University of Nairobi

School of Engineering

DEPARTMENT OF GEOSPATIAL AND SPACE TECHNOLOGY

Mapping Mineral Potential Using Geospatial Techniques: A Case Study of Mui Basin in Kitui County

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F56/7936/2017

A project submitted in partial fulfillment of the requirements for the Degree of Master of Science in GIS, in the Department of Geospatial and Space Technology of the University of Nairobi.

July, 2019

Declaration

I, Sabina Musangi Mutua, hereby declare that this is my original work. To the best of my knowledge, the work presented here has not been presented for a project in any other university.

Sabina Musangi Mutua **…………………………….** **30th July, 2019**

Name of Student: Signature Date:

This project has been submitted for examination with my approval as university supervisor.

Dr. Ing. D. N Siriba **…………………………….** **30th July, 2019**

Name of Supervisor: Signature Date:

Dedication

I dedicate this project to my Almighty God for the knowledge and wisdom He bestowed upon me to enable me pursue my Masters Degree. I would also like to give a special dedication to my late Dad who always advocated the need for education and his constant reminder for me to pursue my Masters Degree and PhD.

I would also like to dedicate this project to my adorable daughter Shirley, my mum, brothers and sister and my best friend Maryam Swaleh who have been very supportive since I began pursuing my Masters Degree.

Declaration of Originality

Name of student: Mutua Sabina Musangi

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Course Name: Research Project

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Acknowledgement

It is by the grace of God that I have made it this far.

My special thanks go to my supervisor, Dr. D.N Siriba for his encouragement, support and patience while working on this research project.

I would also like to thank my employer, Kwale International Sugar Company Limited (KISCOL) for allowing me to pursue my Masters despite the busy working environment.

I would also like to acknowledge my daughter Shirley who understood that sometimes she had to go to bed without seeing me because I would get home late from school, the rest of the family as well for their endless support since I started my Masters Degree and their encouragement while working on this research project.

I would also like to acknowledge my colleagues Regina Ng'ang'a and Benard Omwenga for their continued support while working on my project.

Lastly, I would also like to acknowledge Department of Geospatial and Space technology in the University of Nairobi, School of Engineering, for equipping me with the knowledge and skills that I require in order for me to be able to work on my research project.

Abstract

The process of mineral exploration over the past has been expensive and time consuming and for this reason advanced techniques are being applied in order to save on cost and time and to identify the mineral potential zones. Geospatial techniques are among the techniques that are being applied in mineral exploration and this study shows how this is achieved using Mui Basin in Kitui County as the case study.

In the study, a Landsat 8 image was used for hydrothermal alteration mapping and an existing geology map of the study area was used to identify the lithological units as well as faults. Hydrothermal alteration which is a geochemical factor and geological factors which include lithological units and faults are the primary factors used to show how suitable the study area is for mineral exploration. Color composites and Principal Component Analysis (PCA) techniques were applied in hydrothermal alteration mapping and the results showed hydroxyls which are associated with altered areas while the geology map was used in the preparation of geological suitability factor maps. These layers were then assigned weights using the Delphi model and integrated in a GIS environment using Weighted Index Overlay technique which yielded the mineral potential map of Mui Basin.

The map classifies the study area according to its suitability for mineral exploration i.e. Most Suitable, Moderately Suitable and Least Suitable. The study was meant to show how suitable the area is for mineral exploration especially potential for coal since it has already been discovered in the study area. The results showed potential for coal where the most suitable area for mineral exploration covers the biggest part of the coal mining block.

This research project can therefore be applied for mineral potential mapping at any other area and use of geophysical data in addition to the data used in this project would yield better results since more factors will have been considered to identify areas suitable for mining. The results of this study have therefore shown that geospatial techniques are crucial in reducing the massive fieldwork and identifying potential areas for mineral exploration.

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Abbreviations

ANN – Artificial Neutral Networks

ASTER – Advanced Spaceborne Thermal Emission and Reflection

DEM – Digital Elevation Model

DN Values – Digital Number Values

E. Values – Eigen Values

GDP – Gross Domestic Product

GIS – Geographic Information Systems

GPS - Global Positioning System

IRS Series – Indian Remote Sensing Series

MOS Series – Marine Observation Satellite

MPI – Mineral Potential Index

MPS – Mineral Potential Score

OLI – Operational Land Imager

PC – Principal Component

PCA – Principal Component Analysis

REE – Rare Earth Elements

RGB – Red, Green, Blue

RS – Remote Sensing

SPOT - Satellite Pour l'Observation de la Terre

TIRS – Thermal Infrared Sensor

WoE – Weights of Evidence

CHAPTER 1: INTRODUCTION

1.1 Background

In the recent years, mineral resource mapping has become more evident since minerals which are easily accessible especially those found on or near the earth's surface have already been exploited and the focus has now shifted to the minerals found deep in the earth's crust and in inaccessible areas. The process of mineral exploration over the past has been expensive and time consuming and for this reason advanced techniques are being applied in order to save on cost and time and to clearly identify the mineral potential zones (Rajesh, 2004).

Geospatial techniques are among the techniques being applied in mineral exploration and they include a range of modern tools that are used for geographic mapping and analysis of the Earth and human societies. These techniques include; Remote Sensing, Geographic Information Systems (GIS), Global Positioning Systems (GPS), geovisualization, cartography, among others. These techniques are now being applied in various fields such as meteorology, agriculture, environmental management, archaeology, architecture, automobile integration, business and commerce, climate change, crime, geology among others.

Mineral exploration aims at discovering deposits that are of economic value and facilitating their extraction. The process involves several stages that range from small-scale to large scale and at each stage, geological, topographical, geophysical, geochemical data is collected, processed, integrated and the best platform for integrating all this data is a geospatial environment.

1.2 Mineral Resource Mapping in Kenya

According to the Ministry of mining (2017), geological information has been found to be of great value worldwide and it is useful in other sectors like agriculture and infrastructure other than mining. Availability of both geological and mineral data will enable the private and public sector to make informed decisions when it comes to development of the mineral sector, the government will be able to negotiate sustainable mineral development contracts with foreign investors and the data will provide a basis for assessing the potential for mineral projects and granting exploration and mining permits.

Kenya Nationwide Airborne Geophysical Survey project will help Kenya expand the scope of minerals in order to capture other facets of the country's geophysics. The project which will map the country’s minerals and natural resources. The project is also meant to ensure that Kenya is able to fully exploit and benefit from its minerals wealth by attracting more mineral investment into the country among other key benefits (Ministry of mining, 2017).

1.3 Problem Statement

Kenya is believed to be endowed with numerous minerals but lack of a geological database has impeded their exploitation. There is therefore a need to provide accurate and timely geological data and information due to increased interest in the mining sector. According to the Ministry of mining (2017), Kenya's colonial government had given special focus to the minerals sector. However, after independence the successive government focused mainly on agriculture and tourism. As a result, old colonial information on Kenya’s mineral resources is the one mostly being used to guide investments. With technological advancement, fresh discoveries can be made and this research project therefore shows how geospatial techniques can be applied to identify mineral potential zones using Mui Basin at Kitui County as the case study.

Mui Basin in Kitui County is approximately 60 Km long and 15Km wide and stretches from South to North. Coal deposits have been discovered in the area and for this reason it is a coal basin which is further subdivided into four blocks i.e. Block A, B, C and D. From previous studies of Mui Basin, geospatial techniques have not been applied yet they form valuable supplements to more traditional methods and provide information and perspectives not otherwise available. This study involved mapping of the lithological units, structure and alteration of part of Mui Basin and the different factor maps were assigned weights using Delphi Model and integrated in a GIS environment in order to prepare the mineral potential map of Mui Basin in Kitui County.

1.4 Objectives

Overall Objective

The overall objective was to map mineral potential using geospatial techniques: A case study of Mui Basin in Kitui County.

Specific objectives:

1) To identify factors that influence occurrence of minerals.
2) To generate a hydrothermal alteration map based on a Landsat 8 Image of Mui Basin.
3) To prepare a geological suitability factor map of Mui Basin.

4) To integrate results from (2) and (3) above and prepare a mineral potential map of Mui Basin.

1.5 Justification for the Study

Kenya is known to have numerous minerals which have not been fully exploited. This study will show how geospatial techniques can be applied in mapping mineral potential areas and the same techniques can be applied in Kenya Nationwide Airborne Geophysical Survey project which will aim to ensure that the country's mineral resources are fully explored and exploited and that the country fully benefits from the generated wealth.

The results will help provide a GIS-based decision support to all interested parties for instance Ministry of Energy, National and County Government of Kitui County as well as the general citizenry.

1.6 Scope of work

This study focused on analyzing remotely sensed data and geological data in a GIS platform in an attempt to develop a mineral potential map of part of Mui Basin in Kitui County. The suitability map generated was based on weighted overlay analysis technique and shows how suitable the study area is for mineral exploration and not the specific mineral deposits found in the study area.

Image enhancement techniques such as Principal Component Analysis (PCA) and color composite were used to establish anomalous zones within the study area. Generally, this study involved desktop studies, data analysis, interpretation and presentation.

1.7 Organization of the Report

The first chapter gives the background of the project, problem statement and the objectives of this study are stated. It further indicates the project justification of study and its scope. Chapter two gives in details the literature reviews of the project on areas of; mineral resource exploration, the geology of Kenya and its mineral potential, mineral resources in Kitui County, geospatial techniques and their application in mineral exploration and lastly previous studies of the project. Chapter three begins by showing the study area in relation to the map of Kenya and a clear outline of the methods and tools that were used to achieve the objectives of this study is shown.

The methodology used is discussed in line with the specific objectives of the study and the same is applied in Chapter four which shows the results of the study as well as the discussions of the results. Lastly Chapter five gives the conclusions and recommendations of the study. Results and findings are summarized in the conclusions section while the study is recommended for use in mineral potential mapping in any other part of the world.

CHAPTER 2: LITERATURE REVIEW

2.1 Mineral Resource

Minerals are inorganic substances that occur naturally in the Earth's crust and they constitute the vital raw materials for many basic industries and are a major resource for development. According to Carranza (2008), the demand of minerals in national economy promotes the basic stimulus for investment.

2.2 Mineral Resource Exploration

According to Haldar (2013), minerals with commercially viable concentrations are the ones that are usually targeted when it comes to mineral exploration. The process of selecting these minerals is divided into four phases:

a) **Area selection –** This involves selection of mineral potential zones which requires knowledge of the environment at or near the earth’s surface. This information helps identify any geological processes which may lead to formation of mineral deposits.
b) **Target generation –** having identified mineral potential zones, this step helps demarcate the area and further investigations done until the specific minerals in the area are discovered. Mineral exploration models are used together with geochemical, geological and geophysical datasets.
c) **Resource evaluation –** At this stage, the grade of the discovered minerals and its tonnage is estimated and this is usually largely based on systematic drilling.
d) **Reserve definition –** This phase helps with the classification of the mineral deposits to whether they are ore reserves or mineral resources. This is usually based on technical and economic feasibility analysis.

This study focuses on the first two phases; Area selection and Target generation by identifying the factors that influence the occurrence of minerals and applying some of the factors to show how suitable Mui Basin is for mineral exploration.

2.3 The Geology and Mineral Resource Potential of Kenya

Geology is a science that deals with the physical structure and substance of the earth, their history, and the processes which act on them. Numerous minerals are known to occur in the country and they include both metallic and industrial (Barreto *et. al.,* 2018).

The geology of Kenya is generally grouped into five major geological successions which are clearly indicated in Figure 2-1. The geological successions are as follows;

a) Archean (Nyanzian and Kavirondian)

The Kavirondian system includes the following lithological units; Conglomerates, Sandstones, Mudstones, and Granitic intrusions while the Nyanzian system includes; Pyroclastics, Ironstones, Cherts, Rhyolites, Shales, Andesites and Basalts.

The Archean Nyanzian Craton area is found in Western Kenya and the following minerals have been discovered in the area; Silver, Gold and copper. The same area is also known to have Kimberlitic bodies and a potential for ferrous and no-ferrous metals has been discovered.

a) Proterozoic (Mozambique Belt and Bukoban)

The Bukoban system has volcanics with sediments while the Mozambique belt comprises of quartzites, biotite/hornblende gneisses, schist, granitoid gneisses, amphibolites, migmatites and intrusives include syntectonic granites.

The Proterozoic Mozambique Belt is most extensive in Central Kenya and runs from north to South and contains the following minerals; kyanite, corundum, graphite, wollastonite, marble, asbestos, fluorspar, magnesite, kaolin and a variety of gemstones. The Mozambique belt passes along the area of study.

