UNIVERSITY OF NAIROBI

MULTI-CRITERIA SUITABILITY ANALYSIS FOR OPTIMAL SITING OF A GEOTHERMAL WELL: CASE STUDY OF THE GREATER OLKARIA GEOTHERMAL AREA (GOGA)

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DECLARATION

I **PETER NDIRANGU MAINA,** hereby declare this project is my original work. To the best of my knowledge, the work presented here has not been presented for a degree in any institution of higher learning.

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Signature Date

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

Name of Supervisor: Dr.-Ing. S.M. Musyoka

Signature: é é é é é é é é é é é é é

Date: é é é é é é é é é é é é é

DEDICATION

I dedicate this project to my family for the moral and material support they gave me during my entire academic journey and in this project. My Dad Gerald, my brothers Chaura, Kimani and Mwangi as well as my sisters Esther Maina and Mary Maina. May the Almighty Father abundantly bless you.

I wish to single out my mother, who has been my pillar throughout my entire life, I dedicate this project to her for the sleepless nights she has spent on her knees praying for me. I love you mum.

To my loving girl friend Grace Ndegwa, thank you for the moral support, this would not be a reality without your support.

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I would like to acknowledge the assistance I received from different individuals and organizations. In particular, I would like to single out the following for their priceless support:

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ABSTRACT

In this study, the focus was on the applications of Geographical Information Systems (GIS) as a decision support system in geothermal resource exploration in the Greater Olkaria Geothermal Area (GOGA).

The main objective of the project was to demonstrate how GIS can be applied in Geothermal well siting, making use of data sets from three key Geo-scientific fields- geological, geochemical and geophysical disciplines. Specific objectives included the determination of key factors in each of the geo-scientific fields that will be used in generation of suitability maps for each of the three fields. The three individual suitability maps were then integrated in ArcGIS 10.1 and used to generate the final geothermal well-site suitability map.

The methodology employed included determination of various factors for each of the three involved Geo-Scientific fields and a criterion for suitability was determined for each of the factors. Results of all factors for each of the disciplines were overlaid and a suitability map for each of the three fields was generated. The final Suitability map for geothermal well siting was obtained from the results of integration of the three suitability maps. The results of the final suitability map was a classification of the study area into three primary regions namely; most suitable area, moderately suitable area and the least suitable area.

The results of the study were compared with results obtained by current exploration methods employed by KenGen at Olkaria. On numerous occasions, current methods have led to siting and consequent drilling of dry wells. The studied approach aimed at avoiding location and drilling of dry wells as it was inclusive of a more thorough approach at exploration stage as opposed to the current methods employed by Kengen.

The study recommends adoption of this criteria by the management at KenGen as it guarantees accuracy and an easier decision making process for sustainable location of well sites by effectively making use of GIS as decision support system.

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LIST OF ABBREVIATIONS

Absl ï Above sea level

Bsl ï Below sea level

GIS ï Geographic Information Systems

GOGA ï Greater Olkaria Geothermal Area

GDC ï Geothermal Development Company

MWe ï Megawatts of Energy

OWA ï Ordered Weighted Averaging

MCDM ï Multi Criteria Decision Making

Ma - Million Years

CHAPTER 1

1. INTRODUCTION

1.1 Background

The Olkaria Geothermal field is located along the Rift Valley in Kenya. It is a high temperature geothermal resource zone, with the geothermal potential of the entire area estimated at 7000 MWe. The Olkaria geothermal area has been divided into seven development sectors three of which have been committed to development. Named with respect to the Olkaria Hill, these fields include Olkaria North East, Olkaria East, Olkaria South East, Olkaria South West, Olkaria North West, Olkaria Central and the Olkaria Domes (Baker et. al, 1972).

In this study, the possibility of application of the Geographic Information System (GIS) as the main decision-making tool for targeting potential geothermal resources in the Greater Olkaria Geothermal field is explored. The aim of the study is to identify promising areas for geothermal exploration through application of GIS as a base study for future regional scale geothermal investigation and subsequent drilling of geothermal wells.

The most important data layers for site selection in geothermal area are summarized in three datasets namely; geochemistry dataset (carbon dioxide, hydrogen sulphide concentration and temperature values), geophysical dataset (resistivity datasets) and Geological dataset (volcanic craters, volcanic domes and calderas). The three data layers are explored in this study and a criterion of delineating the most promising areas established based on the evidences derived from the layers. An integration model in a GIS environment was developed and run in ArcGIS 10.1 and the most promising areas were identified by assigning weights depending on their suitability. A final suitability map of the study area is generated based on the results of integration of the three data layers.

1.2 Problem Statement

Studies have shown that the cost of exploration and drilling stages in a geothermal project can account up to 42% of the overall costs. Similarly, a significant portion of geothermal financial risks in a geothermal development project emanate from uncertainties that are closely associated with the early stages of a project. These uncertainties revolve around exploration and drilling stages, which make the two most sensitive stages of resource development. A close analysis of the current exploration and drilling technological applications and practices employed at KenGen reveal that they are not efficiently accurate as some dry wells have been drilled in the past hence leading to massive losses in financial investments.

Exploration technologies must be able to locate geothermal resources in a better way that will minimize costs. They must also be able to provide highly accurate imaging of the structure of the all-important subsurface reservoir. This implies that they should be able to give reliable information such as reservoir temperatures and other properties at specified depths. In order as to better locate geothermal resources, it is necessary to employ the use of GIS at early exploration stages to enhance efficiency and accuracy in the siting of geothermal wells.

This report proposes the establishment of a GIS unit at KenGen with an objective of creating an integrated spatial database for geothermal resources that can be used in resource development operations. It is recommended that KenGen acquires and installs an ćenterpriseô GIS system comprising the data acquisition hardware, high speed computer systems and soft-wares.

1.3 Objectives

1.3.1 Main Objective

The main objective of this study is to demonstrate the use of Geographical Information System (GIS) in a multi-criterion suitability analysis for optimal siting of a geothermal field within the Greater Olkaria Geothermal field.

1.3.2 Specific Objectives

i). To review the current exploration criteria employed in the study area.
ii). To generate factor maps based on the applied criteria for each of the three geo-scientific disciplines.
iii). To generate three suitability maps, one for each geo-scientific discipline studied.
iv). To generate a final suitability map showing optimal areas for siting of geothermal wells based on the three geo-scientific disciplines.

1.4 Justification for the study

In geothermal resources exploration and development, vast amounts of data/information from multiple data sources are dealt with. In all phases of resource development in geothermal projects development, resource appraisal, exploration, management of exploitation activities such as drilling and operating steam/hot water fields, data and other information is location based (or geographic data). Therefore, GIS is the best method of handling and organizing the information used in these phases.

It is worth noting that the three key data sources in geothermal resource exploration are geological, geochemical and geophysical data layers. These layers are integrated in a GIS environment to make use of evidences drawn from the three layers. This study therefore is necessary in ensuring the application of the three disciplines before the final decision making process hence ensuring accuracy and effectiveness in siting geo-thermal wells for optimal generation of geothermal power.

Apart from the three key data layers, there are other additional layers partially observed in this study and are proposed to KenGen for further analysis as they are important considerations when siting a geothermal well. This may include the spatial distribution of slopes, rivers, faults, population centers, access roads, anomaly zones, well and hot springs location. The application of GIS is key in integrating this data on a single platform that makes the process of geothermal resource exploration and identification of suitable areas easier to cope as well as accurately and efficiently make decisions.

1.5 Scope of Work

The scope of work in the study included a reconnaissance survey of the Greater Olkaria Geothermal Field. This was undertaken between February 26th and March 1st 2013. The aim of the reconnaissance was to familiarize with the study area, project expected challenges and limitations during the actual field study and seek permission from the relevant authorities in the station.

The reconnaissance study was then followed by the actual field study. This was carried for a period of ten days from the 6th March to the 16th of March 2013. All the necessary data was collected at this stage. This included data related to the geology, geophysical and geochemical evidences within the study area. This was done through actual field measurements carried out in the company of KenGenõs geological, geochemical and geophysical teams as well as collection of previously collected data sets.

Upon completion of the field survey, the data collected was analyzed, results interpreted and conclusions drawn. The data layers in the form of maps and raster data sets were integrated in a GIS environment using ArcGIS 10.1 and necessary processing, digitizing and editing performed.

Favorable and unfavorable terrains in a study area in terms of geothermal potential can be defined using the three suitability layers. This will be done by application of the Boolean integration methods. Suitability maps for each of the three fields will be generated showing the potential of the area based on the criteria applied for each of the geo-scientific disciplines. The result will be analyzed and presented as to determine the sites with the highest potential for geothermal well development.

In this study, a Geographic Information System (GIS) is used as a decision-making tool to target potential geothermal resources in the Greater Olkaria Geothermal Field. The aims of the study are to update and identify promising areas for geothermal exploration, as the base study for the future regional-scale geothermal resources investigations and exploration drilling.

The most important data layers for site selection in geothermal area are summarized in three datasets; Geological dataset (volcanic rocks, volcanic craters and faults), geochemistry dataset (hot springs and acidic hydrothermal alteration zone) and geophysical dataset (resistivity datasets). The three data layers are explored in this study and a criterion of delineating the most promising areas established based on the evidences derived from the layers. An integration model in a GIS environment was developed and run in ArcGIS 10.1 and the most promising areas were marked by assigning weights depending on their suitability.

1.6 The Study Area

The Olkaria geothermal resource is located in the Kenya Rift valley, about 120 km from Nairobi. Geothermal activity is widespread in the Kenyan rift and 14 major geothermal prospects have been identified. The Olkaria geothermal field is inside a major volcanic complex that has been cut by N-S trending normal rifting faults. Numerous volcanic domes characterize the area. This can be interpreted to be indicative of the presence of a buried volcanic caldera. These structures will be key in suitability analysis using the geo-chemical layer.

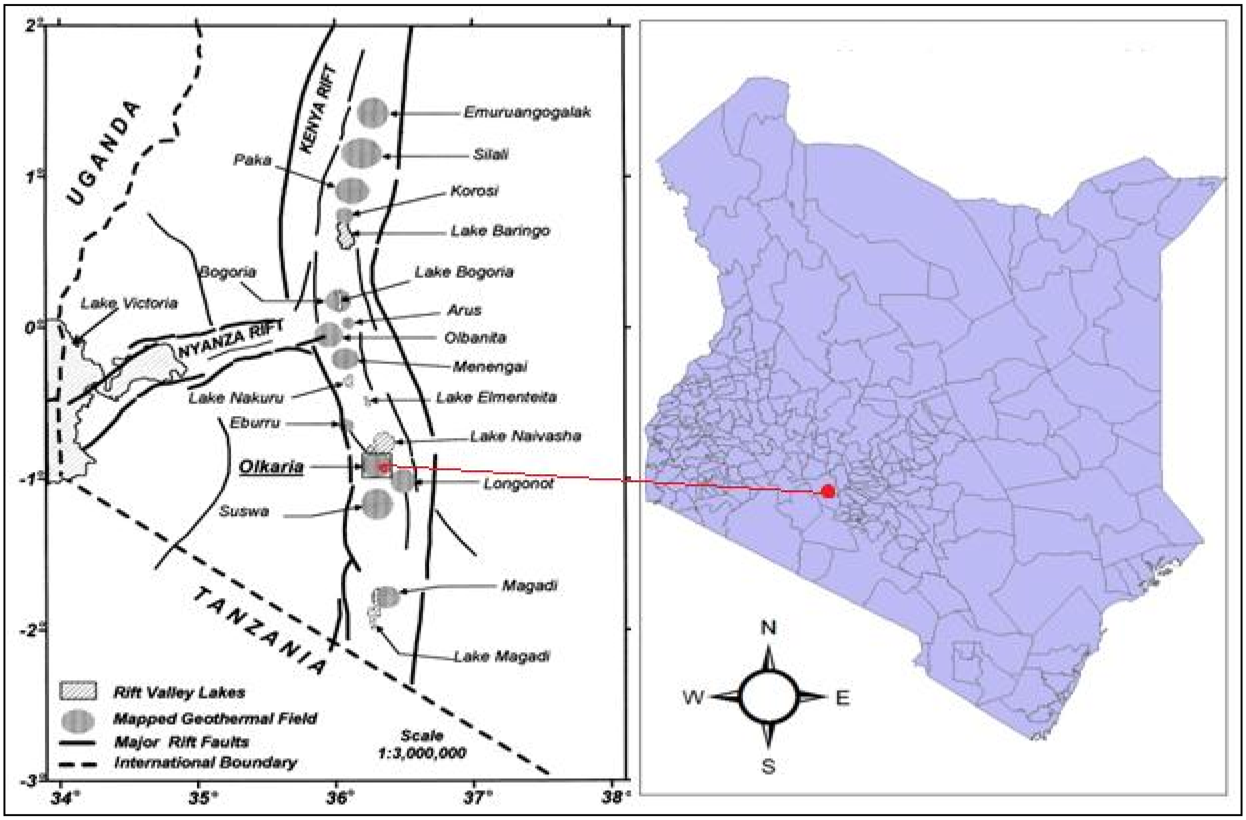


Figure 1.1: Map Showing the Location of the Study Area (Omenda, 2000)

