the percentage of influence as shown in Table 3. The percentage of influence on the respective datasets was assigned as guided by a radio astronomer who was consulted in the study.

***Table 3:** Weighting Criteria*

Serial	**Data**	**Weight (%)**
1	Cell Tower	25
2	DEM	25
3	LULC	15
4	Wind speed	15
5	KETRACO Power lines	10
6	Rainfall	10
TOTAL		**100**

Figure 25 shows suitable areas for siting a radio telescope in Kenya. The areas are ranked from the most suitable areas to moderately suitable areas then marginally suitable and finally to areas that are not suitable.

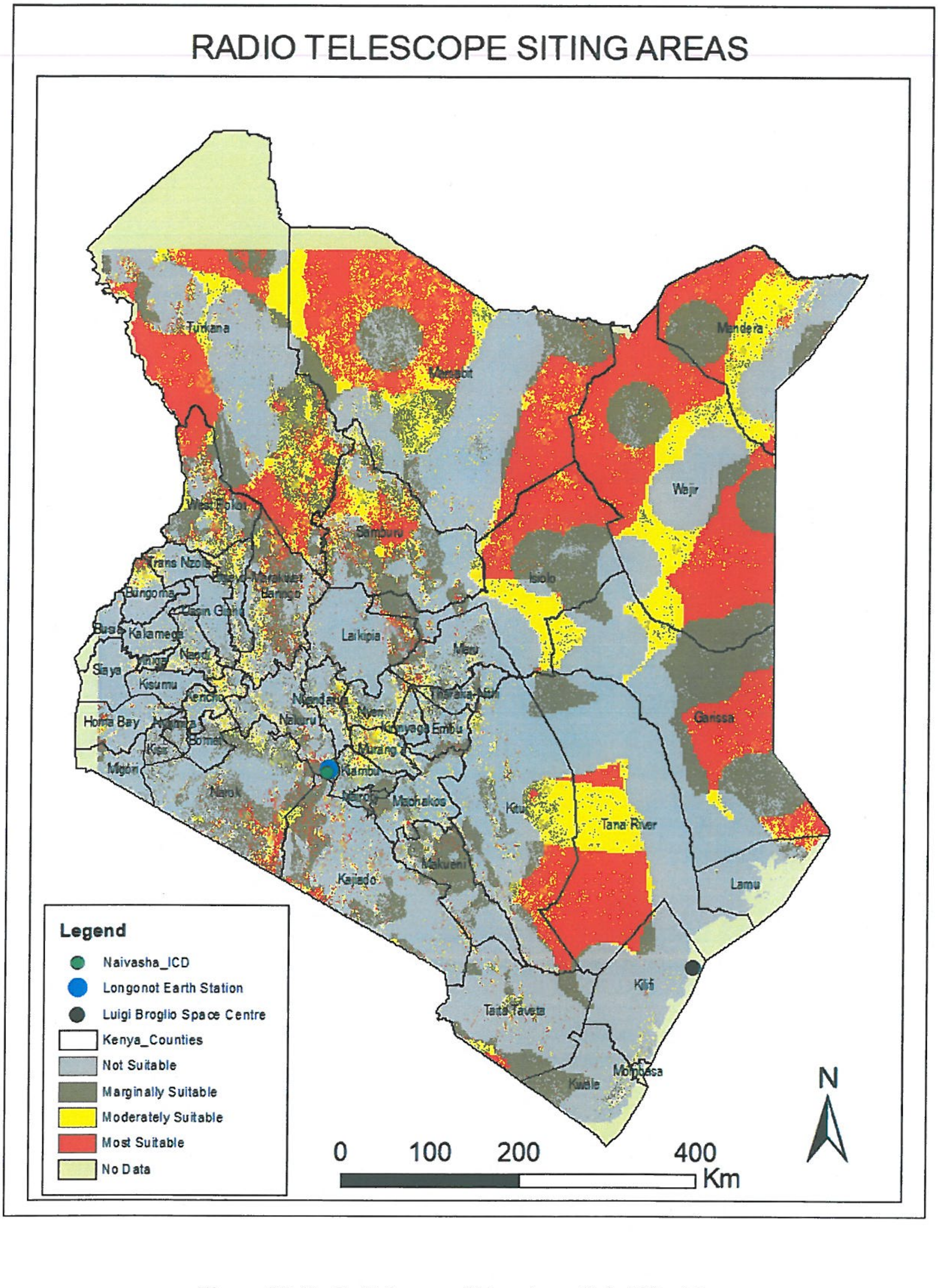

Figure 25: *Radio Telescope Siting Areas Suitability Map*
Source: *Author*

4.4 Discussion of the Results

The most suitable areas are spread across the country. However, northern Kenya and lower eastern Kenya enjoys several areas that can host a radio telescope in Kenya based on the datasets used in the study. The areas are spread across eighteen counties namely: Turkana, Marsabit, Mandera, Wajir, Isiolo, Samburu, West Pokot, Trans Nzoia, Bungoma, Baringo, Laikipia, Meru, Nakuru, Narok, Tana River, Kajiado, Nyeri, and Nyandarua counties. It is important to note that a radio telescope enjoys better shielding from RFI if in a valley than in a plain.

Based on the proposal to construct KIRO, it was suggested that the observatory be constructed in the sparsely populated Northen Kenya just along the equator. Samburu County is ideal for this.

It is important to note that suitable areas in Garissa, Wajir, Mandera, Marsabit, Turkana, West Pokot, Narok, Kajiado, and Taita Taveta counties lie next to Kenya's outer boundary. It may not be advisable to sit a radio telescope in such areas because of national security reasons and varying anthropogenic conditions in the neighboring countries. Such conditions was not factored in in this study which is a recommendation for further study.

Whereas there are proposals from radio astronomy enthusiasts in the country to have the Longonot Earth Station refurbished to a radio astronomy site, as was with Ghana Radio Astronomy Observatory (GRAO), it is important to note that the defunct earth station currently suffers from higher RFI. This is because of growing human settlement around the area. This is because of the considerable infrastructure development in the area key among them being the Inland Container Depot operated by Kenya Railways as shown in Figures 25 above.