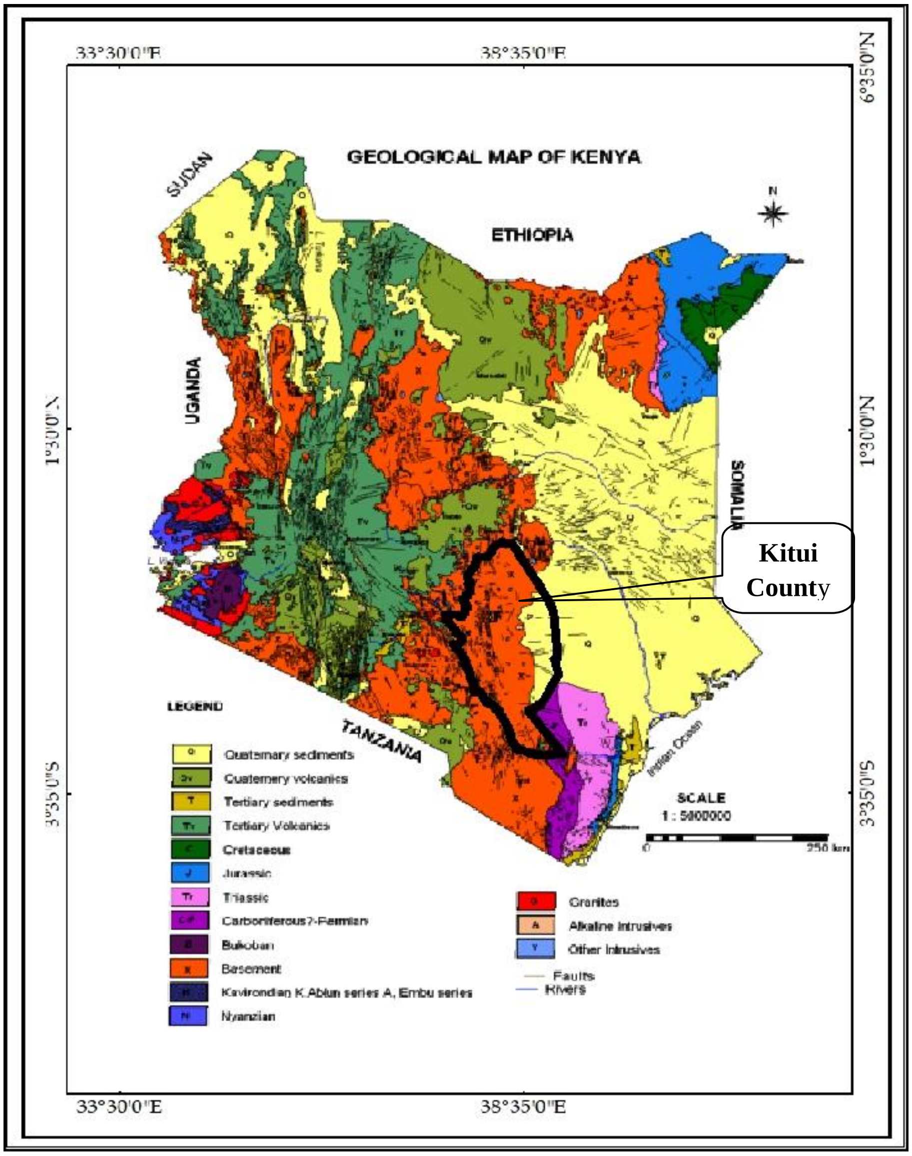

Figure 2-1: Geological Map of Kenya (Source: Barreto et. al., 2018)

b) Palaeozoic/Mesozoic sediments.

These are found in the North Eastern and Coastal areas of Kenya. The earliest of these rocks are Permo-Carboniferous which is largely comprised of sandstones and Shales that form the Duruma series. Mesozoic rocks are found in the north-east part of the country and along the Coastal belt.

c) Tertiary and Quaternary Volcanics

Volcanic rocks cover the central parts of the country occurring in the floor of the Rift Valley and on the plains west and east of the valley. The volcanic rocks associated with Rift System host a variety of minerals and construction materials.

d) Tertiary and Quaternary Sediments

There are many sediments deposits in various parts of Kenya and they host limestone, gypsum, clays, evaporites, trona (soda ash), diatomite, natural carbon dioxide, kunkar, manganese and construction materials and possibly hydrocarbons.

The geology map shows lithologic units some of which are associated with minerals but in order for the specific minerals found in the area to be known further studies or exploration have to be done. This therefore means that the geology map is not sufficient enough to help identify areas potential for mineral exploration. Apart from the lithologic units, inferred faults are also mapped since there are some minerals which are usually found along the faults. For this reason, the geology map is used to facilitate the process but for better results of identifying minerals in an area or determining how suitable an area is for mineral exploration, the geological data obtained from the geological map has to be combined with hydrothermal alteration information as well as geochemical and geophysical data.

From the geological map of Kenya, the study area is covered by tertiary and quaternary sediments. This study combined the data obtained from the geology map (lithologic units and faults) with hydrothermal alteration information in order to show how suitable Mui Basin is for mineral exploration.

2.4 Mineral Resources in Kitui County

Kitui County is believed to have the most mineral deposits within the same area in the whole of Eastern and Central African region. Kitui County would be among the top four richest counties in Kenya if the mineral deposits found within the county were mined and utilized properly.

Mineral deposits found in the county are as shown in Figure 2-2 and include the following;

a) Coal Deposits in Mui-Zombe Basin

Mui Basin in Kitui County is approximately 150Km east of Nairobi and 25Km northeast of the county's capital, Kitui. It is found between latitudes 00° 53' S and 01° 29' S and longitudes 38° 09' E and 38° 19' E. The basin is approximately 60 Km long and 15Km wide and stretches from South to North. It is bounded by Mutitu Hills to the West and Nuu Hills to the East and lies at about 700m altitude (Wamalwa, 2011).

Mui Basin is an area where coal deposits have been discovered and has been subdivided into four exploitation blocks (A - D) and this study focuses on Block C which covers an area of 131.5 Km^2 and is believed to be one of Africa's richest coal deposits estimated at about 400million metric tonnes and worth over Kshs. 3.5 trillion. Although coal has already been discovered at the study area, geospatial techniques have not been applied and that's the focus of this study; to show how geospatial techniques can be applied in mineral potential mapping.

Mining of the coal has however not yet started due to some outstanding issues and for this reason getting coal deposits data or any data for the coal blocks is a great challenge. For this reason, neither the electrical resistivity data nor coal deposits data of the study area was acquired in order to help with the validation of the study results.

b) Iron Ore

Next to the coal deposits are large amounts of ore deposits. The ore deposits are at Timboni in Mutomo- Ikutha area as well as at Tharaka as shown in Figure 2-2.

c) Limestone Deposits

Huge amounts of limestone are found in Mutomo area in Kitui South Sub-County almost adjacent to the coal zone. Other major limestone deposits have been recently established in Ngaaie area in Kyuso Ward, Mwingi North Sub-County.

Some cement manufacturing firms have currently shown some interest in prospecting and eventual mining of limestone in some parts of Kitui County for instance Dangote Quarries Mining Company in Kanziko area and Athi River Mining PLC Company in Ngaaie area of Kyuso ward in Mwingi North Sub-County.

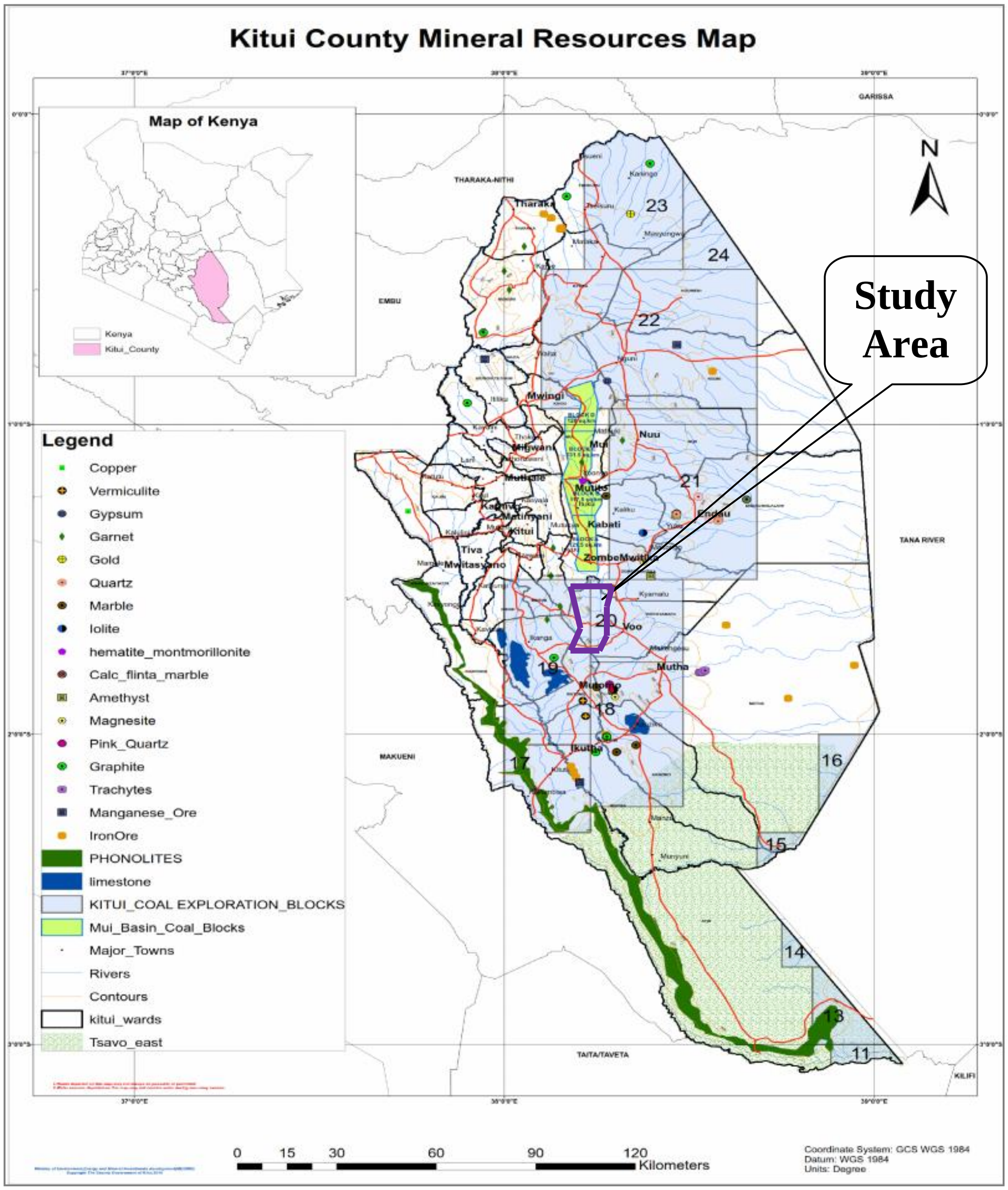

Figure 2-2: Mineral Resource Map of Kitui County (Kitui County, 2018)

d) Copper Carbonate, Zinc and Gold Minerals

Copper Carbonate deposits are known to occur in the County in Mithikwani area of Kitui West, Kwa Vonza in Kitui Rural and Kamuwongo in Mwingi North Sub- Counties. These can be used to extract copper.

Zinc deposits are also found in Kitui and they are used together with copper to produce the brass alloys which have many uses in the industrial production.

Gold is usually found in association with Copper ores in the areas named above. But ores rich in gold are also found in some parts of Kitui East Sub- County. There is therefore need for extensive exploration to be undertaken to clarify the amounts and qualities of the copper, zinc and gold ore deposits.

e) High Quality Sand for Construction

Kitui is endowed with huge amounts of very high quality sand in all its many rivers and streams. Sand is an important commodity in the construction and glass making industries. The County Government of Kitui is in the process of developing Kitui County Sand Harvesting Bill to streamline sand harvesting in the county.

f) Granites and Phonolite Deposits

The County has also huge deposit of granites and phonolites and phonolite (clinkstone) that are used in the construction and building industries. These minerals are crushed with heavy machinery to generate ballast to various sizes which have many uses in the building and construction industries.

g) Clay for Brick and Ceramic Making

Clay deposits are also found throughout the County. Clay is as an important commodity for making bricks and ceramics. The presence of sand, clay and granites can therefore support the construction and building industries in the County as well as exporting to neighboring Counties.

h) Sillimanite and Gypsum Deposits

Other notable minerals found in Kitui County include sillimanite which is important in the manufacture of glass and in refractory insulation.