The Olkaria region of the Kenya rift valley is a potentially important geothermal area due to the occurrence of young volcanic activity and surface geothermal manifestations that include hot springs, fumaroles and thermally altered ground. In order to determine subsurface structures, gravity measurements, together with existing regional gravity data are used to propose a subsurface model (Baker et. al, 1972).

An increase in the thickness of volcanics in the western part of Olkaria is responsible for the observed negative Bouguer anomaly in that area, while vertical density contrasts between the dyke-like intrusions and the host rock generate model anomalies in good agreement with the observed positive Bouguer anomalies in the central part of Olkaria. The largest and most recent intrusion, which is probably still in a magmatic state, occurs along the Ololbutot fracture zone and is apparently the main heat source for the geothermal phenomena in Olkaria (Mungania, 1992).

1.7 Organization of the Report

The report is divided into 5 chapters.

(i) Chapter 1: Introduction

This chapter contains an introductory part, background, problem statement, objectives, scope and limitations of the study and organization of the report.

(ii) Chapter 2: Literature Review

This chapter outlines the relevant literatures and the recent works related to the study.

(iii) Chapter 3: Materials and Methods

The study parameters, data sources, data preparation criteria, and test methods employed are discussed.

(iv) Chapter 4: Results and Discussions

This chapter shows the results that were obtained for the operations that were carried out and a discussion of the results.

(v) Chapter 5: Conclusions and Recommendations

Necessary conclusions and recommendations are given as per the results obtained.

The detailed collection of data sheets for all the materials applied in the study is given in appendices A to D.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Background Information of the study area

Exploration of the Olkaria geothermal resource was initiated in 1956 but deep drilling commenced in 1973. This was followed by a subsequent feasibility study conducted in 1976 revealing the feasibility of developing a geothermal resource. This culminated into the establishment of a 30 MWe power plant. Three fully-fledged power plants are currently installed in the field and producing electricity; Olkaria I with 45 MWe capacity, Olkaria II with 105 MWe capacity and Olkaria III with 48 MWe capacity. KenGen operates the first two while OrPower4 Inc., a private geothermal power generating company, operates the third plant (Ouma, 2010).

2.2 History of Development of Geothermal Energy in Kenya and the Potential

Geothermal energy exploration in Kenya began in the 1960ôs with surface exploration that culminated in the drilling of two geothermal wells at Olkaria. More geological and geophysical work continued in early 1970ôs between Olkaria and Lake Bogoria. This survey identified several areas suitable for geothermal prospecting. Subsequently, by 1973, drilling of deep exploratory wells at Olkaria funded by UNDP commenced. The Government through the Ministry of Energy, GDC, KenGen and other partners has undertaken detailed surface studies of some of the most promising geothermal prospects in the country.

The areas that have been studied in detail include Suswa, Longonot, Olkaria, Eburru, Menengai, Arus-Bogoria, Lake Baringo, Korosi and Paka. Other areas with not very detailed studies include Lake Magadi, Badlands, Silali, Emuruangogolak, Namarunu and Barrier geothermal prospects. Evaluations of these data sets suggest that the high temperature resource areas in Kenya can generate over 7,000 MWe (Mungania, 1992).

Figure 2.1 below shows the spatial locations of different geothermal fields within the study area.

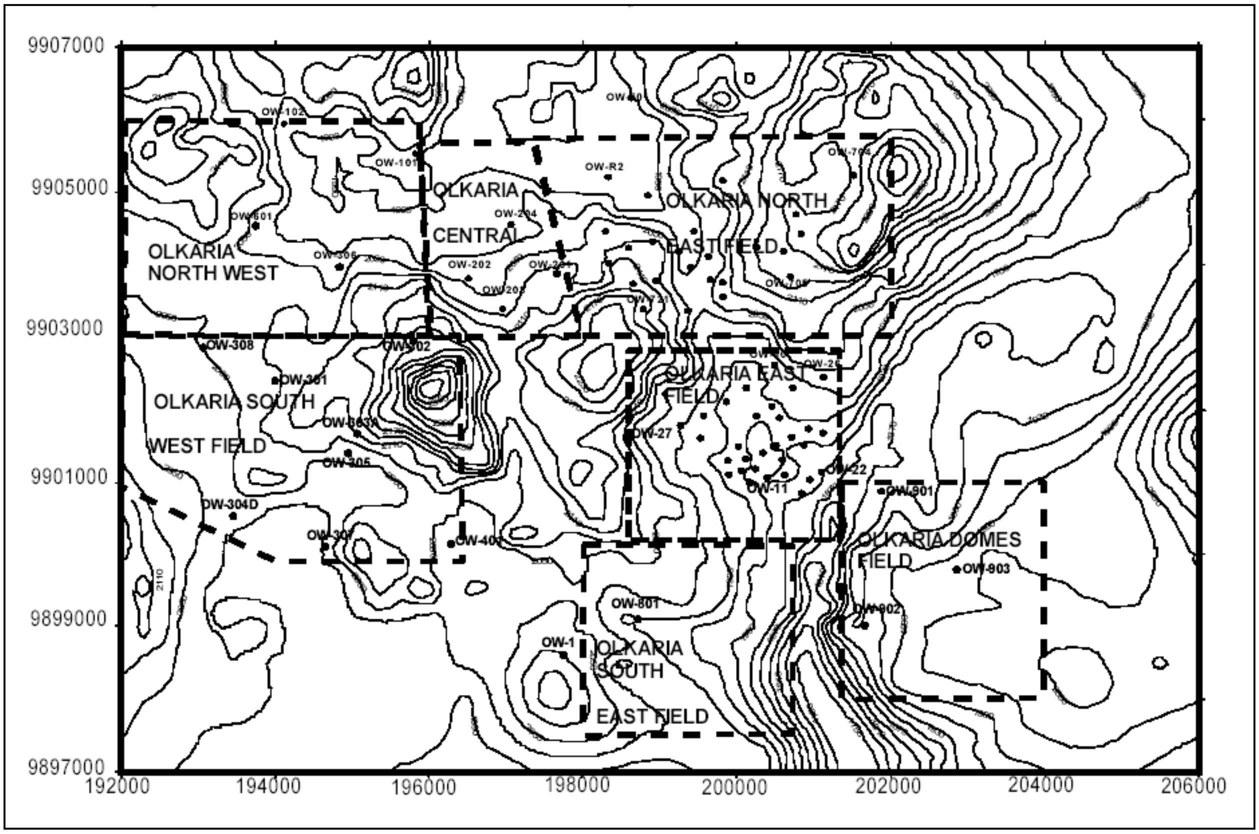


Figure 2.1: Map Showing Geothermal Fields within the Greater Olkaria Geothermal Area.

(www.sciencedirect.com)

The Olkaria 1 power plant, which was commissioned between 1981 and 1985, is made of three units. Olkaria 2 is also made of three units and was commissioned between 2003 and 2010. The third Olkaria power plant was commissioned in two phases between 2000 and 2009. This indicates that the entire geothermal power plant project is progressive in terms of growth and expansion. Other geothermal resources exist in the area. For instance, some geothermal resources at the North Western part of Olkaria are utilized by a flower farm known as Oserian for direct heat generation and for small-scale electricity generation (Axelsson, 2008).

2.3 Previous Studies of the Research Area

Kenya is the first African country to tap energy from the crust of the earth for electric power generation. At Olkaria, geothermal investigations started as long as 1956 when exploratory drilling was undertaken by a consortium of companies, which included the East Africa Power and Lighting Company Limited and Balfour Beatty and Company. Two wells were drilled without any marked success. It was not until the end of the next decade that interest in geothermal power revived.

In 1967, a resistivity survey was carried out in the Rift Valley between Lake Bogoria in the North and Olkaria in the South to determine the nature of the underground rocks and the possibilities of obtaining steam. The survey was encouraging and in 1969, the Kenya Government requested the United Nations to assist in financing further investigations.

A project was agreed upon and between 1970 and 1972 investigations were undertaken at Olkaria, Lake Bogoria and in the Eburru area. Further work, which produced positive results, was carried out on the two exploratory wells drilled at Olkaria in the fifties. On that basis, drilling started in earnest in 1973 and by 1975, four more wells had been drilled in the area. A feasibility study was then undertaken to evaluate Olkariaôs potential for generating electricity from geothermal steam. The study found that the Olkaria Geothermal field covered some 80 km^2 and has a steam potential for 7,000 MWe (Ouma, 2010).

The Kenya Power Company (now Kenya Electricity Generating Company) subsequently took over the responsibilities formerly carried out by the East African Power and Lighting Company in the Olkaria project in 1977. Drilling was resumed in July 1978 and today 100 wells have been drilled with depths varying from between 180 and 2,600 meters below the earthôs surface for exploration, production, monitoring and re-injection. Thirty three (33) wells are in the Olkaria East field alone. Production drilling at the Olkaria Northeast field was completed and a 2 x 32 MWe power station was commissioned in 2004 (Mungania, 1999).

2.4 Geothermal Energy Potential in the Study Area

The word geothermal is derived from the Greek words ógeoô (Earth) and óthermeô (heat). Geothermal energy is heat from within the Earth. Geothermal energy is generated in the Earthôs core, almost 4,000 miles beneath the Earthôs surface. Melted rock known as magma makes the double-layered core, which is characterized by a very solid iron center. The high temperatures at the core of the earth are as a result of energy emissions from slow decay of radioactive particles. This implies that radioactivity, which as natural process in all rocks, is behind the high temperatures at the earthôs core. The outer core is surrounded by the mantle, which is about 1,800 mile in thickness and made of magma and rock (Ndombi, 1981).

2.5 Generation of Geothermal Energy

Geothermal power plants utilize super heated water from the earthôs surface as a result of volcanic activities. This allows the flow of geothermal fluids into hot subsurface rocks, creating reservoirs for steam or hot fluids. In the event that geothermal wells are formed, geothermal energy is brought onto the earthôs surface. The physical fact that the steam is usually under high pressure drives the turbines, producing electric power. Fluids are re-injected into the hot reservoirs after condensation to repeat the cycle.