It is important to note that this study forms a base study on siting a radio telescope in Kenya. The proposal for constructing KIRO in 2005 by J.O. Malo of the University of Nairobi only recommended areas in Northern Kenya along the geomagnetic equator (Malo and Thide, 2005). However, their proposal does not highlight any scientific method they employed in recommending areas in Northern Kenya as suitable sites; a fact that this study justifies.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The data sets used in this study were cell-tower data, national electricity grid data, rainfall, land-use land cover, wind speed and slope. ESRI's ArcGIS 10.8 software was used for analysis.

Based on the results from the study, it clear that the intended objectives of the study were met. The MADM process of MCDA in GIS was employed to find the suitable sites for siting a radio telescope in Kenya. These areas are distributed among several counties which are: Turkana, Marsabit, Mandera, Wajir, Isiolo, Samburu, West Pokot, Trans Nzoia, Bungoma, Baringo, Laikipia, Meru, Nakuru, Narok, Tana River, Kajiado, Nyeri, and Nyandarua counties.

It is, however, important to avoid areas that lie next to international borderline because of various reasons among them security of state and change of anthropogenic conditions in neighboring states. These conditions were not factored in in this study.

5.2 Recommendations

It is therefore recommended that:

- Further RFI Analysis be conducted in the suitable sites
- Wind gradient analysis be conducted in the suitable sites
- Anthropogenic conditions and national security be incorporated in furthering the study.
- Further suitability analysis to be conducted in respective suitable counties with respect to atmospheric dust, and precipitable water vapor.
- More studies on the subject area should be conducted which should include atmospheric dust, precipitable water vapor, and Kenya's pipeline data which were not factored in this study.

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