Gypsum occurs alongside limestone and has applications in the manufacturing of wall boards, cement and plaster.

i) Gemstones

A variety of rubies; green, red and yellow garnets, amethyst; and sapphire gemstones that already are exploited by artisanal miners are present across the County especially at Kathua and Kanondo area. If proper extraction methods are applied, the production of gemstones would greatly improve and attain commercial levels.

j) Vermiculite

This mineral has many industrial uses such as high temperature and refractory insulation and in brake–linings. Vermiculite is also used in the manufacture of structural steels and pipes, paint and packaging materials. It is used in agriculture as a soilless growing medium, soil conditioner and in the storage of bulbs and root crops.

k) Magnesite for Magnesium Extraction and Barium

Other notable minerals known to occur in Kitui County are magnesite that is used to extract magnesium. Magnesium has wide industrial applications in the manufacturing of beverage cans, iron, steel, motor parts and batteries among others.

Baryte also occurs in some places and can be used to produce barium which is used in the production of fireworks, in glassmaking and in the electronics industry as well as in X-ray tubes.

2.5 Coal Origin and Composition

Coal has been known to be a carbonaceous sedimentary rock which is solid black or brownish black formed as rock strata called coal seams. It is formed through biological changes and subsequent effects of temperature and pressure which alter accumulated partially decomposed vegetation to coal. Coal is comprised of mainly carbon and other elements which include hydrogen, sulphur, oxygen, nitrogen, moisture and noncombustible inorganic matter (Wikipedia, 2019). According to nptel.ac.in (2019), the three major components of coal are carbon, hydrogen and oxygen.

Table 1: Classification of Different Types of Coal (Source: Wikipedia, 2019)

Types of Coal	Description
Peat	It is the precursor of coal formed
Lignite	With increased temperatures the peat is converted to lignite which is considered as the lowest rank of coal. It is considered as immature coal and is brown colored, soft, low calorific value coal and compact in texture.
Sub-bituminous	It is black colored and more homogeneous in appearance and its properties range from lignite to that bituminous coal.

Bituminous Coal	It is usually black, with higher carbon content and calorific value
Anthracite Coal	It is highest rank coal and is harder and glassy black coal known to contain the highest carbon and calorific value.
Graphite	Graphite is the highest rank and is difficult to ignite.

2.6 Geospatial Techniques and their Application in Mineral Exploration

2.6.1 Remote Sensing

Remote sensing is the science and art of acquiring information about the Earth's surface without actually being in physical contact with it. Increased launching of satellites has enabled widespread adoption of the Remote Sensing technique. Some of these satellites include; SPOT series, LandSat series, Skylab, ASTER, IRS series, JERS-l, ERS series and MOS series. LandSat and ASTER images are used for geological mapping due to their spectral capabilities (Abrams *et al*., 2002).

a) Landsat and ASTER Systems

Landsat data is used for various purposes like locating iron oxides or even hydrous minerals as well as hydrothermal alteration. ASTER obtains information on reflectance, surface emissivity, elevation and temperature. ASTER obtains data in 14 spectral channels of the EMS from the visible through thermal infrared regions of the EM. It consists of three separate instrument subsystems (Abrams *et al.*, 2002).

According to Rajesh (2004), ASTER 4 operates in the spectral range 1.6-1.7 µm, which is a general high-reflectance band; ASTER 6 (2.225 – 2.245 µm) is absorbed by the AI –OH minerals, whereas ASTER 8 (2.295 – 2.365 µm) corresponds to the absorption by Mg –OH minerals.

Since the study area has already been mapped as a coal block, this study used Landsat 8 image where principal component analysis (PCA) technique was applied for hydrothermal alteration mapping in order to determine how suitable the area of study is for mineral exploration. Principal Components of bands 2, 5, 6 and 7 were used to map hydroxyls since oxygen and hydrogen are among the main components of coal. The same technique was used by Guha *et. al* (2018) to map hydroxyls in Malanjkhand in India.

b) Spectral Signatures of Minerals and Rocks

Rocks and minerals reflect and absorb electromagnetic radiation as a function of the wavelength of the radiation. Different rocks have different spectral signatures and it's from this that individual minerals and groups of minerals can be identified. The absorption in the wavelength region 0.4 µm–2.5 µm is commonly used to determine the mineralogical content of rocks. According to Hunt (1977), mineral structures are such that there are numerous absorption bands which are as a result of electronic transitions and ion vibrations. Although there are a wide variety of minerals, electronic transitions are most common and often created by iron while vibrational ones are created by water, hydroxyl ions or carbonates.

c) Satellite Imagery Processing

The following digital processing techniques are applied in mineral exploration;

i. Panchromatic Sharpening (Pan-Sharpening)

This technique is very important when it comes to image processing because it makes an image twice as detailed. The image becomes more valuable since features that would have been hard to see are revealed. The technique involves the combination of a high-resolution detail from a panchromatic band with the lower-resolution color information of other bands (usually only the visible bands).

The spectral bands of Landsat 8 have a resolution of 30 meters per pixel, while the panchromatic band has a resolution of 15 meters per pixel. Unlike other bands, the panchromatic image captures a much wider range of light, allowing it to be significantly sharper. As a result, panchromatic imagery is twice as detailed as the individual spectral bands.

ii. Red, Green, Blue (RGB) Color Composites

Table 2 shows the various Band combinations for Landsat 8;

Table 2: Landsat 8 Band Combinations

	Color Composite	**Band Combinations**
1.	Color Infrared	5, 4, 3
2.	Natural Color	4, 3, 2

3.	False Color	6, 5, 4
4.	False Color	7, 6, 4
5.	False Color	7, 5, 3

In order for a composite image to be created, Red, green and Blue bands are used. The three bands which form the visible portion of the EMS are combined with the multispectral information hence making it visible to the human eye (Lillesand et al. 2015). The image is further enhanced by combining the RGB bands and infrared portions (Mia and Fujimitsu, 2012).

iii. Band Ratio Technique

Band ratio is one of the many techniques that have been developed to get significant performance and image quality enhancement of features. It helps identify hydrothermally altered rocks.

Band ratio is a multispectral image processing method and is a powerful technique in remote sensing. It is prepared by dividing the Digital Number (DN) of one band by the corresponding DN in another band for each pixel and displaying the new DN value as grayscale image (Sabins, 1999; Drury, 2001). It highlights the spectral difference between materials and reduces the variable effects of solar illumination and topography.

Band ratio technique has been widely utilized for visual interpretation and thematic classification of multi-spectral remote sensing data, especially for geological mapping. It has also been widely used to extract information about hydrothermal alteration zones in the analysis of different satellite sensors data.

The band ratio is expressed mathematically as

$$BV_{i,j,r} = \frac{Bv_{i,j,k}}{Bv_{i,j,k}}$$

Where, $BV_{i,j,r}$ is the output ratio for the pixel at row i; column j ; $BV_{i,j,k}$ is the brightness value at the same location in band k, and $BV_{i,j,l}$ is the brightness value in band l. Theoretically the range of BV i, j, r is from 0 to ∞, but actually, the range is from 1/255 to 255.

In band ratio images, the black and white extremes represent the areas with the greatest difference in the spectral reflectance of the two bands (Sabins, 1997).

Band ratios are employed to map and identify altered rocks. Ratio images can be combined to produce a color image of any three monochromatic ratio datasets as G-R-B (Green- Red- Blue): this technique provides more geological information and shows greater contrast between rock units and very easy for visual interpretation.

According to Manuel *et. al.* (2017), the following ratios are the most commonly used in geosciences;

i. B6/B7 – the clay ratio which is used for distinguishing argillic and non-argillic materials
ii. B4/B2 – the iron oxide ratio which allows the contrast between FeO and non-FeO materials
iii. B6/B5 – the ferrous mineral ratio which is used to enhance iron-bearing materials
iv. B4/B5 – the ratio used for contrasting rocks / soil and vegetation
v. (B5 - B4) / (B4 + B5) – called Normalized Difference Vegetation Index (NDVI) which is used for distinguishing between vegetation and non-vegetation.

iv. Principal Component Analysis (PCA)

PCA is a multivariate statistical technique which selects uncorrelated linear combinations (eigenvector loadings) of variables in such a way that each successively extracted linear combination, or principal component (PC), has a smaller variance. The statistical variance in multispectral images correspond to the spectral response of various surface materials such as rocks, soils, and vegetation, and it is also controlled by the statistical dimensionality of the image data (Loughlin, 1991; Singh & Harrison, 1985). The algorithm (Richards, 1995) can be defined as:

$$y = G \# x$$

Where:

y is the transformed, or rotated data (i.e., the principal components data),

G is the transformation matrix,

x is the original data,

refers to matrix multiplication.

Crosta Technique

This technique specifically uses four image bands to evaluate of PCA eigenvector loadings to decide which of the principal component images will concentrate information directly related to the theoretical spectral signatures of specific targets.

2.6.2 Geographic Information Systems (GIS)

GIS is a computer-based information system that enables capture, modeling, storage, retrieval, sharing, manipulation and presentation of geographically referenced data. When it comes to mineral exploration, geophysical, geological and geochemical data is used together with data acquired from aerial photos, topographic maps, remote sensing among others.

GIS helps identify anomalies associated with target mineral areas, gradually reducing the original extent area to a small set of anomalies. This process is usually complex and needs both analysis and integration of the above multithematic exploration information, from which decisions must be made over time and at different stages.

This process usually involves four steps;

i. Creating a spatial digital database
ii. Extracting predictive evidence for a particular mineral deposit type
iii. Calculating weights for each predictive evidence map
iv. Combining the maps to predict mineral potential

The probability that a mineral deposit exists increases where the predictor themes overlap.

The database building is the most time consuming process and it includes; remote sensing data, geophysical data (magnetic, gravity), geochemical data (structural, lithological), topographical data (DEM), and mineral occurrence data.

The main function of GIS is to analyze the spatial relationships between data sources and it can be done through the following ways;

i. Based on the criterion on combining (overlaying) multi-class maps (Bonham Carter, 1994)

ii. Referenced to a practical concept called Mineral Potential Index (MPI) or Mineral Potential Score (MPS). This involves assigning scores to each class-map and weights to each input-map according to some criteria thus leading to the final MPI or MPS map.

GIS Integration Models

The integration models can be divided into two according to Bornham Carter, (1994);

a) Knowledge-Driven Models

These models determine the weights and the ratings using subjective experts knowledge and they include; AHP, Delphi, Ratio Estimation, Weighted Index Overlay, Fuzzy Logic and Multi-Criteria evaluation among others.

This study will apply the Delphi Model which according to Hosseinali & Alesheikh (2008), the model helps provide reliable information for weighting. The method involves gathering information from a group of experts using questionnaires and the method is characterized by anonymity, controlled feedback and statistical response. The questionnaires are then used to come up with the decision about the assigning of weights.

Once the weights have been established from the Delphi process, Weighted Index Overlay will be applied in an ArcGIS environment and hence used to achieve the fourth specific objective which will be preparing a mineral potential map.

b) Data-Driven Models

These models reduce the biasness of the knowledge-driven models by estimating model parameters using quantitative data. Samples of results are required in order for them to be executed and evaluated. The models include; Logistic Regression, Weights of Evidence (WoE) Modeling, Dempster-Shafer Belief Functions, Certainty Factors, Bayesian Statistics and Artificial Neutral Networks (ANN) among others.

The data-driven approach requires one to have mineral data of the target area which is unlike the knowledge-driven models. Both data-driven and knowledge-driven models involve assumptions that are difficult to satisfy when dealing with geological variables such as linear relationships. ANNs, however, are an exception and seem to offer other methods because they make no assumptions about the data.

2.6.3 Application of Geospatial Techniques in Mineral Exploration

According to Rajesh (2004), geospatial techniques are applied in mineral exploration in the following ways;

a) **Lithologic Mapping**: This is usually the first step when it comes to mineral resource mapping projects. When geospatial techniques and potential field data are used for lithologic information extraction, better results are usually achieved. Some of the lithological information extracted includes; weathering and landform, general geologic setting, drainage, structural features, soil, vegetation, and spectral characteristics.

b) **Structural Mapping**

This is the identification and characterization of structural expression that includes; faults, folds, synclines and anticlines and lineaments. It is necessary for supplementing the lithologic information extracted from the stage above. It involves the mapping of linear and geologic features that help locate specific minerals. This information helps in the planning process of mineral exploration.

c) **Hydrothermal Alteration Zones Mapping**

The presence of altered rocks is the main indicator of the possible ore deposit in the case of hydrothermal alteration zones mapping which is one of the most common applications in Remote Sensing for mineral exploration (Sabins, 1999; Rajesh, 2004). The way hydrothermally altered rocks are spatially distributed helps in identifying the main outflow of hydrothermal systems which are then used to identify mineral deposits.