These are referred to as enhanced geothermal systems, which describes geothermal reservoirs designed by engineers to produce electricity from areas with very low permeability and porosity. This is facilitated by introducing pumped water into hot rock through an injection well that has been artificially fractured. The pumped water is then redirected back to the surface, once it has been heated, for utilization in a geothermal power plant. This is the reason geothermal energy is referred to as renewable energy given that the water is replenished by rainfall, allowing continuous production of steam deep within the Earth (Ndombi, 1981).

Although, drilling a production well is costly, most developers prefer drilling their first production well after a complete exploration regimen has gathered sufficient evidence that can guarantee some degree of confidence of reaching a specific reservoir temperature, at a specific depth, and with adequate flow rates. Exploration regimen is characterized by a combination of geochemical, geological, and geophysical surveys, which are established to boost the chances of success after drilling the initial production well.

2.6 Current Exploration Criteria Employed by KenGen

Currently, investigations at Olkaria have mainly incorporated the use of magnetotellurics (MT) and transient electromagnetic (TEM) because of their better depth of penetration of the former and ease of deployment. Combined TEM and MT models are more effective in characterizing the conductivity from near surface to deeper levels. A combination of MT, gravity and seismic has provided further information in regard to the heat sources. KenGen has mainly relied on Geophysical exploration methods for resource exploration within Olkaria with other datasets only used partially for supporting geophysical findings (Onacha 1993).

Such integration of multiple data sets is carried out in an analogue way and decisions are made by integrating different information from various sources, using experts and engineersô skills.

This project proposes an efficient integration method of data sets which is carried out digitally using a Geographic Information System (GIS) as a decision support system.

2.6.1 Suggested Criteria of for Exploration of Geothermal Resource

In this study, GIS is used to carry out the site selection process suitability analysis due its ability to handle considerably large data amounts, is capable of visualizing new and existing data and it can facilitate the production of maps to aid in decision making.

The study involved the use of three key data layers in, geology, geochemistry, and geophysics in the determination of suitable areas for geothermal resource exploration. The study therefore aims at suggesting a better exploration criteria to the management of KenGen where the suitable areas for geothermal power production are identified by application of GIS with all available digital data layers categorized in the three key datasets including geology, geo-chemical and geophysical data layers.

2.7 Geology and tectonic settings of the Kenyan Rift

The Kenya rift, also called the Gregory rift, is the eastern branch of the continental East African rift system (EARS) which extends to about 3000 km from the afar triangle to southern Mozambique. Geologically, the rift is made up of cenozoic, volcanic and sedimentary rocks. Baker et al. (1972) divided the cenozoic rocks into four litho-stratigraphic units, namely, Miocene basalts, Miocene phonolites, and Pliocene and Quaternary volcanic and sedimentary rocks. The crustal structures of the Kenya rift have been investigated using integrated seismic, magnetic, and gravity data. Using a 2D seismic velocity model, he described a 5 km deep, sediment- and volcanic-filled basin on a thinning crust beneath the rift valley of about 8 km in a 100 km-wide zone (Baker, 1972)

Baker (1972) reported three major stages of rifting, accompanying intense alkaline volcanism in its tectonic development:

(i) the pre-rift stage (30ï 12 Ma), forming deformation and minor faulting,
(ii) the half-graben stage (12ï 4 Ma), forming the main boundary faults, and
(iii) the graben stage (<4 Ma) with an increase and inward migration of faulting.

The volcanism and rifting of the Kenya rift began 40ï 45 Ma and ~25 Ma ago, respectively, in the north and propagated to the south. Investigations during Kenya Rift International Seismic Project (KRISP) revealed an increase in the crustal extension to the north and the presence of primary low velocity anomalies, which are possibly caused by magma rising from below and are trapped in the uppermost mantle.

2.7.1 The Geology of the Greater Olkaria volcanic complex

The major characteristic of the Greater Olkaria volcanic complex are the numerous volcanic centers of Quaternary age. It is the only area within the Kenyaês rift where comendite occurs on the surface. Other Quaternary volcanic centers near the Olkaria include Suswa caldera to the south, the Eburru volcanic complex to the north, and the Longonot volcano to the southeast. The ring of volcanic domes in the south, southwest and east has been utilized to invoke the presence of a buried caldera.

Another support for the caldera hypothesis postulates that the ring structure resulted from Olkariaês magmatic stresses in the ñmagma chamberò with the center for volcanism being the line of weaknesses in the underground rocks. Similarly, lava petro chemistry within the Olkaria area reveals that the discrete magma chambers were the main sites of their production (Omenda, 2000).

2.7.2 Structures in the Greater Olkaria volcanic complex

The Olkaria Geothermal field is characterized by several structures. Some of these structures include the ring structures, the OlêNjorowa gorge, the Olkaria faults, calderas and the craters. As a result of the thick pyroclastic cover in the Olkaria domes area, the faults are more prominent in the East, Northeast and West Olkaria fields but are scarce in the Olkaria domes area. The development of the rift is attributed to the faults, which are thought to be the oldest. The most prominent of these faults is the Gorge farm fault, which bounds the geothermal fields in the northeastern part and extends to the Olkaria domes area (Mungania & Onacha, 1993)

On the northern edge of the Olkaria domes area, lies a series of craters that mark magmatic explosions (Mungania, 1999). The craters form a row along where an extrapolated caldera rim trace passes. Dike swarms exposed in the OlêNjorowa gorge trend in a NNE direction further attesting to the recent reactivation of faults with that trend. Faulting along the trend of the gorge imitated the development of the OlôNjorowa gorge; however, the feature as it is known today was mainly due to catastrophic outflow of Lake Naivasha during its high stands (Clarke et al., 1990). Volcanic plugs (necks) and felsic dikes that occur along the gorge provides additional evidence of the fault control in the development of this feature.

Most parts of the Olkaria have encountered sub-surface fault wells as reported in geological well reports (Mungania, 1992; Lagat, 1998). The wells encountered drilling problems when these faults were dissected as result of loss of drilling fluids. Materials collected when the circulation of the drilling fluid was normalized were mainly fault breccias.

2.8 The Geo-Scientific Evidence Layers Applied

2.8.1 Geological Data Factors

In almost all geothermal exploration stages, geological studies play a crucial role. The geological formations that play host to hydrothermal systems tend to require; suitable formations of rock to allow circulation of water to the deep levels, a heat source, adequate water availability, sufficient surface area of heat exchange, as well as time to enable heating of water, and a return path that leads back to the surface. In the early stages of geothermal exploration, the main aim is usually to perform an evaluation of possibility of a heat source presence, a downward pathway that allows infiltration of meteoric water for system recharge, an upward pathway for channeling geothermal fluid, and geothermal formations that host geothermal fluid. (McNitt, 1964)

Most geothermal fields' structures are usually products of tectonic activity such as formations of grabens, block faulting or rift valley formations. Whereas most fields are associated with specific volcanoes, there are a number of fields that are related to volcanic caldera structures. Local meteoric waters are normally the main source of water. The waters may descend to significant depths via fault-fissure systems before they are heated and channeled upward by convective forces. Fissure zones and faults with high permeability form the main locations of the major up-flow routes. At such depths, conductive heat that originates from magma body is usually the main source of heat for water heating. In general, geological evidence layers in the selection process of geothermal potential sites mainly include the conditions necessary for a geothermal system development. As such, the presence and subsequent distribution of active volcanoes, volcanic rocks, calderas, faults and craters, constitute the main data used in geothermal resource prospecting as geological evidence (Sherrod & Smith, 2000).

Quaternary volcanic zones tend to have the most geothermal potential. Their sources of heat are therefore, linked to volcanoes. The presence of Quaternary volcanic rocks provides evidence layers used in identification of geothermal prospects because they produce sources of heat in form of intrusive dykes. Large igneous-related geothermal systems with high temperatures are also associated with volcanic fields. However, their geothermal potential usually decline as time elapses (Axelsson, 2008).

In most cases, high-grade recoverable geothermal energy are commonly associated with silicic volcanic systems, which have been active one million years ago (Sherrod & Smith, 2000). On the other hand, lower grade (lower temperature) may also be associated with older rocks, nevertheless, volcanic rocks emplaced more than two years are unlikely geothermal targets (Smith & Shaw, 1975).

2.8.1.1 Volcanic Craters and Calderas

Volcanoes are regarded as obvious indicators of underground sources of heat. Volcanic craters normally constitute one of the elements of geothermal resources for geological exploration. Geologists assume that the presence of crater signifies that the area hosted or hosts a great deal of volcanic activity. As such, the location of craters is one line of evidence for making decision regarding where to concentrate additional exploration work to locate a potential prospect. (McNitt, 1964). A geological map of the study area was used to locate the position of calderas and craters in the study area. The results were standardized in an ArcMap environment.

2.8.1.2 Faults and Fractures

Understanding the role of faults and fractures in channeling subsurface fluid flow is crucial when targeting a geothermal potential region. Faults and fractures play an important role in geothermal fields because fluid mostly flows through source rock fractures. Hanano (2000) affirms that faults influence the character of natural convection in geothermal systems. This is an indication that geothermal systems in certain regions might be controlled by fault planes acting as conduits for fluid flow, which are constantly being extended by tectonic activity (Blewitt, 2003).

Fractures and faults are attributed to the occurrence of natural convection in the observed geothermal systems. Subsequently, they can also be used as evidence layer in selecting potential geothermal sites. Within a study area, faults and fractures can be determined from geological or structural mapping defined as a polyline feature class in the GIS environment.

2.8.2 Geochemical Data Factors

Geochemical surveys are important in determining whether a geological systems is water or vapor-dominated. Similarly, the survey can be used to estimate the minimum temperature expected at certain depths. Additionally, it can also help in estimation of homogeneity of water supply, as well as inferring determining the source of water recharge before inferring the chemical characteristics of the deep fluid (Smith & Shaw,1975).

A geochemical survey employs sampling and subsequent chemical and isotope analysis of the water and gas from geothermal manifestations (hot springs, fumaroles, etc.) in the study area. As the geochemical survey provides useful data for planning its cost is relatively low compared to other more sophisticated methods, such as geophysical surveys. Therefore the geochemical techniques should be utilized as much as possible before proceeding with other more expensive methodologies.

2.8.2.1 Geothermometers

Various geochemical studies have been carried out during exploration for geothermal resources in the study area. In order to evaluate reservoir temperatures and their distribution, geochemical studies including sampling of fumaroles and other ground manifestations have been carried out and using several geothermometers such as CO_2 and H_2S, average temperatures have been calculated and used for modeling reservoir temperatures. A detailed representation of the CO_2 and H_2S samples applied in the study is shown in appendix A (Ndombi, 1981).

The use of geothermometers based on the relative amounts and subsequent ratios of the variety of isotopes and elements in the water is critical for obtaining the information. The level of the elements in the geothermal fluid relative to each other provides crucial insights into the temperature of the geothermal reservoir. Geochemists will gather and interpret data points from multiple geothermometers in order to make the most reliable subsurface temperature estimates.

Geothermal studies such as those pertaining to the occurrence and spatial distribution of fumaroles, hot springs, and acidic alteration zones, are usually crucial in the exploration of geothermal resource prospect areas. The geochemical methods are commonly used at every stage of the geothermal exploration, as well as in the preliminary prospecting. Refer to appendices A and B to show the spatial locations of all the geo-thermometers applied in this study, appendix A for CO_2 and H_2S and appendix B for temperature sample wells.

2.8.2.2 Fumaroles

Fumaroles are among the most commonly occurring geothermal features, especially in volcanic areas. They emit mixtures of gases and steam to the atmosphere. The existence of these features within a given area provides a base for the geothermal researchers to assume the probability of the availability of geothermal resources at depth.