The characterization and delineation of hydrothermal alteration can thus be of great value in exploration of minerals and assessments of mineral potential zones.

2.6.4 Previous Studies

The use of geospatial techniques in mineral exploration is not a new idea. Several studies have been undertaken as discussed below;

Guha *et al.*, (2018) evaluated the Crosta technique for alteration mineral mapping in Malanjkhand copper mines in India. A Landsat 8 (OLI) image was used for the study and the Crosta technique was applied using six bands (2, 3, 4, 5, 6, 7), then four bands (2, 4, 5, 6) to map iron-oxides and bands 2, 5, 6, 7 to map hydroxyls in the study area. The resulting images were then compared and they concluded that the Crosa technique is more effective in determining alteration types using six bands than the selected four Landsat OLI bands.

Hosseinali & Alesheikh (2008) showed how spatial information can be weighted in GIS for copper mining exploration. They identified and assessed six weighting methods which they grouped into two; Knowledge-Driven and Data-Driven. The Knowledge-Driven included Ratio Estimation, Analytical Hierarchy Process (AHP) and Delphi while the Data-Driven included Weight of Evidence (WoE), Logistic Regression and Artificial Neutral Networks (ANNs). The six methods were applied and evaluated to assign weights to the following factors that were used for the study. That is, Boreholes, geochemical, geophysical and geological data. The different factor maps were then integrated and a mineral potential map prepared. They concluded that the ANN approach yielded the most accurate map.

Manuel *et. al* (2017) used remote sensing for mineral exploration in Central Portugal. They used elevation data and satellite imagery to provide new digital images for the interpretation of the geology. The new interpretations were integrated with information from other sources in order to define locations suitable for Au-Ag and Sn-W occurrences. The digital processing techniques used were: RGB color composites, directional spatial filters, Principal component Analysis (PCA), band ratios and image classification. This enabled them to rank the areas they had targeted according to their potential for the minerals.

Mia & Fujimitsu (2012) mapped hydrothermal altered mineral deposits using Landsat 7 ETM+ image in and around Kuju volcano, Kyusu, Japan. They applied color composite, band ratio and Principal Component Analysis (PCA) techniques in their study and according to them, color composite and band ratio techniques showed efficiency in defining the area of hydrothermal alteration while PCA illustrated the iron-oxides and hydroxyl altered minerals area of the region very clearly. The Crosta technique was applied in this study to map the Principal Components and it can be seen that they were able to successfully map all the hydrothermally altered minerals within the study area.

Muriithi (2008) used GIS as a tool for mineral exploration. He prepared geomorphological, lineament, ferrous mineral, iron oxide, clay minerals and mineral composition layers and weightages map of all layers for overlay analysis. His results showed that a considerable amount of area has moderate iron oxide but poor clay mineral and ferrous contents and that faults controlled the mineral occurrences in the area.

Pour & Hashim (2015) used Landsat 8 data for hydrothermal alteration mapping at Sar Cheshmeh copper mining district in the South-eastern Islamic Republic of Iran. They were able to identify vegetation, iron-oxides and hydroxide and clay and carbonate minerals, silicate mineral and lithological units for the exploration of porphyry copper.

Rajesh (2004) showed how geospatial techniques can be used in mineral resource mapping. He focused on application of remote sensing in structural, alteration and lithologic mapping and also showed how hyperspectral Remote Sensing can be used to identify and map areas of exploration potential by the use of distinct absorption features of most minerals.

Sabins (1999) also used remote sensing technique for mineral exploration and the following were his findings: rock structures, types, and hydrothermal alteration can be interpreted on a digitally processed TM image; wavelengths that cannot be detected by human eye are used to express occurrences of important hydrothermal minerals; Image interpretation produces a mineral potential map; the image can also be used for planning how the mineral potential areas can be accessed; and a geologist can efficiently locate, evaluate, and sample the mineral potential areas.

This study adopted the methodology used by Guha *et al*., (2018) in preparing the hydrothermal alteration map of Mui Basin in Kitui County as well as Hosseinali & Alesheikh (2008) study where the Knowledge-Driven methods: Delphi and Weighted Overlay Analysis techniques were applied in this study to assign weights to the primary factors used and their integration in order to prepare a mineral potential map of Mui Basin in Kitui County.

The Crosta technique was used since it clearly maps the hydrothermally altered areas (Guha *et al*., 2018) and the Knowledge-Driven methods as used by Hosseinali & Alesheikh (2008) were adopted because the coal deposits data for the study area could not be obtained and hence only the Knowledge-Driven methods could be applied in this study to assign weights to the primary factors considered in this study.

CHAPTER 3: MATERIALS AND METHODS

3.1 Study Area

Mui Basin is located in Kitui County and is approximately 150Km east of Nairobi and 25Km northeast of the county's capital, Kitui. The study area which covers an area of 131.5 Km^2, lies within the larger Mui Basin which is bounded by latitude 1°30'S and 1°1.03'S and longitudes 38°09'E and 38°17'E (Wamalwa, 2011).

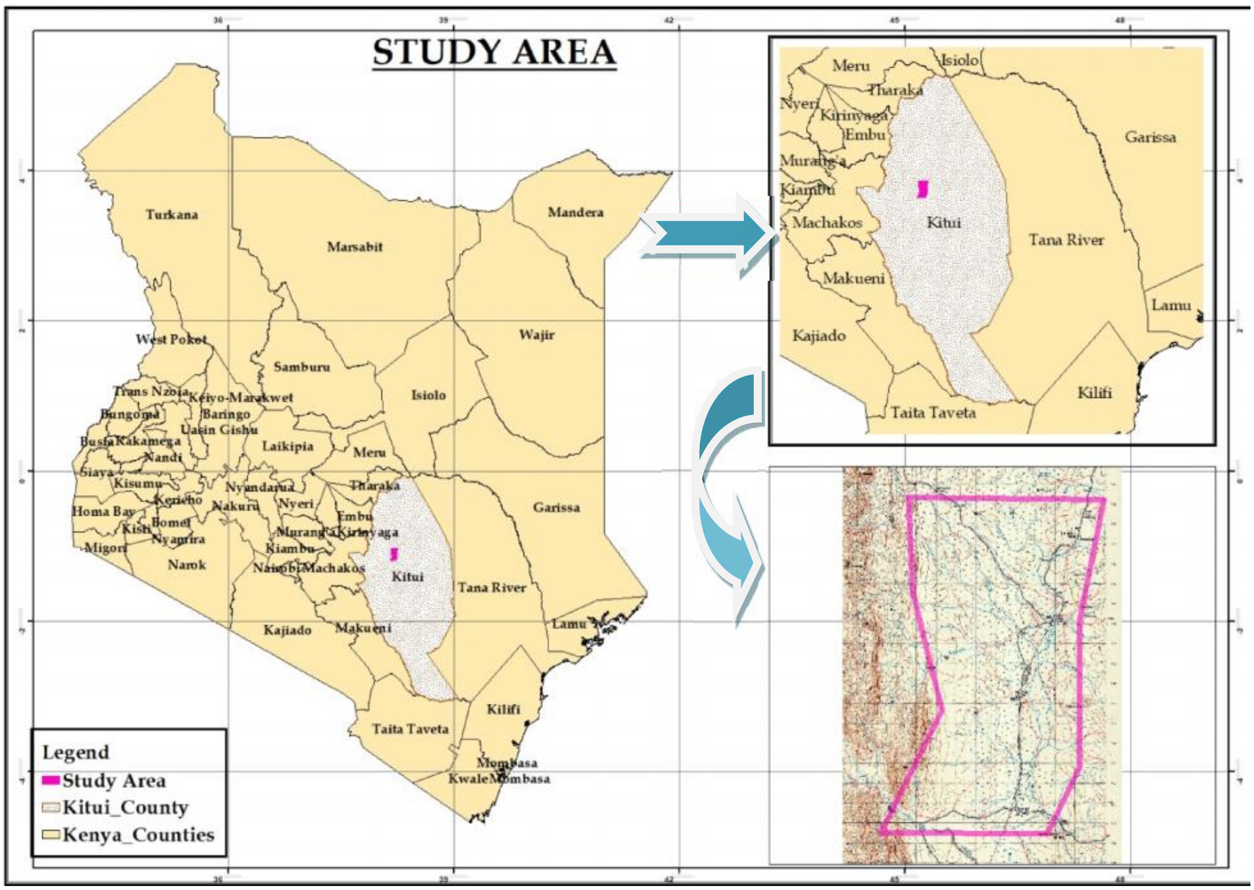

Figure 3-1: Study Area

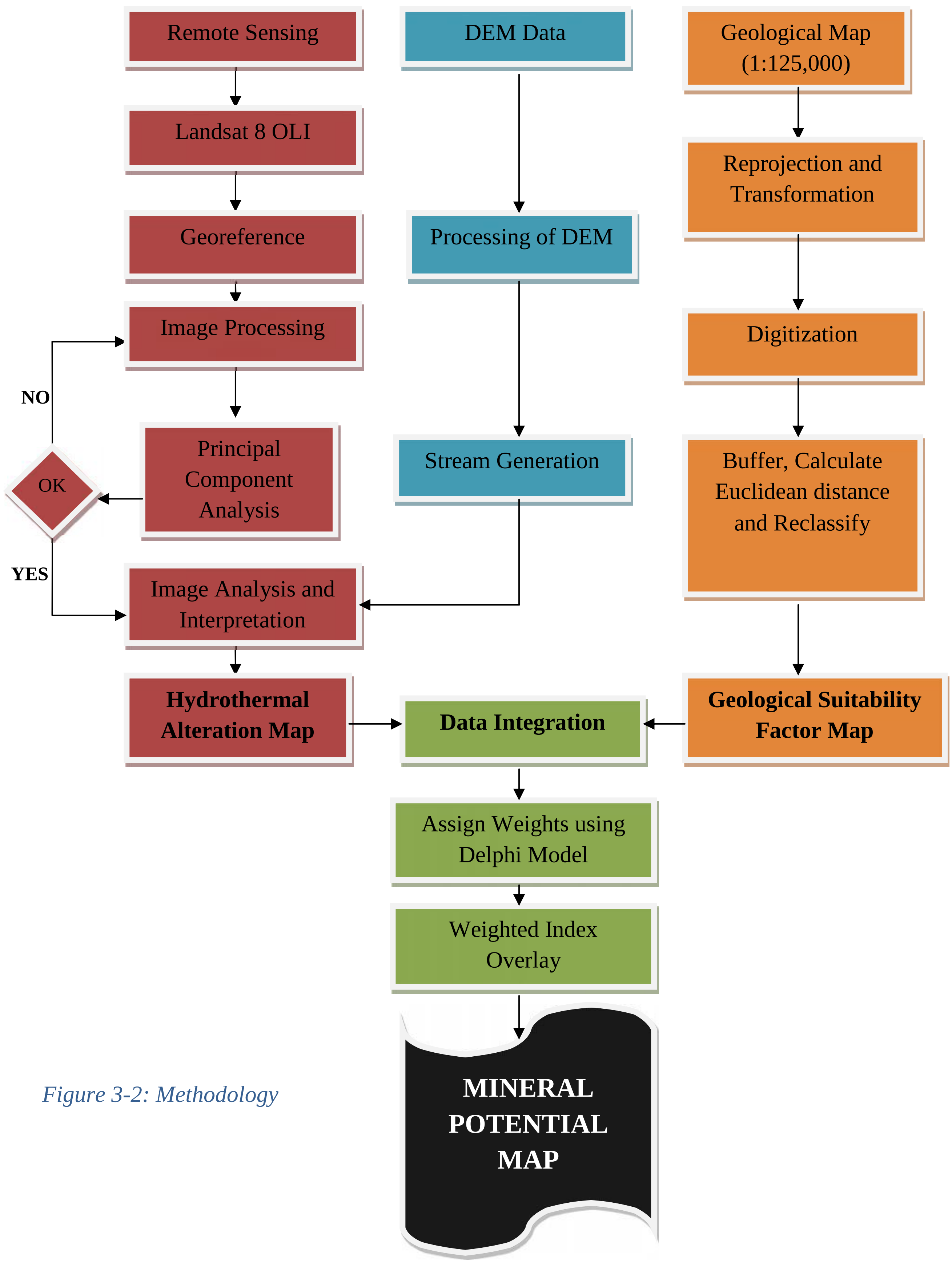

Figure 3-2: Methodology

According to Gupta (2017), in order to select the most efficient methods and tools used for mineral exploration studies, the mode in which the targeted minerals is formed and occur has to be considered. The methodology that was adopted for this study is as described in Figure 3-2 and is clearly explained in section 3-2 which is the next section of this report.