The locations of fumaroles within the study area were extracted from different source maps such as geological and hydrological maps and digitized as a point feature class data layer in an ArcMap environment. Appendix D shows the spatial locations of fumaroles as applied in this study (Ndombi, 1981).

2.8.3 Geophysical Data Factors

Geophysical technologies provide cues of the events happening in the subsurface. Other than just identifying potential temperature, the techniques also provide indications of the subsurface geology structure and the best drilling procedure that would bring hot water to the surface from the geothermal aquifer. Geophysical studies combined with geochemical studies, seeks to identify permeability, temperatures, and the orientation of factures at depth (Onacha, 1993).

Whereas 3D Seismic tomography has been extremely effective in locating subsurface oil and gas in the oil industry, there is no such ósilver bulletô geophysical technology that currently exists for the geothermal industry. Instead, geothermal developers employ various studies from a range of geophysical exploration methods to comprehensively understand a geothermal reservoir before drilling (Simiyu, 2000).

The combination of various methods of geophysical survey as employed in an exploration program commonly depends on intrinsic factors such as hydro-geochemistry and local geology, as well as extrinsic factors such as land issues and local weather. Thus, some methods may be effective in certain resource areas than others, which guarantee their widespread use. Nevertheless, the certain geophysical technologies are widely used than with incremental improvements in their use and technology could yield better exploration success rates.

2.8.3.1 The Concept of Geophysics

The rocks within the earth's subsurface have many physical properties that vary from place to place. The common ones include electrical conductivity, seismic energy transmission, magnetic acquisition and retention and, finally, gravity attraction. Geophysics is the science that studies the variation of any of the mentioned properties across the surface of the earth. If the measured property over an area is different from that of the surrounding regions, it is referred to as anomalous (Onacha,1993).

For purposes of geophysical data collection, KenGen employs the Magneto-Telluric method where iso-resistivity maps are generated. These are maps representing resistivity values of the study area at different altitude heights. They are used to indicate the nature of the earthôs interior at different heights.

2.8.3.2 Temperature Gradient

Subsurface temperature data are used to determine the temperature gradient and thermal anomalies in many areas around the world for geothermal resource prospecting. Temperature gradient data can be collected from different sources such as petroleum, ground water, mining and geothermal wells. The gradient can be obtained from measurements of subsurface temperature in wells at specified depths. The geothermal gradient represents the rate of change in temperature (φT) with depth (φȻ) in the sub-surface. High geothermal gradients are commonly found in areas around hot springs and volcanoes (Ndombi,1981).

2.9 Current Geophysical Methods Employed by KenGen

Geophysical studies have been carried out in Olkaria geothermal area since early sixties but most of the detailed work which included resistivity, gravity, seismology and magnetic were conducted in the 1980ôs and continues to the present date. The results from these measurements indicated that the low resistivity anomalies are controlled by structural trends and that the geothermal resource is defined by a low resistivity of 15Ý. This may however be characterized by a range of between 10 Ý - 60 Ý (Onacha, 1993).

The commonest method employed in exploration for geothermal energy is the electrical conductivity technique. In the transient electromagnetic (TEM) method an electrical current is injected into the ground and its decay and the magnetic field created are measured from which the resistance of the underground rocks is determined. The TEM method, in ideal conditions, can investigate down to 1 km. For deeper studies, the magneto telluric (MT) technique is preferred in which fluctuations of the earth's natural electrical and magnetic currents are used.

Due to the presence of hot rocks and saline hot waters, geothermal areas tend to have low resistivities. The gravity and magnetic methods assist in identifying heat sources. Micro-seismic as well as magnetic investigations assist in identifying structures such as faults (Ndombi, 1981).

2.9.1 Geophysical Exploration History of the Greater Olkaria Geothermal Station

2.9.1.1 Seismic Studies

The United States Geological Survey first conducted seismic studies at Olkaria. This was done using both passive and active source seismic studies. In addition, the firm (Hamilton et al., 1973) used the eight-station network. Approximately, 87 events with a magnitude of less than two and less restricted within four kilometres were observed. This was parallel to the NS trending Ololbutot fault zone. According to the time distance plots the area has a three layer volcanic sequence measuring 3.5-km thick underlain by a granitic layer with a P-wave velocity of 6.3 km/s (Gichira, 2012).

A seismic monitoring program that ran for two years was carried out between 1996 and 1998 in Olkaria (Simiyu 2000; Mariita 2003; Simiyu et al., 1998). This program had been designed to carry out and analysis of the wave parameters in the area. This was aimed at determining earthquake location, an achievement that would help in relating different locations to the presence of structures that influence in Olkaria patterns in reservoir fluid flow. During this period more than 4800 local earthquakes originating within the study area (ts-tp<3 sec) were recorded.

Zones of hot intrusions that were found to be magnetic were also found to mark these zones after seismic gaps were mapped within the Olkaria filed. The discovered intrusions raised the temperatures to as high as 4500^{o}C. The determination of anomalous low S wave amplitudes beneath the young volcanic of the Olkaria geothermal area and then back projecting the same to map the position of attenuating anomalies in the region was done using source-receiver ray path overlap density (Gichira, 2012).

2.9.1.2 Current Power Generation at Olkaria Geothermal Power Station

The present estimate of KenGen possible generating capacity for their total concession area is estimated at 204 km2 in Olkaria is an indication of the potential to sustain an additional 840 MWe long-term generation (KenGen in-house data). Of these 280 MWe have entered the implementation phase, a 140 MWe expansion of Olkaria I and a 140 MWe installation in Olkaria IV. Consequently, with the intensive production drilling of approximately 60 wells in progress since 2007, based on discharge testing of each of the well after heating-up, the corresponding steam availability to as much as 440 MWe has been associated to the Olkaria Domes sectors and Olkaria East. Therefore, a capacity of about 400 MWe or more remains untapped, according to KenGenӧs estimates (Ouma, 2010).

2.10 Application of GIS in this Study

A Geographic Information System is a set of computerized tools including both software and hardware, for gathering, storage, retrieval, transformation, and display of spatial data. GIS is essentially an amalgamation of computerized mapping and data base management systems. Anything capable of appearing on a map can be encoded into a computer before comparing them to anything on any other map, using any coordinate systems, in other words. GIS system is capable of assembling, storing, manipulating, and displaying geographically referenced information to its locations.

The ability of GIS to integrate maps and databases, using the geography as the common feature among them has been extremely effective in the context of planning development. The attribute database can be analysed by multiple queries, linked to multiple databases related to different projects to arrive at a comprehensive picture of the current scenario in a given area (Keenan, 1997).

A GIS is considered a composite of computer-based decision support tools for integration of spatial data from a variety of sources for manipulation, analysis, and or display of data. As such, it is a crucial tool for the management of large bodies of spatially extensive data while offering the advantages of a computer supported environment such as consistency and precision eradicating computational errors.

Examples of the applications of the unique capabilities of a GIS in evidence analysis in geothermal fields include,

i) Investigation of the spatial relationship between subsurface faults and well locations using buffer zones and topological overlay,
ii) Calculation of fault density and assessing its implication on subsurface fluid flow,
iii) Modeling of fault and fracture-related fluid flow using cost surfaces and
iv) Spatial overlay of hydrocarbon reservoir information and fault-related permeability distributions.

2.10.1 Application of GIS in Geothermal Resource Generation

GIS is a crucial tool for integral interpretation of Geo-scientific data using a computerized approach, especially in exploration work. This approach can be used to determine spatial associations among diverse evidence layers in an area of interest. GIS models have also been successfully applied in regional exploration for mineral resources. Technical experts such as scientists and engineers can select the evidence layers in making decisions on further works (Campbell et al., 1982).

A GIS-based technique can be used for geothermal exploration at several exploration stages (Noorollahi et al., 2007; Noorollahi, 2005). The geothermal exploration program requires data analysis by combining various Geo-scientific information sets, such as the location of geothermal manifestations, surface geology, thermal data (temperature gradient and heat flow), the geochemistry of surface manifestations, geomagnetic and gravity measurements and remote sensing data. Experts analyse the data and subsequently determine the location and extent of the most promising geothermal prospect area.

2.10.2 Applied Multi-Criteria Suitability Analysis Method

2.10.2.1 Weighted Linear Combination Method.

The weighted linear combination and the Boolean overlay operations, such as intersection (AND) and union (OR), are the most often employed. Weighted Linear combination (WLC) or simple additive weighting is based on the concept of a weighted average. The decision maker directly assigns the weights of ŕelative importanceô to each attribute map layer. A total score is obtained for each alternative by multiplying the importance weight assigned for each attribute by the scaled value given to the alternative on that attribute, and summing the products over all attributes (Gichira, 2012)

When the overall scores are calculated for all of the alternatives, the alternative with the highest overall score is chosen. The operation can be undertaken using any GIS system having overlay capabilities. For purposes of this study, ArcGIS 10.1was employed for this application. The overlay techniques allow the evaluation criterion map layers (input maps) to be combined in order to determine the composite map layer (output map).

The methods can be implemented in both raster and vector GIS environments. Some GIS systems have built-in routines for the WLC method. There are, however, some fundamental limitations associated with the use of these procedures in a decision making process. The Ordered Weighted Averaging (OWA) approach provides an extension to, and generalization of the conventional map combination methods in GIS.

The ordered weighted averaging (OWA) is a class of multi-criteria operators. It involves two sets of weights: criterion importance weights and order weights. An importance weight is assigned to a given criterion (attribute) for all locations in a study area to indicate its relative importance (according to the decision-makers preferences) in the set of criteria under consideration. The order weights are associated with the criterion values on a location-by-location (object-by-object) basis. They are assigned to a locationǿs attribute values in decreasing order without considering which attribute the value comes from (Cambell et al. 1992).

2.10.3 GIS and Multi-criteria Decision Making.

2.10.3.1 Role of GIS

The distinguishing feature of GIS is its capability to perform an integrated analysis of spatial and attributes data. GIS can be used not only for automatically producing maps, but it is unique in its capacity of integration and spatial analysis of multisource datasets such as data on land use, geothermal power exploration, population, topography, hydrology, climate, vegetation, transportation network, public infrastructure, etc. The data sets are manipulated and analyzed to obtain useful information applicable for geothermal well-site suitability analysis. The aim of a GIS analysis is to help a user to answer questions concerned with geographical patterns and processes (Keenan, 1997).

a). Spatial Decision Making Process

Decision alternatives can be defined as alternative courses of action among which the decision maker must choose. A spatial decision alternative consists of at least two elements:

- Action (what to do?) and
- Location (where to do it?).

The spatial component of a decision alternative can be specified explicitly or implicitly.

b). Evaluation Criteria.

In the spatial context, evaluation criteria are associated with geographical entities and relationships between entities, and can be represented in the form of maps. A criterion map models the preferences of the decision maker concerning a particular concept, while a simple map layer is a representation of some spatial real data.

A criterion map represents subjective preferential information. Two different persons may assign different values to the same mapping unit in a criterion map (Keenan, 1997).

c). Constraints.

A constraint represents natural or artificial restrictions on the potential alternatives. Constraints are often used in the pre-analysis steps to divide alternatives into two categories; óacceptableô or óunacceptableô.

d). Quantification.

The evaluation of alternatives may be quantitative or qualitative. Several methods require quantitative evaluations. When most of criteria are qualitative, quantitative criteria may be converted into qualitative ones and a qualitative method may be used otherwise, a quantification method is applied.

The scaling approach is the mostly used one and application of a quantification method requires the definition of a measurement scale. An example with three levels which has been adopted in this study is,

- very suitable,
- moderately suitable,

- Least suitable.