3.2 Methodology

3.2.1 Factors that Influence the Occurrence of Minerals

This first specific objective was achieved using existing literature and the factors were grouped into the following according to Hosseinali & Alesheikh (2008);

a) Geological Factors.

b) Geochemical Factors.

c) Geophysical Factors.

The above factors are usually considered when determining how suitable an area is for mineral exploration. The generated individual maps are called factor maps which are then assigned weights according to their influence in the occurrence of minerals and integrated to form the mineral potential map of a study area. There are different methods that can be used to assign weights to the factors and they are grouped into Data-Driven and Knowledge-Driven. This study applied the Knowledge-Driven methods since the mineral deposits data could not be obtained in order to apply the Data-Driven methods which are more accurate in assigning weights according to Hosseinali & Alesheikh (2008). Assigning of weights is important since different factors have different influences on occurrence of minerals.

This study applied the following factors;

a) Geological factors which included lithological units and faults and;

b) Geochemical factor which in this study was hydrothermal alteration.

The Delphi method was therefore used for this study and a Monkey Survey was sent to twenty eights geologists and fifteen responses were received.

3.2.2 Hydrothermal Alteration Mapping

This objective was achieved using a satellite image and the DEM of the study area. The satellite imagery and DEM data were both processed in order to provide new digital images for geological interpretation.

a) Satellite Imagery

This study used a satellite image that was clipped from the Landsat 8 scene LC08_L1TP_167061_20180530_20180614_01_T1 (available at: earthexplorer.usgs.gov), collected by sensors OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor). The digital processing of the image was done using ArcGIS 10.6.1 software. This study used bands 1,2,3,4,5,6,7 of the image for hydrothermal alteration mapping.

b) Satellite Imagery Processing

The following digital processing techniques were used;

i. Panchromatic Sharpening (Pan-Sharpening)

The Landsat 8 image used for this study had a resolution of 30 meters and therefore a composite of bands 1, 2, 3, 4, 5, 6, 7 was created and pan-sharpened using Band 8 of the same image. This yielded a sharper image with a resolution of 15 meters. The resulting image was then used to create the color composites as well as performing Principal Component Analysis (PCA).

ii. Red, Green, Blue (RGB) Color Composites

Three color composites were produced for this study. They include natural color composite which was created using bands 4, 3, 2; false color using bands 6, 5, 4 and Color infrared using bands 5, 4, 3. The three color composites were used in the interpretation process of the resulting image from PCA process. They helped distinguish the various features found in the study area and hence identify the hydrothermally altered areas.

iii. Principal Component Analysis (PCA)

This study aimed at identifying hydroxyls in the study area in order to show the altered and unaltered areas. Hydroxyl (OH) component shows evidence of water which when it interacts with rock units causes alteration. Presence of Hydroxyl would mean presence of Hydrogen and Oxygen in the study area which form major components of coal which is found in the study area.

Crosta Technique was applied where band 6 and 7 were be used to highlight hydroxyl bearing and clay minerals which tend to have high absorption at band 7 and high reflectance at band 6.

c) Digital Elevation Model (DEM) data

The DEM data was clipped and processed using ArcHydro Tools in ArcGIS 10.6.1 software environment and was use to generate streams in the study area. The streams tend to flow along altered areas and for this reason they were generated and overlaid with the map showing presence of hydroxyls. This helped with the interpretation of the hydrothermal alteration map prepared in this study.

In the Arc Hydro Tools window, terrain preprocessing was first done using the following process; **Fill Sinks –** This function helped fill sinks in the grid. If cells with high elevation surround cell, the water is trapped in that cell and cannot flow. The Fill Sinks in ArcHydro Tools hence helped modify the elevation value in order to eliminate these problems. The output was the Hydro DEM layer ("Fil") which was then used in computing the flow direction as explained in the next step.

Flow Direction – This function was used to compute the flow direction of the grid and the values in the cells of the flow direction grid indicated the direction of the steepest descent from that cell. The input of this procedure was the Hydro DEM layer ("Fil") from the previous procedure of filling sinks and the output Flow Direction Grid ("Fdr") was added to the map and used in the next step of computing the flow accumulation.

Flow Accumulation – This function computed the flow accumulation grid that contained the accumulated number of cells upstream of a cell, for each cell in the input grid. The input for this procedure was ("Fdr") from the previous step and yielded the flow accumulation grid "Fac" which was added to the map

Stream Definition – This function computed a stream grid which contains a value of "1" for all the cells in the input flow accumulation grid "Fac" that had a value greater than the given threshold.

Once the streams were defined, in order for them to be visible they were converted from the grid file into shapefile through the following steps: Spatial Analysts Tool> Hydrology> Stream to Feature> Input Stream Raster (Select str) Input Flow Direction Raster (Select Fdr)>Ok

The streams of the study area were therefore obtained and overlaid with the results of the PCA to help in the interpretation process of the image.

3.2.3 Preparation of a Geological Suitability Factor Map

Mineral resources are associated with the lithology of the area as well as other geological features like faults. For this reason, in order to prepare the geology factor map of the study area, the Geological Map of the Kitui Area (Sheet No. 53; Scale 1:125,000) was used. The geological map was obtained from Mines and Geological Department. The georeferenced and clipped map of the area of interest was processed using ArcGIS 10.6.1 software.
The following methods were applied in order to achieve this specific objective. The summary of the methods used is shown in Figure 3-2.

a) Re-projection and Transformation

Re-projection and transformation of the geology map of the study area was done in order to have all the data in a uniform coordinate system.

b) Digitization

The different rock units found in the study area were digitized as well minerals and faults in the area. These are the features that were used to determine how suitable the study area is for mineral exploration by assigning weights to them. They were digitized since some minerals are associated with certain rock units and at the same time some minerals are usually found along faults. The digitized layers were used to prepare a geology map of the study area.

c) Proximity Analysis

Buffering Technique was used to filter unsuitable areas for mineral exploration. The technique was also used to establish proximity to an evidence layer in this case proximity to faults.

According to Noorollahi *et. al*., (2015), faults are buffered using 1000m and the same was applied for this study.

Euclidean Distance Calculation and Reclassification

The euclidean distance was then calculated for the faults and reclassified into three classes; Most Suitable, Moderately Suitable and Least Suitable.

This step yielded several maps showing how suitable the study area is based on the faults found in the area.

3.2.4 Preparation of a Mineral Potential Map

The final specific objective was achieved by the integration of the results from hydrothermal alteration mapping and geological factor mapping as shown in Figure 3-2. Delphi Model was used for this purpose in order to assign weights to the various factors used to determine how suitable the study area is for mineral exploration. The factors considered include; Faults, Lithologic Units and hydrothermal alteration. The lithological units were subdivided into two; weathered Mozambique Belt rock units and Intrusives. The resulting four factors were used in the Monkey survey and fifteen responses were received out of the twenty eight invitations sent to geologists. The Monkey Survey involved providing the following information;

a) Email address.
b) Knowledge in Geology and GIS (Very Good; Good; Fair; Poor)
c) What is the relative importance of each of the data listed below in the overall decision making of a site suitable for mineral exploration? (1: Most Suitable; 2:Moderately Suitable; 3:Least Suitable)

The results were analyzed and used to assign weights and hence perform Weighted Overlay Analysis.

Weighted Overlay Analysis

This is one of the methods used for modeling suitability of an area. It was applied for this study in ArcGIS environment. It is a systematic process that involves the following steps;

a) Assigning of weights to the various raster layers that are being used for assessing the suitability of an area (Delphi Model was applied in this study);
b) The values obtained from the Delphi Process were then reclassified;

c) Raster layers were overlaid, multiplying each raster cell's suitability value by its layer weight and totaling the values to derive a suitability value;

d) The values are then written to new cells in an output layer and finally the symbology generated and based on the new values.

Multiplying each layer's weight by each cell's suitability value produced a weighted suitability value. Weighted suitability values were then totaled for each overlaying cell and then written to an output layer.

Accuracy assessment and validation of the results were also done at this stage by overlaying the results on an existing minerals map of Kitui County since neither the resistivity data nor mineral data of the study area could be obtained in order to validate the results. The final mineral potential map of the area was therefore prepared and hence the general objective of the study was achieved.

3.3 Tools for the study

Hardware

a) Computer PC with relevant specifications such as 320 GB hard disk memory, 2GB RAM and supporting processor

b) Printer

Software

a) ArcGIS version 10.6.1

b) Microsoft Word Version 2007

Data sources

The table below shows types of data that will be used for this study, their source, the format in which the data will be and the spatial resolution of the data as well as the scale in the case of raster data.

Table 3: Data types, their Source, Format and Spatial Resolution/Scale

Data Type	Source	Format	Spatial Resolution/ Scale
Landsat 8 Image	https://earthexplorer.usgs.gov/	Raster (GeoTiff)	30m
Geological Map	Mines and Geology Department	Raster (Image)	1:125,000
DEM	https://earthexplorer.usgs.gov/	Raster (GeoTiff)	30m

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Factors that Influence Occurrence of Minerals

In order for an area to be explored for minerals, collection, analysis and integration of various thematic geoscience data sets have to be done in order to extract pieces of spatial geo-information, namely;

a) **Geological Anomalies -** Examples include Lithology, Faults and Topography. Some minerals are associated with some lithologic units, as well as faults and the topography of an area. The lithologic units and faults were digitized from an existing geological map of an area while the topographic data can be obtained from the topographical map of the study area.

b) **Geochemical Anomalies -** A geochemical anomaly is defined as a departure from the geochemical patterns that are normal for a given area. It can represent either geogenic (i.e., natural) or anthropogenic (i.e., industry-induced) enrichment in one or more elements in Earth materials. In mineral exploration, geochemical anomalies associated with mineral deposits are called significant anomalies, whereas geochemical anomalies associated with other natural processes or anthropogenic processes are called non-significant anomalies. An example is hydrothermal alteration which was applied in this study using various remote sensing image enhancing techniques such as pan-chromatic sharpening, color composites and Principal Component Analysis (PCA).

c) **Geophysical Anomalies -** A geophysical anomaly on the other hand is a variation from normal background patterns of measured physical properties of the Earth's upper crust (e.g., magnetism), which can be attributed to localized near-surface or subsurface materials such as metallic mineral deposits. Examples of surface geophysical methods include seismic refraction, gravimetric surveys, electromagnetic surveys and electrical resistivity. Gravity measurements (gravimetric surveys) indicate subtle differences in the density of rocks in Earth's crust. The gravity anomaly can therefore be used to indirectly map the distribution of different rock types and hence help in the identification of minerals in an area.

This study applied two geological factors; lithological units and faults and one geochemical factor which is hydrothermal alteration, in order to determine how suitable Mui Basin is for mineral exploration.

4.2 Hydrothermal Alteration Mapping

4.2.1 Panchromatic Sharpening (Pan-sharpening)

This technique was applied and the resulting image was significantly sharper as can be seen in Figure 4-1 which compares the two images. The spectral bands of Landsat 8 had a resolution of 30 meters per pixel, while the resulting image has a resolution of 15 meters.

The Pan-sharpened image was then used to apply the Principal Component Analysis (PCA) technique.

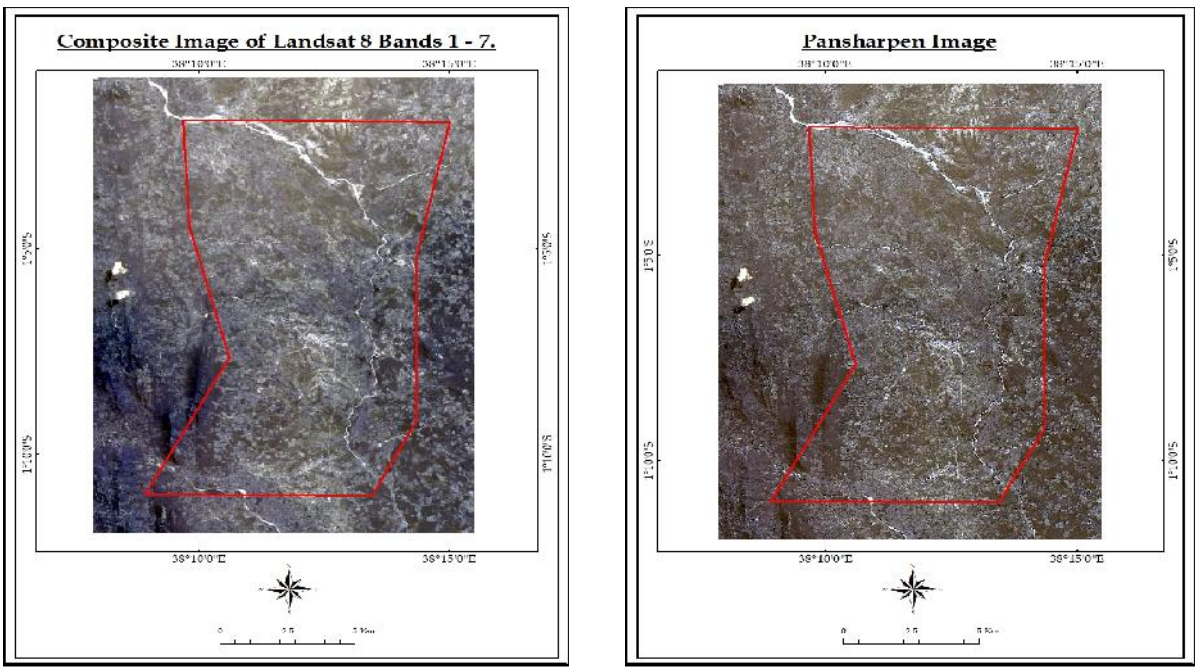

Figure 4-1: Composite Image (Bands 1 - 7) and the Pan-Sharpened Image

4.2.2 Color Composites

Three color composites were produced as shown in Figure 4-2. They include;

i. A color infrared image was produced using bands 5, 4, 3 (Red, Green and Blue);
ii. False color composite was produced using bands 6, 5, 4 (Red, Green and Blue);

iii. Natural color composite was produced using bands 4, 3, 2 (Red, Green and Blue). This band combination is applicable for exploratory analysis (Frutuoso, 2015). Alteration zones are identified as (brown), vegetated areas as green, rivers and lakes as blue.

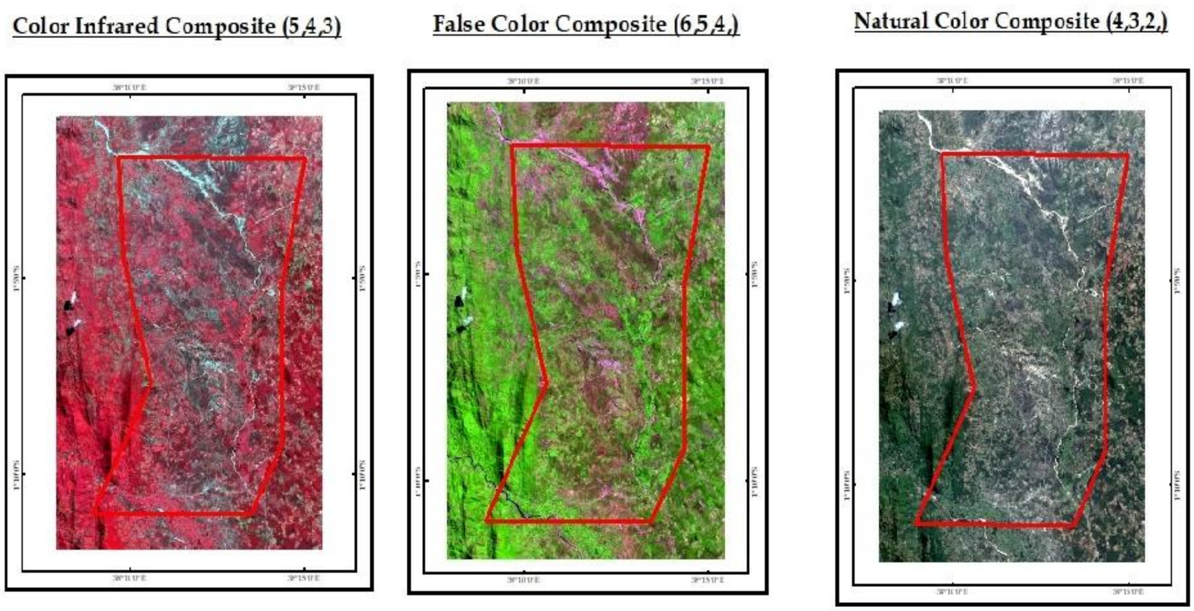

Figure 4-2: Color Infrared, False Color and Natural Color Composite Images

The color composites were used in the interpretation of PCA techniques images. This helped in the identification of hydrothermally altered zones on the area of study.

4.2.3 Principal Component Analysis (PCA)

The results of the principal component analysis including bands 2, 5, 6, 7 to map hydroxyl-bearing minerals are shown in Table 7. The eigenvector loading for PC4 showed a large negative value for band 7 (47%) and a positive value for band 6 (26%). The values significantly correlated with the spectral response for hydroxyl since hydroxyl bearing minerals have high absorption in band 7 (negative loading) and high reflectance in band 6 (positive loading).

Table 4: Principal component band load for hydroxyl mapping (Bands 2, 5, 6, 7).

	PC1	PC2	PC3	PC4
Band 2	0.15597	-0.00313	0.51209	0.84464
Band 5	-0.03612	0.99419	0.09095	-0.04478
Band 6	0.71875	0.09611	-0.63950	0.25535

Band 7	0.67659	-0.04831	0.56615	-0.46836
% of Eigen Values	**70.6970**	**28.0048**	**0.9023**	**0.3959**
Accumulative of Eigen Values	**70.6970**	**98.7018**	**99.6041**	**100.0000**

The inverse image of PC4 as can be seen in Figure 4-3 represents the hydroxyl-bearing rocks as bright pixels.

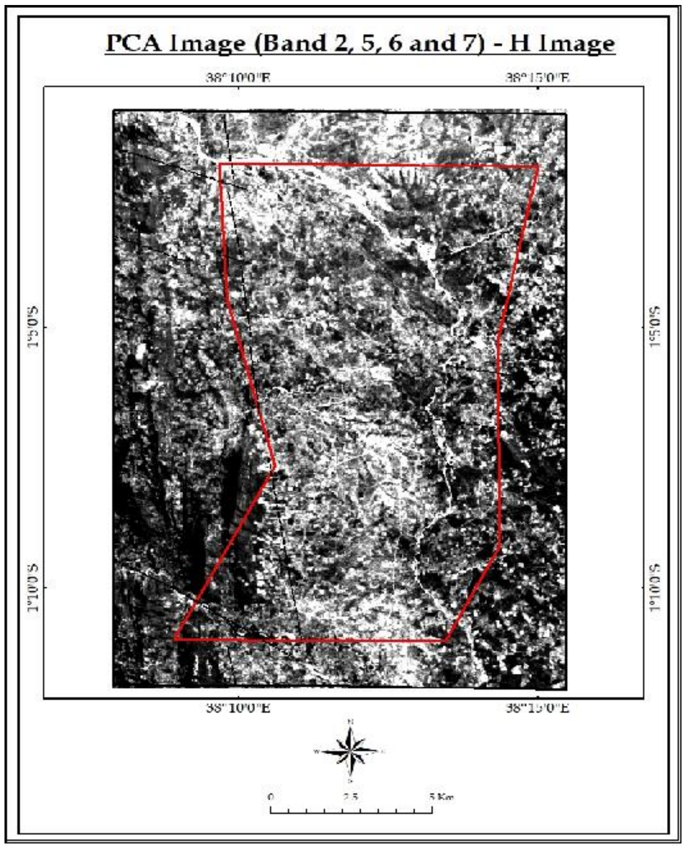

Figure 4-3: Results of the Crosta technique applied to bands 2, 5, 6 and 7, where PC4 is shown as bright pixels represents the hydroxyl-bearing rocks (H-Image)

It is therefore evident from Figure 4-3 that hydroxyls, which are represented by bright pixels, are found in the study area. This proves presence of coal in the study area since oxygen and hydrogen are among the major components of coal. Areas where hydroxyls are found represent areas of high alteration while the remaining areas show areas of low alteration.

4.2.4 Stream Generation

Streams were also generated from the DEM of the area of study and overlaid on Figure 4-3. It is evident from Figure 4-4 that; hydroxyl efficient areas are located adjacent to streams for instance in the northern and north-eastern sides of the study area. Streams can be seen to be flowing along the areas in white which represent hydroxyls efficient zones.

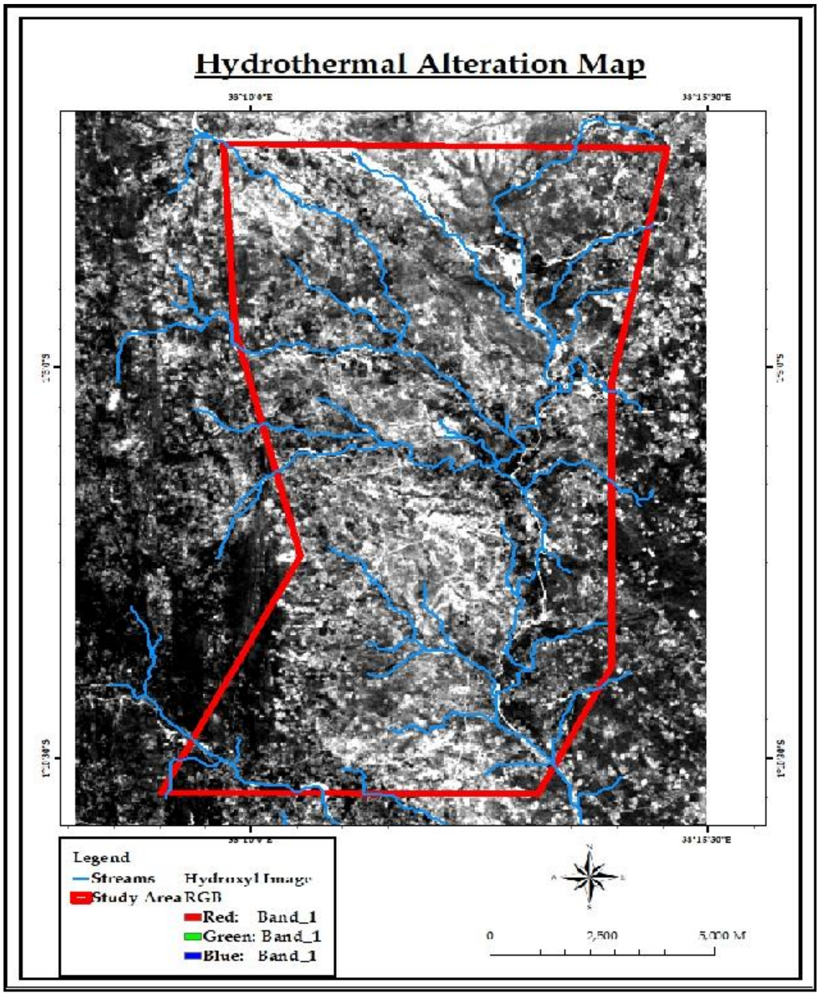

Figure 4-4: Hydrothermal Alteration Map with streams overlaid.

4.3 Geological Suitability Factor Map

4.3.1 Geology Map of Mui Basin

Figure 4-5 shows the geology map of Mui Basin and different rock units are found in the area as well as faults. The rock units were classified into four as seen in Figure 4-5. The rock units include;

- **i. Intrusives:** These are associated with minerals. For instance titanomagnetite.
- **ii. Sediments:** This category contains sands, clays and shales, with carbonaceous marcasite clays and lignite (immature coal). They cover the biggest part of the study area and these shows potential for coal in the study area.
- **iii. Weathered Rock Units:** An example is sillimanite which is a mineral.
- **iv. Undifferentiated rocks:** These include Talus, sandy alluvium, albite, biotite, and biotite granulite.

The faults can also be seen in the area and their presence shows a high likelihood of minerals being found in the study area.