Other more detailed measurement scales may also be used. The quantification procedure consists of constructing a measurement scale like the one with three points mentioned above. Then, numerical values are associated with each level of the scale. For instance, the numbers 1, 2, or 3 may be associated with the three-point scale from very suitable to very unsuitable.

e). Standardization.

The evaluation of alternatives may be expressed according to different scales (ordinal, interval, and ratio). However, a large number of multi-criteria methods require that all of their criteria be expressed in a similar scale. Standardizing the criteria permits the rescaling of all the evaluation dimensions between 0 and 1. This allows between and within criteria comparisons.

2.10.3.2 Criteria Weights.

Generally in multi-criteria problems the decision maker more than often considers one criterion to be more important than the other. This relative importance is expressed in terms of numbers which are often referred to as weights, and are assigned to different criteria. These weights deeply influence the final choice and may lead to a non-applicable decision when the interpretations of such weights are mis-understood by the decision maker (Keenan, 1997).

Many direct weighting techniques have been proposed in the literature. When a simple arrangement technique is used, the decision maker sets the criteria in an order of preference. The cardinal simple arrangement technique involves each criterion being evaluated according to a pre-established scale. Some other indirect methods are also available such as the interactive estimation method. There are also a relatively complex weight assignment techniques such as the indifference trade-offs technique and the analytic hierarchy process (AHP). These however, are beyond the scope of this study.

2.11 Industrial Applications of Geothermal Energy

2.11.1 Agricultural

Energy from geothermal energy is used in very many industrial processes. They include but not limited to timber drying, laundries, milk pasteurization, food dehydration, spas among many other electric energy dependent processes. Hot steam is applied in sterilization processes for equipments and rooms without necessarily using chemicals that may be toxic or environment friendly. Drying plants, food processing among other industries also uses geothermal energy especially in making powders and other concentrates for preservation; this minimizes the use of chemical or agrochemical preservatives.

2.11.2 Refrigeration

The food processing industry in Naivasha and in the other areas can use geothermal steam to sterilize foods at an affordable cost. This is advantageous especially in areas where geothermal energy abundantly exists. The local community at Eburru utilizes geothermal heat during the process of drying pyrethrum. This can be made more beneficial if proper harnessing of steam enhances such projects. Other plants like tobacco and maize can be achieved this way too.

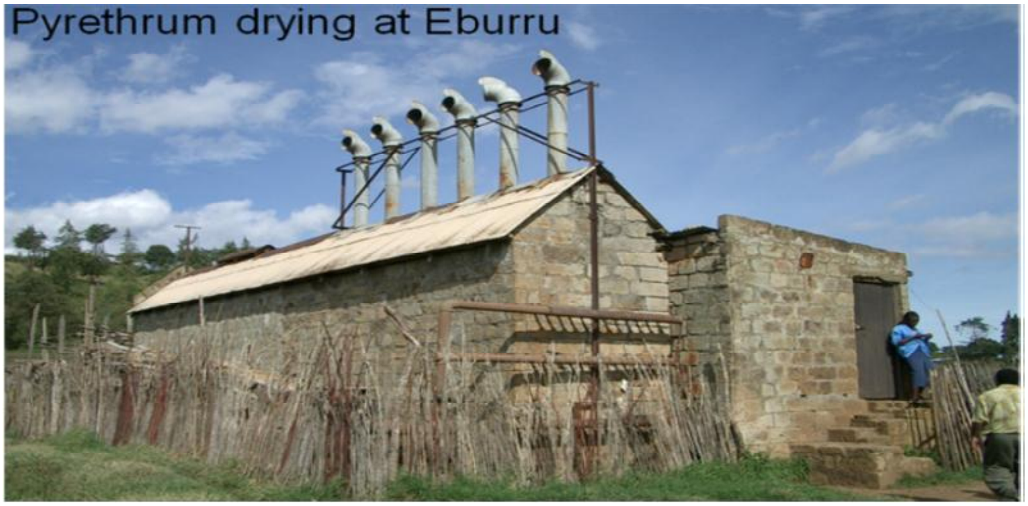


Figure 2.2: Geothermal energy being used by the local community at Eburru for pyrethrum drying.

In areas where ground water quantities are minimal, some communities harvest water for domestic uses from down the geothermal steams. This implies that geothermal resources also supplies water for different uses such as watering of animals, irrigation, and for domestic use like drinking water, washing, cleaning and other general uses.

At Olkaria, water from the steam is harvested for use by the wild animals within the Hellôs Gate National Park as shown in Figure 2.3.

Figure 2.3: Harvesting of water from a spring by members of the local Maasai community.

CHAPTER 3

3. MATERIALS AND METHODS

3.1 Tools Applied in the study

3.1.1 Hardware.

- Computer with specifications of 320 Gb hard disk memory, 2Gb RAM and 2.13 Intel [R] Pentium [R] M Processor
- Mapping Grade GPS receiver (Trimble Geo XT)
- Zonge Geo-physical machine
- Flash disk of capacity 8 Gb
- SD card of capacity 8 Gb
- Digital camera
- Printer

3.1.2 Software

- Arc View version 3.2a
- Arc GIS version 10.1
- Global Mapper version 10.1
- Microsoft Office 2010 Suite

3.2 Overview of Methodology.

The first step was identification of relevant datasets for the study. In this, three key factors were applied in the study. These were the main factors considered in the suitability analysis for optimal siting of a geothermal well in the Greater Olkaria Geothermal area. There are several more factors that can be incorporated in the study but due to the limited time available and data set limitations, these three factors were considered sufficient. A flow chart showing the procedure followed is shown in Figure 3.1 below.

Thes applied datasets were collected from the Kenya Energy Generating Company (KenGen), a state corporation mandated with the task of generating hydro, wind, solar and geothermal power in Kenya. The interest of this study however is limited to geothermal power generation only. On collection of all the relevant data sets, data editing and creation of a database for efficient data management was done. The various factors influencing the location of geothermal wells were then identified processed, standardized, weighted and overlaid to produce individual suitability map for the three data layers. A final suitability map was generated by integration of the three geo-scientific data layers and referred to as the Geothermal well-site suitability map.

The study involves describing a GIS-based multi-criterion decision support system using geo-scientific data from three disciplines, geology, geo-chemistry and geo-physical data sets. This is enabled by integrating the three geo-scientific methods as digital data layers in a GIS environment (ArcGIS) for supporting decision makers in targeting the exploration wellsô appropriate location with respect to the reservoir.

Evaluations of geothermal prospects are based solely on the results of geological, geophysical and geochemical surveys and investigations in the early stages of exploration. The geo-scientific data available are examined to infer the nature, characteristics and the probable location of the geothermal resource. Table 3.1 shows the data types applied in this study as well as their sources.

Table 3.1: Sources of Data

Data Type	Data Source	Use
GPS Co-ordinates (UTM Projection)	Field collection using a hand held GPS receiver	For Ground Truthing
Soil Map	Kenya Agricultural Research Institute (KARI)	For extraction of soil properties of the study area for soil survey
Iso-resistivity Maps	Kenya Electricity Generating Company (KenGen)	Determination of Geophysical Suitability Areas
Geological Map	Survey of Kenya	For digitizing polygon datasets on calderas, craters and dome zones.
Topographical Map (1:50,000)	Survey of Kenya	Base Map

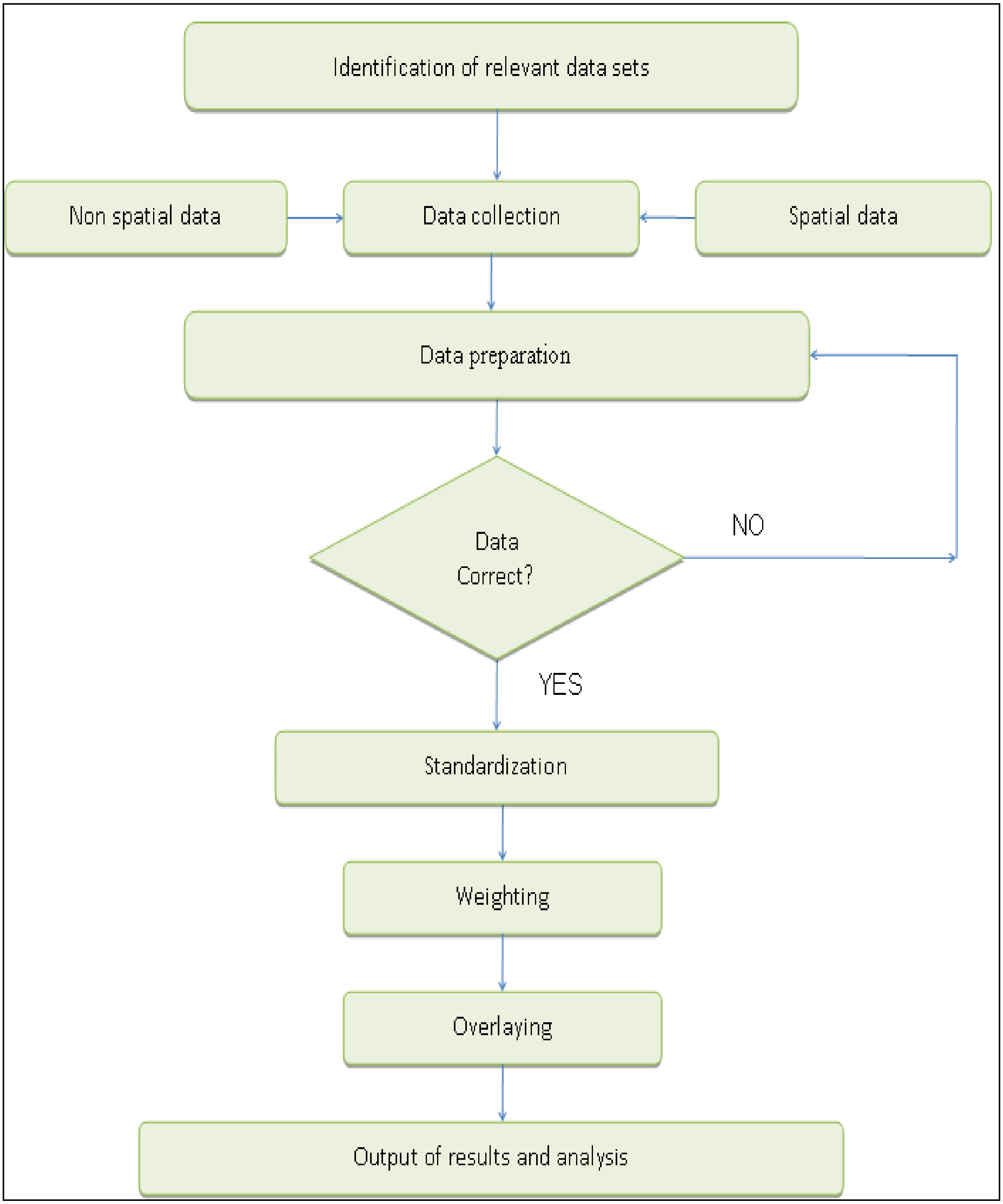


Figure 3.1: Flow Chart of the Methodology Employed.

3.3 Procedure

3.3.1 Data Preparation

The process of data preparation involved the collection of data sets from the 3 geo-scientific fields of interest, the geological, geophysical and geochemical fields. This included actual field site visits for data collection, laboratory visits for lab surveys and collection of data sets on the iso-resistivity maps.

3.3.2 Re-projection

The mapping scale was unified before analysis. Most of the data was in GSC_WGS_1984 projection and hence it was used for all data and result presentation. Re-projection and transformation was done to any other data in different format to register them into a uniform coordinate system. The re- projection process was carried using ArcView 3.2a.