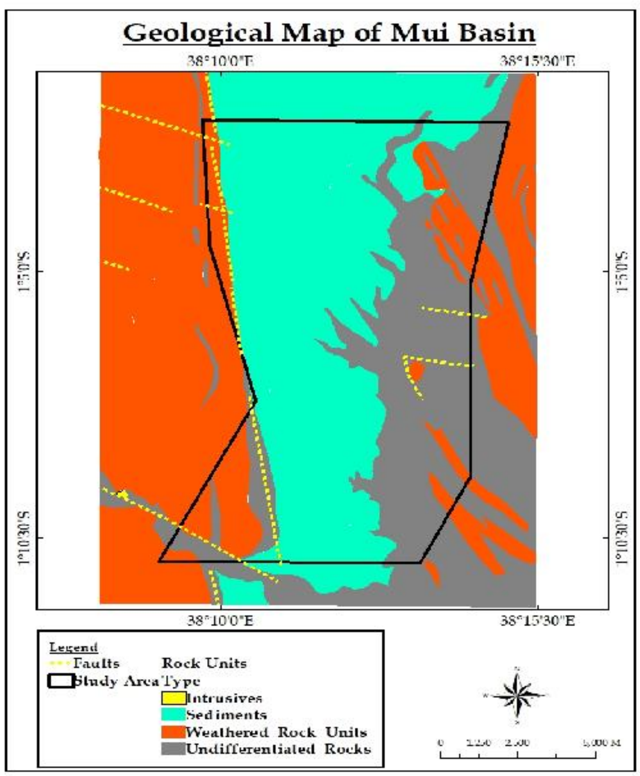

Figure 4-5: Geological Map of Mui Basin

4.3.2 Buffering, Calculating Euclidean Distance and Reclassification

These three procedures were applied on the faults, Intrusives and weathered rock units shown in Figure 4-6.

i. **Buffering -** 1000m was used for buffering the faults and the results are as shown in Figure 4-6.

ii. **Calculating Euclidean Distance -** Once the faults were buffered the euclidean distance was calculated.

iii. **Reclassification -** Once the euclidean distance was calculated reclassification was done and three classes were generated; Most Suitable, Moderately Suitable and Least Suitable as shown in Figure 4-6. The areas in green therefore show the areas which are the most suitable for mineral exploration based on the faults, in blue the areas moderately suitable and in brown the least suitable areas for mineral exploration based on the faults in the study area.

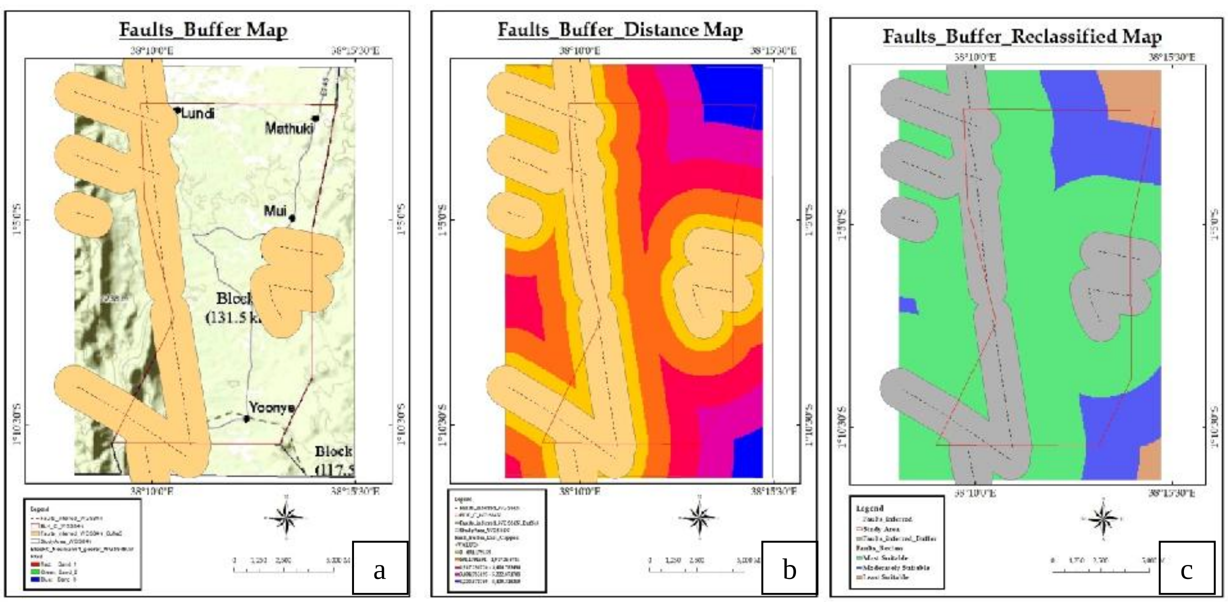

Figure 4-6: Maps showing Faults Map after buffering (a), after calculating the euclidean distance (b) and after reclassification (c).

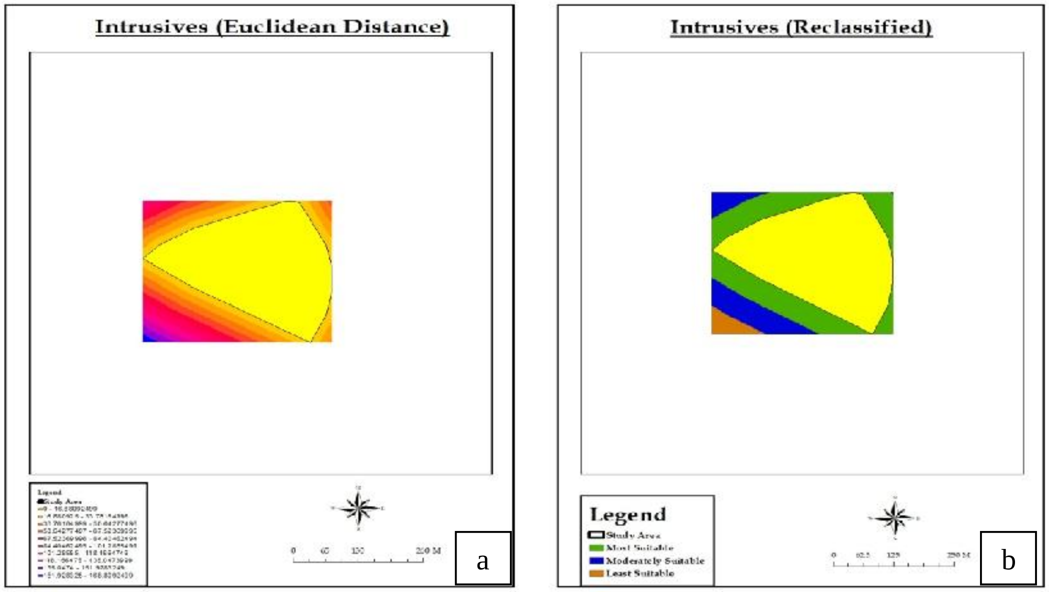

Figure 4-7: Images showing Intrusives with the euclidean distance calculated (a) and the reclassified image (b).

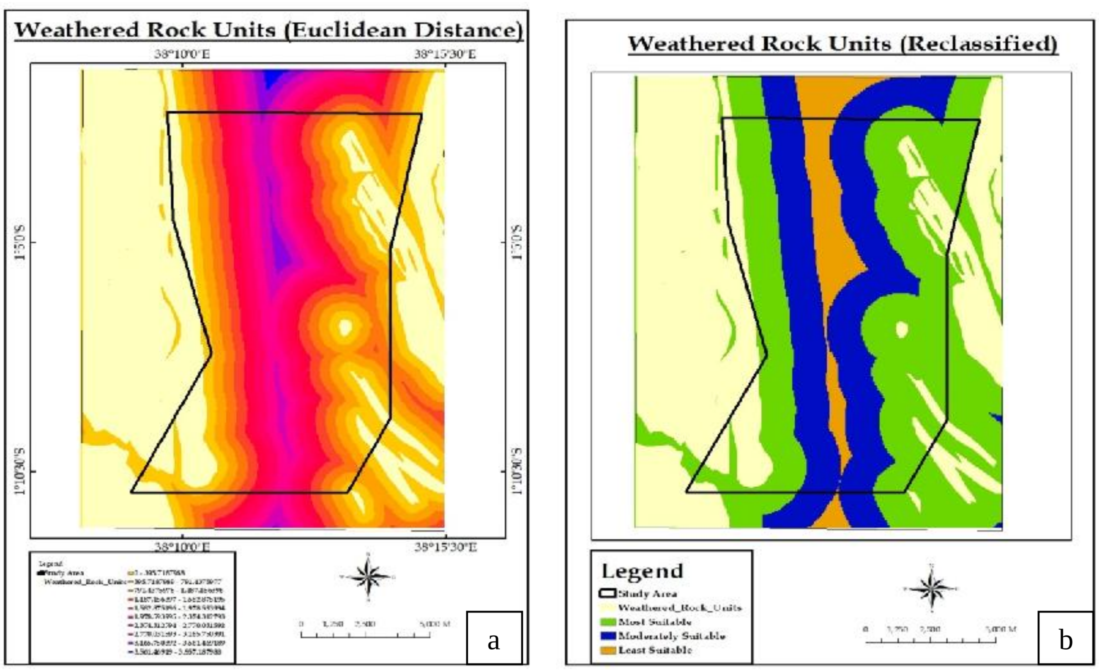

Figure 4-8: Images showing Weathered Rock Units with the euclidean distance calculated (a) and the reclassified image (b).

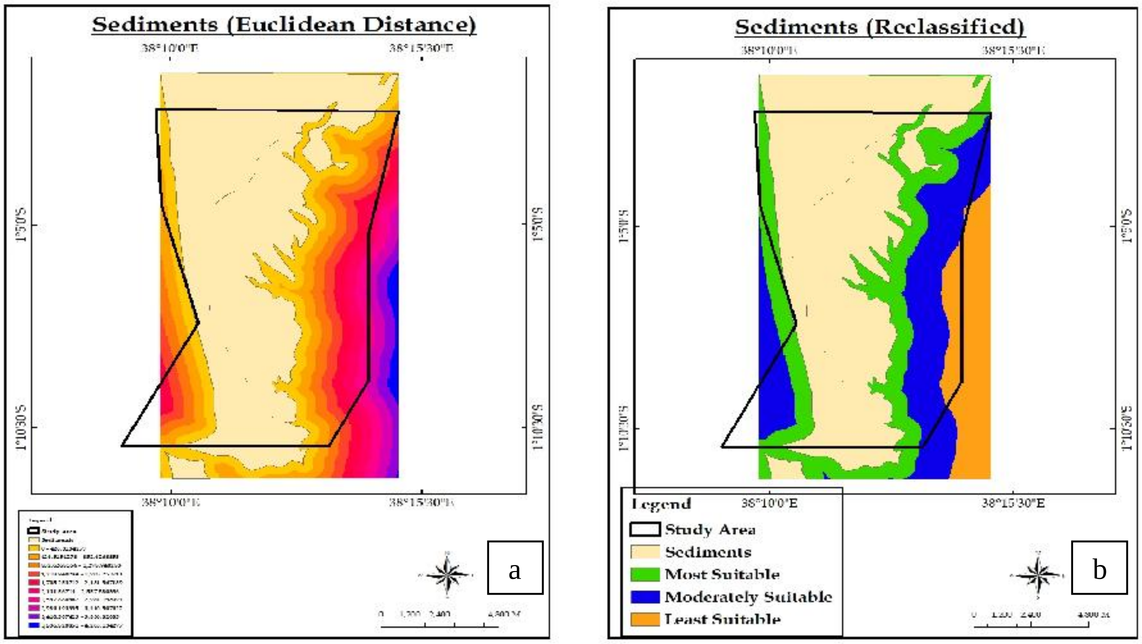

Figure 4-9: Images showing Sediments with the euclidean distance calculated (a) and the reclassified image (b).

Reclassification was also done on the hydrothermal alteration map (Figure 4-3) and was reclassified into three; Altered Zones, Unaltered zones and vegetation as shown in Figure 4-10.