3.3.3 Digitizing of Data sets

To ensure accuracy in the entire process of digitizing, re-registering of the data sets was carried out. Only data sets from the geological data layer were digitized to delineate boundaries for the three factors that were applied in this study, the caldera, the crater and the dome areas. These data sets were in the form of polygons and conversions to raster were performed before further processing.

3.3.4 Buffering

The selection query applied with respect to the geological structures was the buffer size for generating factor maps of each data layer. To identify suitable areas, a buffer distance of 3000m for all the three geological parameters were used to delineate suitable from unsuitable areas. This buffer distance was chosen because it is the approximate maximum distance from which geological structures have been found to influence the occurrence of geothermal energy.

Table 3.2 shows the criterion that was applied in determining the level of suitability of an area based on the location from the centre of the buffer zones.

Table 3.2: Table Showing the Buffering Criteria Applied for Geological Factors

Buffer Zone (m)	Weight	Description
1000	3	Most suitable
2000	2	Moderately Suitable
3000	1	Least Suitable

Areas falling within the buffers are regarded as suitable areas depending on whether they are located in the first, second or third ring of the buffered zones. On the other hand, areas falling outside the buffer zones are taken to be unsuitable for geothermal resource exploration.

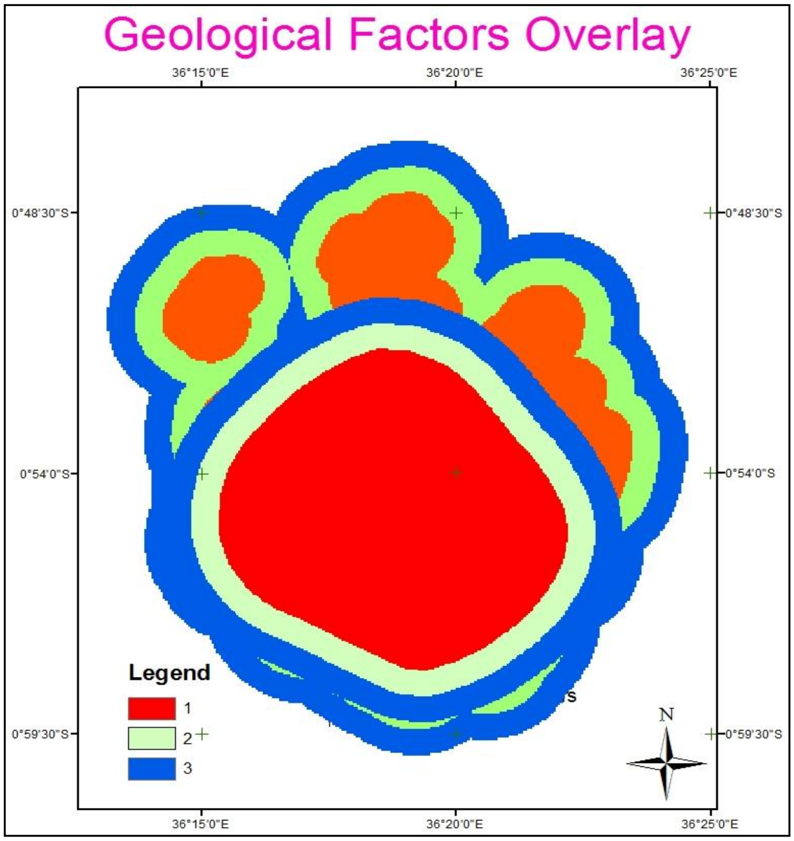


Figure 3.2: Map showing the process of buffering geological factors in ArcMap 10.1

3.3.5 Conversion of Feature Data sets to Raster

The original data sets collected from the field were digitized in the form of points, poly lines and polygons. This included the geological data sets e.g. volcanic domes, craters and the caldera. The geochemical datasets were converted to rasters from point features.

3.3.6 Re-sampling

The purpose of re-sampling is to alter the raster dataset by changing the cell size and resampling method while keeping the extent of the raster data sets as required. The nearest neighbour re-sampling method was adopted for this purpose since majority of the data sets are discrete. This method was preferred because it does not change the values of the cells and the maximum spatial error will be one-half the cell size. Re-sampling technique is necessary because rarely do the centres of the input cells align with the transformed cell centres of the desired resolution.

Creation of a continuous surface was carried out by Inverse distance weighting (IDW). IDW interpolates a raster surface from points to create a uniform surface. Because IDW is a weighted distance average, the average cannot be greater than the highest or less than the lowest input. Therefore, it cannot create ridges or valleys if these extremes have not already been sampled, hence was preferred for this study.

3.3.7 Re-classification

The reclassification of values into intervals or by area considers all values and their distributions in a raster simultaneously and reclassifies the values into a specific number of groups. Reclassifying values into intervals or by area groups the input values by dividing the value range into an equal number of specified intervals (equal interval) or by distributing the number of cells into a defined number of groups until each group has the same number of cells (equal area). Reclassification was necessary to assign values of priority to the applied criteria for each of the layers involved.

3.3.8 Weighting

When some features are more important than others are, the weights can be used to reflect those feature differences. Weights are numeric attributes associated with the features in a given dataset. The higher the numeric values of a given data set, the greater the weight for that feature. For the three data sets that were considered in this study, weights were awarded to each layer depending on the scientific importance of the field in geothermal energy siting as shown in Table 3.3 below.

Table 3.3: Table Showing Weighting of the Geothermal Data Layers in terms of % Influence

Field	**% Influence**	**Description**
Geophysics	50.0	Most Important
Geology	33.3	Important
Geochemistry	16.7	Least Important

3.3.9 Standardization of applied criteria.

After data preparation and processing, the different factors were arranged in an order matching their importance or weight. This process is also referred to as rating. For geothermal power generation, geophysical method of data collection is assigned the highest priority as shown on Table 3.4.

Table 3.4: Table Showing the Rating Criteria Applied to the Three Geo-Scientific Fields

Geo-Scientific method	Weight	% Influence
Geophysical	3	50
Geological	2	33.3
Geochemical	1	16.7

As there were three classes, considering the optimum conditions for geothermal well-siting, the classes were numbered one to three with three representing the class that fulfilled the optimum requirements, two indicating the class that moderately met the requirements and one numbered the class that least met those optimum site requirements. Based on these criteria, individual suitability maps were obtained. The sub factor maps were re-classified and this was performed using ArcGIS 10.1. The results of this process is the individual suitability maps for sub factors which would be weighted and overlaid to produce the individual suitability maps for the three identified main factors. The results of this operation are discussed and displayed in Chapter four.

3.4 Individual Suitability Determination Criteria

3.4.1 Geophysical Suitability

In the development of the Geophysical suitability map, the iso-resistivity maps of the study area are used to define suitable areas from unsuitable areas. The resistivity distribution map is used as an input file and the area with a resistivity value of between 0-80 Ohms is considered as a prospective area, hence geo-physically suitable. Iso-resistivity maps are maps drawn at different depths within the study area aimed at indicating the resistivity variations within the study area. The results obtained in geophysical exploration should be in line with the structural geology of the study area. The occurrence of a certain geological structure e.g. a fault line leads to a drop in resistivity values as compared to a continuously compacted region. Thus, a geologically suitable region must favourably concur with the results of a geophysically suitable region.

3.4.3.1 Weighting of the Geo-Physical Layer

This is the most important geo-scientific discipline in siting of geothermal wells. The parameter that is applied in this case is resistivity. This is usually controlled by the nature of the earthȏs crust and the structural features present in the study area. The lower the resistivity values of a given area, the higher the potential for geothermal energy.

The observed resistivity values were reclassified and weighted into three classes as shown in Table 3.5 below,

Table 3.5: Table Showing Reclassification and Weighting of Resistivity Variation

Class Range (Ohm)	Weight	Description	Colour code
0 - 80	3	Most Suitable	Red
81 - 200	2	Moderately Suitable	Green
201 - 400	1	Least Suitable.	Blue

3.4.3.2 Resistivity

Interpretation of resistivity survey data is aimed at delineating resistivity variation with depth assuming that the earth is electrically homogeneous and the resistivity only varies with depth and relate this to hydro geological and thermal structures. A resistivity survey of a geothermal field reflects the thermal alteration of the field, hence the temperature. Elevated temperatures lead to increasing alteration of minerals in the rocks of the subsurface leading to a lowering of resistivity

a). Iso-resistivity Maps

Iso-resistivity maps indicate the resistivity variation at different depths that show the interesting variations in resistivity properties of the sub-surface of the point under investigation. The programme TEMRESD developed at ÍSOR ï Iceland GeoSurvey is used to generate iso-resistivity maps at different elevations from the 1D-inversion models. The resistivity is contoured and coloured in a logarithmic scale depending on the resistivity characteristics of the area under study. The elevation of the Olkaria field is approximately 2000 metres above sea level (a.s.l).

b). Weighting Criteria of the Iso-resistivity Maps

The iso-resistivity map of measurement taken at 3000m is closest to the average altitude of the study area hence of more importance than all the other maps. The priority of importance then decreases with increasing distance from the average altitude values of the study area as shown in the Table 3.6.

Table 3.6: Table Showing the Weighting Criteria Applied to the Four Iso-resistivity Maps Used.

Depth (m)	Weight
3000 amsl	4
1000 amsl	3
0 amsl	2
-1000 bmsl	1

c). Geo-referencing of the Iso-resistivity Maps

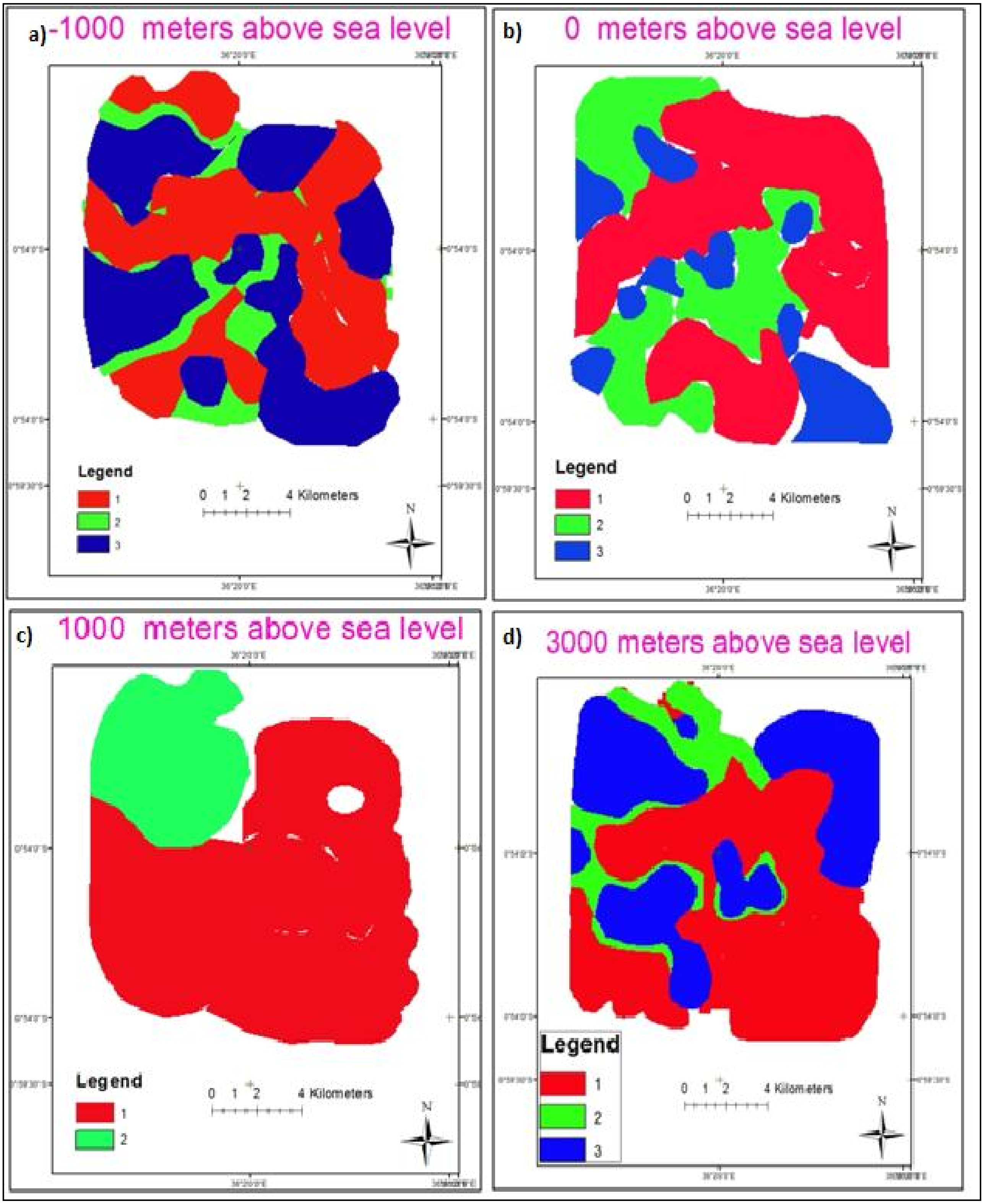
Digital images of the iso-resistivity maps were geo-referenced in ArcMap 10.1 to register the image with its actual co-ordinate locations. This was carried out on all the four iso-maps that were applied in this study. The study area is enclosed between coordinates 9908090N, 200000E to the North West, 9908090N, 210000E to the North East, 9892000N, 210000E to the South East and 9892000N, 200000E to the South West.

d). Digitizing the Iso-resistivity Maps

Once the iso-resistivity maps have been geo-referenced, they are digitized as to identify the high priority areas and to enable weighting of the various resistivity fields observable on the maps.

For purposes of this study, four iso-resistivity maps of the study area were analyzed and various operations were performed on them to enable use in a GIS environment. This included digitization of the maps to enable classification of the iso-maps into resistivity classes as shown in Table 3.6 above.

The four iso-resistivity maps represented depths of 0m a.s.l, 1000m a.s.l, -1000m b.s.l, and 3000m a.s.l. as shown in Figure 3.3



a)-1000 meters above sea level

b) 0 meters above sea level

c) 1000 meters above sea level

d) 3000 meters above sea level

Figure 3.3 Figure showing the four iso-resistivity maps applied in the study.

The iso-resistivity maps are weighted depending on the importance of the heights at which they were taken relative to the average altitude of the study area, which is approximately 2000m.

3.4.3.3 Interpretation of the Iso-resistivity Maps

a). Resistivity map at 0 m a.s.l

This iso-resistivity map is at sea level and it shows a uniformly distributed resistivity variation across the entire area. A high resistivity core of between 200-400 ɋ m occurs at different locations of the study area as evidenced by the blue colour at various points on that map. This is interpreted as an indication of high temperature alteration minerals in which case the zone would mark the core of the reservoir for the Olkaria (Keller et. al. 1994).

b). Resistivity map at -1000 m b.s.l

This map shows resistivity at a depth of about 1000 metres below surface and the resistivity structure of the study area at this point resembles the resistivity structure at sea level, with uniformity in distribution of resistivity across the area. This gives a possibility of the high resistivity core extending to this depth, thus the thick resistivity core would be an indication of a good reservoir for a high temperature system (Keller et. al. 1994)..

c). Resistivity map at 1000 m a.s.l

This is approximately 1000 meters from the surface and the resistivity at this zone is relatively low. The resistivity of the entire study area at this depth is about 40 ɋ m that is a reduction in resistivity as compared to the resistivity at 1000 m a.s.l. This decrease in resistivity could be a reflection of a possible transition from high temperature alteration minerals to low temperature alteration minerals (Keller et. al. 1994).

d). Resistivity map at 3000 m a.s.l

The resistivity at this depth is indicative of the existence of the three possibilities with most suitable areas predominant. The extensive distribution of low resistivity values across the area is evidence of the existence of a geothermal resource within the study area (Keller et. al. 1994).

3.4.2 Geological suitability

The geological suitability of the study area was determined by overlaying the factor maps of three key geological indicators of geothermal energy. This was done by first digitising the factors from a geological map of the study area and converting the polygon features into rasters. The input layers that were used for purposes of this layer include;

(i) Crater

(ii) Domes and Lavas

(iii) Inferred Caldera

The resultant factor maps were overlain and combined (union) to identify geologically suitable areas. The union tool in ArcMap creates a new coverage by overlaying two or more raster coverage for all the involved factors. The output coverage contains the combined rasters and the attributes of all the coverage factors that are input. Figure 3.4 below illustrate how this is done in ArcGIS 10.1.

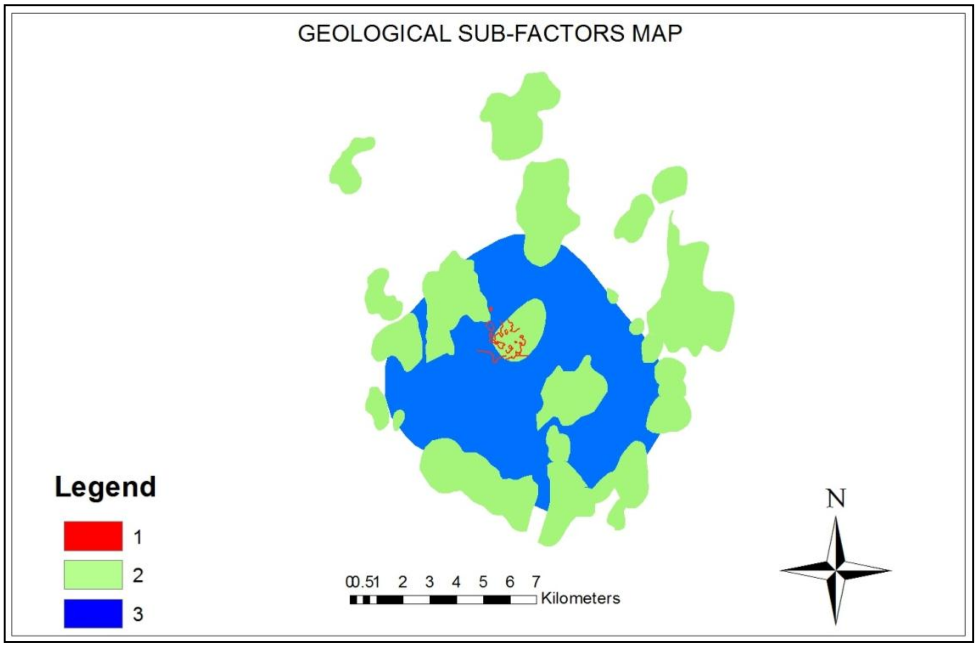


Figure 3.4: Map showing the results of the overlay of the three geological factors as applied.

A weighting criterion was applied for the three parameters based on the importance of each of them with regard to geothermal energy and site identification. An area falling within all the three factors was assigned the highest priority. Since each of these factors has varying influences on the probability of being geothermal indicators, different weights were assigned to each of them. This was done after consultation with experts and geologists at KenGen.

A sample site falling within a dome/lava zone is assigned the 2nd highest priority, followed by an area falling inside a crater zone and the last priority is assigned to an area falling within an inferred caldera as shown on Table 3.7.

Table 3.7 : Table Showing the Criteria Applied for Weighting of Geological Factors

Rank	**weight**	**Geological Factor**	**Description**
1st priority	4	All	Most Suitable
2nd priority	3	Lava/Dome area	Suitable
3rd priority	2	Crater	Moderately Suitable
4th Priority	1	Inferred Caldera	Least suitable

The generated factor maps are combined by intersecting them to generate the final geological suitability map, shown in figure 4.1.

3.4.3 Geochemical Suitability Map

The area under investigation has a number of geothermal manifestations or expressions, which makes it possible to apply geo-chemical methods. Some of the geothermal manifestations present include few low-pressured fumaroles mainly located inside the caldera. A total of 40 sample points were selected and soil samples were taken. Fumaroles were also considered to be sample points and water samples from the fumaroles were taken for the same purpose, laboratory survey of the percentage of CO_2 and H_2S concentrations in parts per million.

3.4.3.1 Laboratory Survey

The chemical survey conducted involved fumaroles sampling and soil gas survey with emphasis on carbon dioxide (CO_2) and Hydrogen Sulphide (H_2S) gas compositions in the soil air. The procedure was undertaken in a geochemical laboratory at KenGen. The soil gas survey was conducted along traverse lines running E-W. The sample points were randomly determined along the traverse lines in areas of high geothermal manifestations and wider apart in areas of low geothermal manifestations. Sampling was done at a depth of 0.7 m below the surface.

Geo-processing tools are used to develop the Geochemical Toolbox in the ArcMap environment for selection of geothermally suitable localities based on geochemical data. Geochemical suitability was identified by integrating factor maps based on concentrations of $C0_2$, H_2S, and temperature values of the sampled points. These three layers are overlain and the selected areas need to be combined (union) to identify the geochemically suitable area. The output of this operation is a geochemical suitability map of the study area.

3.4.3.2 Procedure for Geochemical Sample analysis

Maximum subsurface temperatures experienced by geothermal waters can be recorded by ionic and stable isotope ratios in solutes and the water itself through laboratory experiments. This isotopes and solutes if applied for purposes of determination of certain concentrations in a given sample are referred to as geo-thermometers. For purposes of this study, CO_2 and H_2S gases were used as the indicative geo-thermometers. 40 water samples from completed wells neighboring the sampled points were collected for purposes of determination of the general temperature variations of the study area.

The water samples were collected and analyzed in the laboratory and the concentrations of CO_2 and H_2S in parts per million were determined. An average height of 1500m for each well from which samples were collected was maintained. The results were taken as the reservoir temperatures for each sampled point. The locations of the forty sampled points and the wells for all the three geo-thermometers are represented in Appendix A to C.

3.4.3.3 Interpolation of Results

The results obtained for the concentrations of CO_2, H_2S and temperature for the 40 sampled points were interpolated by the inverse distance weighting method to make them representative of the entire area. Having attained a surface representation of the study area based on all the three factors, overlay operations were conducted in ArcGIS 10.1 and a final geochemical suitability map was generated as below.

3.4.3.4 Resultant Factor Maps

The geochemical parameters applied were reclassified and interpolation done to generate individual factor maps. The procedure for reclassification and interpolation is described below, the results of interpolation to create a uniform surface for the three geo-thermometers used in this study are shown in Figure 3.5, Figure 3.6 and Figure 3.7.

a). Carbon dioxide

For an area to possess any potential for geothermal power generation, it must meet the minimum threshold of 200ppm of CO_2. The study area was re-classified into three classes as illustrated in Table 3.8. while Figure 3.5 shows the CO_2 suitability map after interpolation.