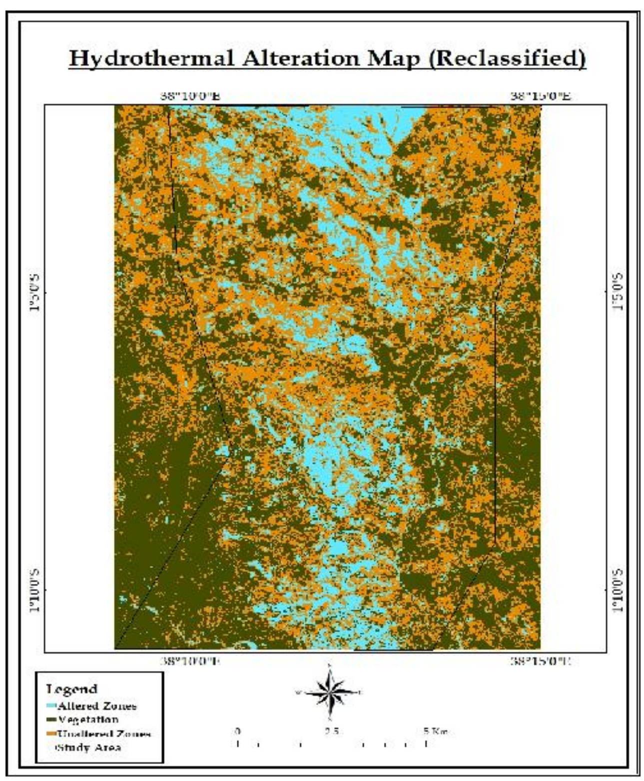

Figure 4-10: Reclassified Hydrothermal Alteration Map

4.4 Mineral Potential Map

The results of the Monkey Survey where six responses were received from geologists are as shown in Figure 4-11 below.

	1	2	3	TOTAL	WEIGHTED AVERAGE
Weathered Mozambique Belt Rock Units	14.29% 1	14.29% 1	71.43% 5	7	2.57
Sediments	66.67% 4	16.67% 1	16.67% 1	6	1.50
Hydrothermal Alteration	14.29% 1	0.00% 0	85.71% 6	7	2.71
Intrusives	0.00% 0	16.67% 1	83.33% 5	6	2.83
Faults	42.86% 3	28.57% 2	28.57% 2	7	1.86

Figure 4-11: Monkey Survey Results

Key: 1 – Most Important

2 - Moderately Important

3 – Least Important

From the results in Figure 4-11 in the column for '1' which represents Most Important, sediments have the same highest score for the most important factor considered when choosing a suitable mining site especially potential for coal, followed by faults, then hydrothermal alteration and weathered Mozambique Belt rock units and lastly intrusives which were ranked as the least important when choosing a suitable mining site. The results were used to assign weights to the five components in the Weighted Index Overlay Analysis and the results are as shown in Figure 4-12 which shows the mineral potential map of Mui basin.

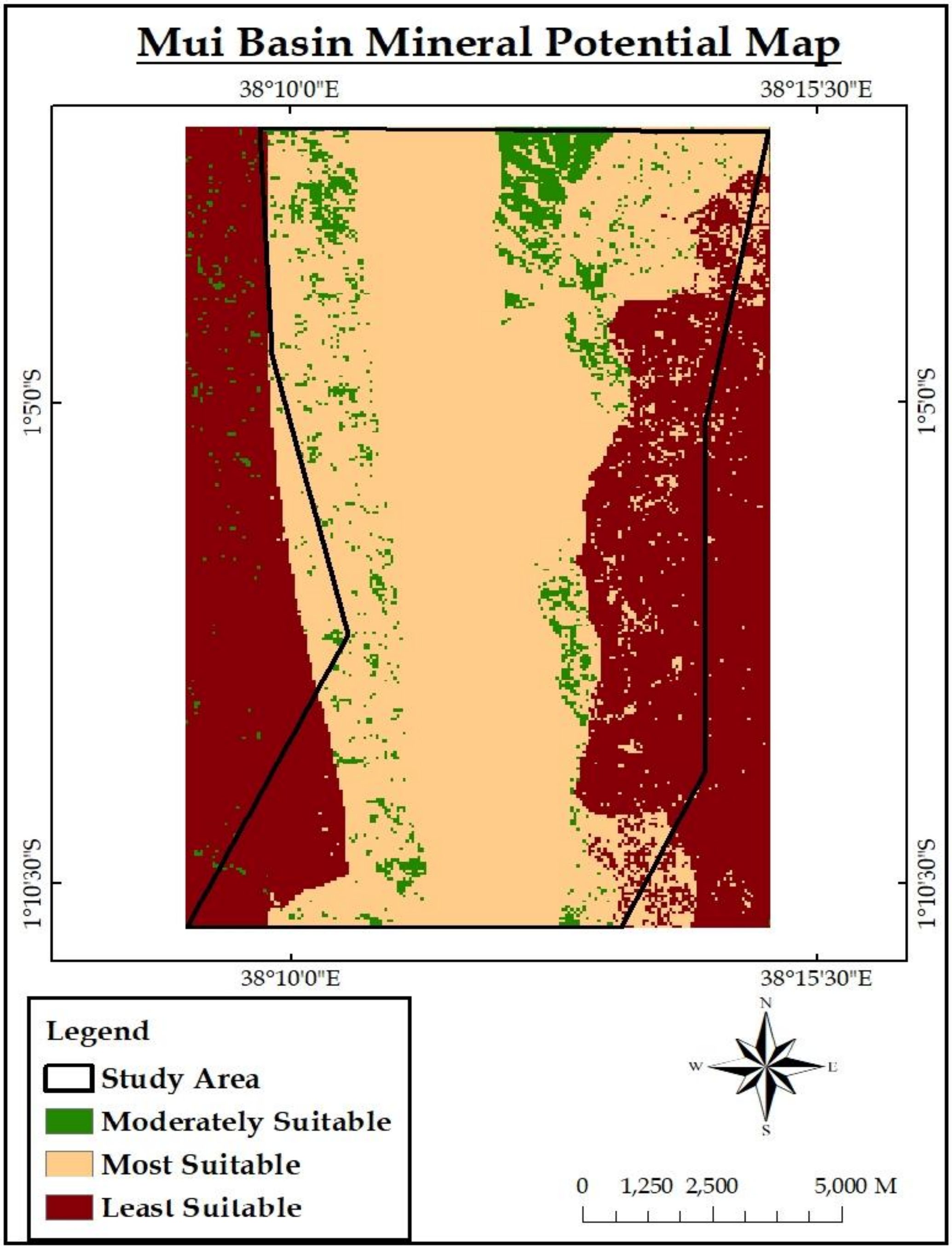

Figure 4-12: Mui Basin Mineral Potential Map

From Figure 4-12 it can be clearly seen that the most suitable area for mineral exploration runs centrally from the north to the south of the study area symbolized by the beige color. The area covers the largest part of the coal mining block and hence has the highest potential for coal since the results from the monkey survey were based on the potential for coal. In green are the moderately suitable areas for mineral exploration and lastly the least suitable areas are shown in maroon.

4.5 Validation and Accuracy Assessment

This study was faced with a major challenge of acquisition of electrical resistivity data of the study area which was meant to be used for validation of the results but this was not the case. The results were however validated using the existing Kitui Mineral Resources Map where the study area overlays with one of the coal mining blocks of Mui Basin as shown in Figure 4-13.

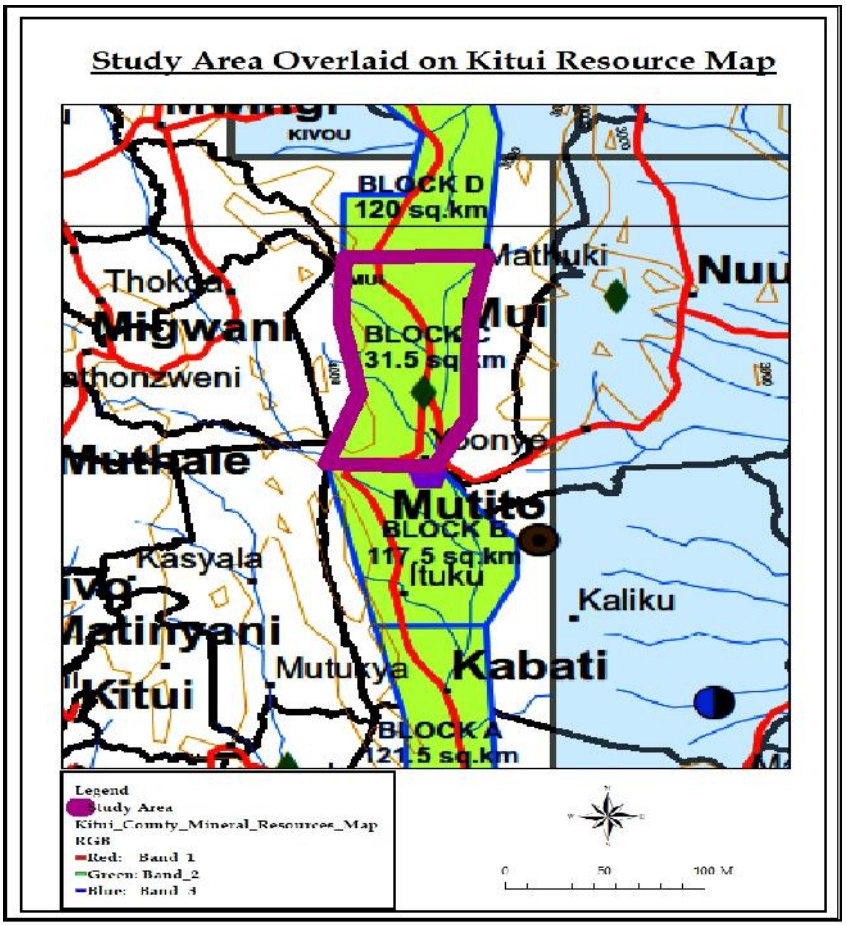

Figure 4-13: Study Area (in purple) overlaid on Kitui Mineral Resources Map.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Different factors that influence the occurrence of minerals can be identified and integrated using geospatial techniques to help show how suitable an area is for mineral exploration. The more the factors identified the better results yielded for mineral potential mapping using geospatial techniques. The factors considered in mineral potential mapping are grouped into three; geological, geochemical and geophysical and this study used geological factors that include lithological units and faults, and hydrothermal alteration which is a geochemical factor. The factors used were sufficient enough to show how suitable the study area is for mineral exploration since the study confirmed the area's potential for coal which has already been discovered in the study area.

Mapping of hydrothermal alteration was done using color composites and Principal Component Analysis (PCA) techniques and the study showed that the Crosta technique used for PCA is very effective in mapping hydrothermal alteration since it clearly illustrated the hydroxyl altered areas. Presence of hydroxyl which contains hydrogen and oxygen showed potential for coal in the study area since the two; hydrogen and oxygen are major components of coal. The hydrothermal alteration map was further interpreted by overlaying streams which seemed to flow along the hydroxyl altered areas. Color composites maps were also very useful in the interpretation of the hydrothermal alteration map generated.

Geological suitability factor maps were prepared from the existing geological map of the study area. Lithological units and faults were mapped and geological suitability factor maps generated.

The overall objective of the study was hence met by applying the Delphi Method of assigning weights to the primary factors and Weighted Overlay analysis done to generate the mineral potential map of Mui Basin. The results classified the study area into three; Most Suitable, Moderately Suitable and Least Suitable.

The results of this study have therefore shown that geospatial techniques are crucial in reducing the massive fieldwork and identifying potential areas for further investigation when it comes to mineral exploration.

5.2 RECOMMENDATIONS

The geological and geochemical factors used for this study were sufficient enough to show mineral potential in the study area but it is recommended that more factors be considered. For instance surface geophysical methods which include seismic refraction, gravimetric surveys, electromagnetic surveys and electrical resistivity.

Different minerals occur under different circumstances and therefore in order for this study to be applied to map a specific mineral, the factors that influence their occurrence should be identified and hence use the appropriate geospatial technique to map the potential of the mineral in question. Generally, this study can be applied at any other region in order to determine how suitable the area is for mineral exploration. Mui basin has already been identified as a mineral potential zone and this study has confirmed the same using geospatial techniques. Since the mining has not yet started, the results of this study can be used for further exploration of the area.

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APPENDICES

APPENDIX A


Mapping Mineral Potential using Geospatial Techniques: A case study of Mui Basin in Kitui County

Personal Information

1. Email Address

Fig A-1a: Monkey Survey Question 1


2. Knowledge in Geology and GIS

- Very Good
- Good
- Fair
- Poor

Fig A-1b 1: Monkey Survey Question 2

3. What is the relative importance of each of the data listed below in the overall decision making of a site suitable for mineral exploration (especially potential for coal)?(1 being the most suitable, 2-moderately suitable and 3-least suitable).

	1	2	3
Weathered Mozambique Belt Rock Units	○	○	○
Sediments	○	○	○
Hydrothermal Alteration	○	○	○
Intrusives	○	○	○
Faults	○	○	○

Fig A-1c 1: Monkey Survey Question 3