Table 3.8 : Table Showing Criteria for Classification of Carbon dioxide

Class Range (ppm)	Weights	Description
0 -200	1	Least Suitable
201-500	2	Moderate
501-800	3	Most suitable

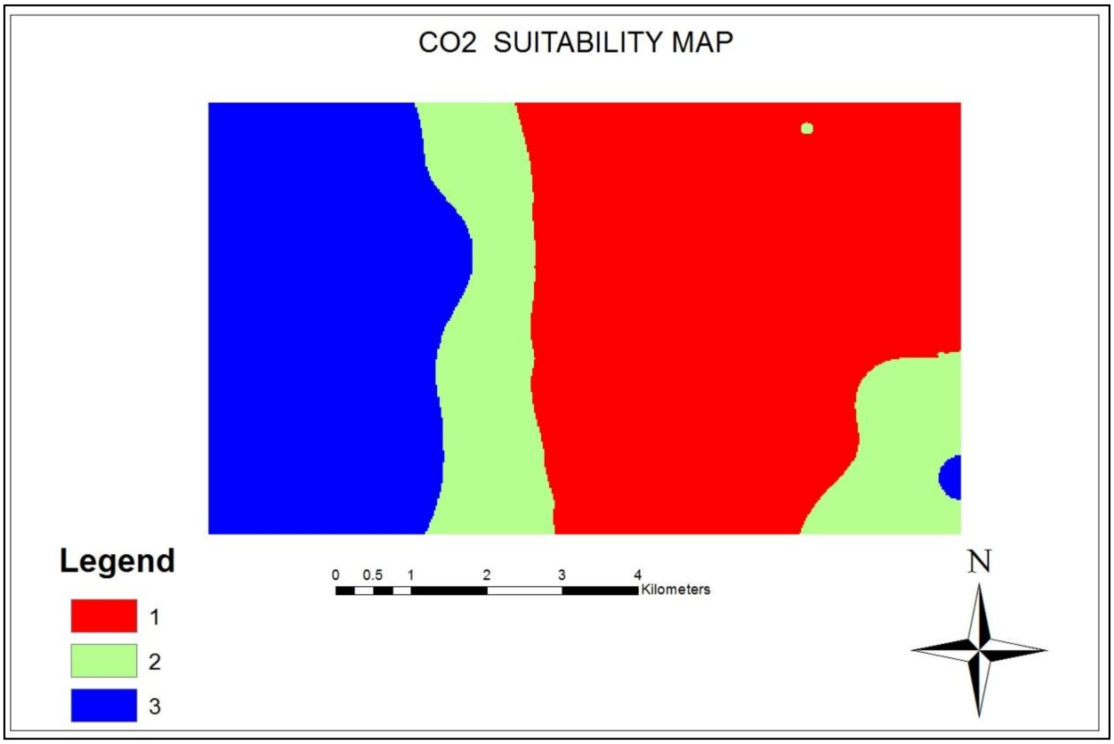


Figure 3.5: Map showing the suitability of the study area based on $C0_2$ concentration.

b). Hydrogen Sulphide

An area with extremely high concentrations of Hydrogen Sulphide is not suitable for geothermal power generation. The threshold for determining suitable from unsuitable areas based on concentrations of H_2S is that a sampled point must contain less than 10 parts per million of H_2S.

The samples were re-classified into three classes as illustrated in Table 3.9 while Figure 3.6 shows the H_2S suitability map after interpolation.

Table 3.9: Table Showing the Criteria Applied Weighting of Hydrogen Sulphide (H_2S)

Class Range (ppm)	Weight	Description
0-5	3	Most suitable
5.1-10	2	Moderate
10.1-15	1	Least Suitable

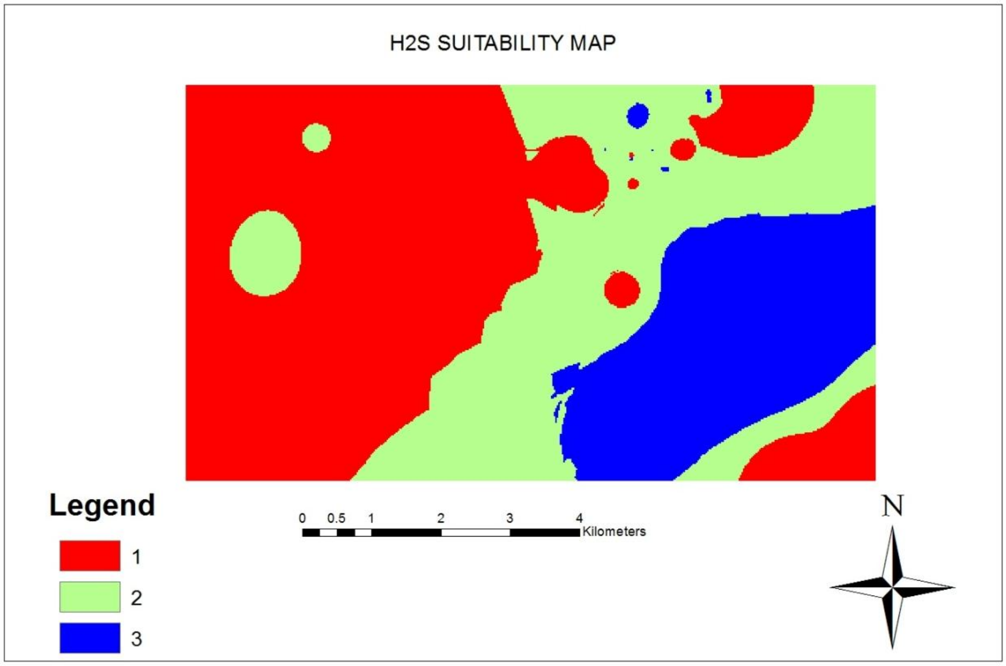


Figure 3.6: Showing the suitability of the study area based on H_2S concentration.

c). Temperature

The maximum observed temperature out of the forty sampled points was 285^0C. The higher the temperature values of a measured point, the higher the potential of the sample to bear geothermal energy. The observed temperature values of the sample points were re-classified into three classes with a range of 100^0C as shown on Table 3.10

Table 3.10 : Table Showing the Criteria Applied Weighting of Temperature

Class Range (^{0}C)	**Weight**	**Description**
0 - 100	1	Least Suitable
101 - 200	2	Moderate
201 - 300	3	Most Suitable

Figure 3.7 shows the temperature suitability map of the study area after interpolation by kriging.

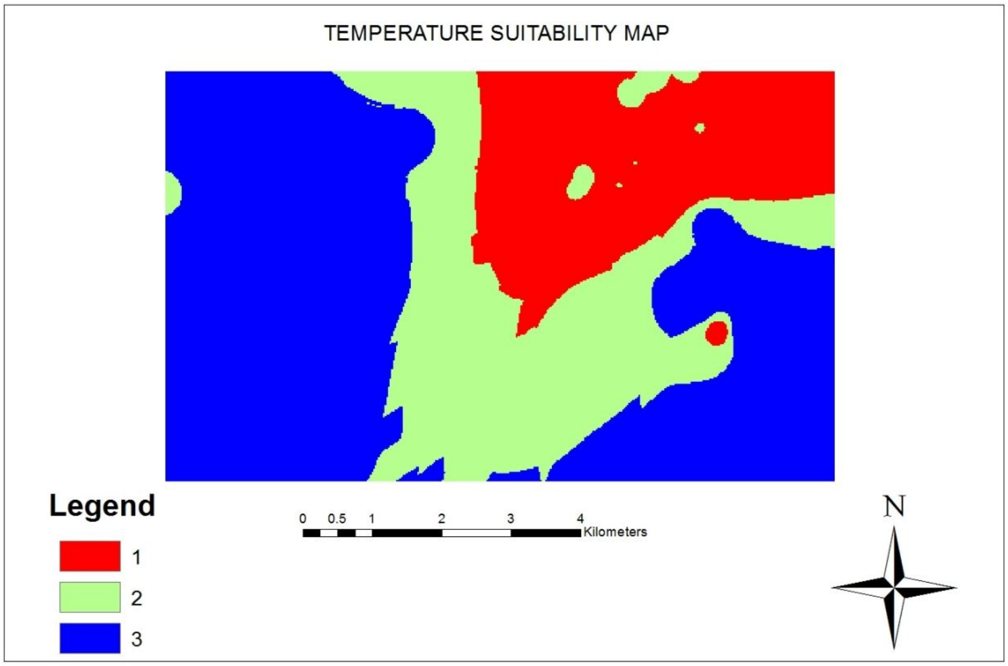


Figure 3.7: Map showing the suitability of the study area based on Temperature values.

3.4.4 Data Processing.

These selected factors adequately represent the decision-making environment and contribute to the final suitability map. The process of selecting these criteria was through consultation with the Geothermal Development Manager at KenGen and my supervisor.

For uniformity and overlaying purposes, all vector data sets was first converted to raster. Re-classification was necessary since the different factors were in different classes. Three classes were set as the optimum for analysis throughout the whole processing as the expected classes were three. All the datasets were in same format and bore same number of classes, three.

3.4.4.1 Integration of the Geo-Scientific Data Layers

Once the three suitability maps for the involved geo-scientific disciplines have been generated, integration is performed in a GIS environment. ArcGIS 10.1 was used for performing a boolean logic model, the study area based on each evidence layer needs to be classified and assigned different values. Three different values have been assigned to the area:

i). For the area found to be suitable for geothermal power generation
ii). For the area found to be moderately suitable
iii). For the area found to be least suitable for geothermal resource generation.

The final sites were selected by running the geothermal potential area identification toolbox that combines the three input data layers. The boolean AND (Intersect) operator was used for overlaying the three layers and the areas that are common for all three layers are selected as the best suitable area. Boolean integration methods are applicable for logical combination of binary maps. Two conditional operators, óORò (Union) and ñANDò (Intersect), are applied for data integration.

The intersect (AND) Tool in ArcMap calculates the geometric intersection of any number of feature classes and data layers that are indicative of geothermal activity (e.g. high-temperature gradients, geological structures and mapped surface alterations). Features that are common to all input data layers are selected using this method. This implies that the selected area is suitable for a study based on all input data layers, and the selected area receives the highest suitability rank. Those areas that are common to some but not all data layers are selected and ranked in the subsequent priority levels.

3.4.4.2 Suitability ranking of the geothermal prospect areas

The project proposes the application of GIS in a multi-criterion approach for suitability analysis for Geothermal well-site selection at the Olkaria geothermal field. It is necessary however to place weights on the three different layers depending on the relative importance of individual methods in geothermal site selection. Geophysical method is scientifically identified as the most important method in identification of geothermal resources as it is key in identification of the nature of the underground where geothermal resources are present.

CHAPTER 4

4. RESULTS AND DISCUSSIONS

4.1 Individual Suitability Maps.

After the stepwise overlay of all the relevant sub factors for the three geo-scientific disciplines, results were obtained for the individual factor maps for the three key disciplines. The three maps show the three different classes of suitability and each class has been consistently displayed in a uniform colour choice. This will assist in quick identification and comparison of suitability level according to each influencing factor. For each of the factors, the study area was reclassified into three classes with the use of primary colours adopted for identification of the three different sections for each map as shown on Table 4.1.

Table 4.1: Table Showing the Colour Code Identification Criteria

Colour Code	Description
Red	Most suitable
Green	Moderately suitable
Blue	Least Suitable

The results obtained were statistically computed by use of ArcGIS 10.1 to find the aerial coverage for each of the three classes forming the final suitability map. Table 4.2 below shows the area in square kilometers for each suitability class.

Table 4.2: Total Area of each Suitability Class.

CLASS	SUITABILITY	AREA (km^2)
1	Most suitable	28.46
2	Moderately suitable	14.66
3	Least suitable	22.81

The 3 data layers when integrated in a GIS environment, enables the program to calculate and select the potential locations. By integrating a different number of data layers, prospective areas are defined and ranked. Priorities of selected areas depend on the number of data layers employed in selecting an area.

(i) The area common to all three data layers is given first priority.

(ii) The second priority area is the area described by geophysical data sets.

(iii) The third priority area is the area described by geochemical data sets.

(iv) The final priority is assigned to areas covered by geological data sets.

4.3.1 Final Geological Suitability Map

In geothermal exploration, geochemical studies carry the least weight in terms of optimal site-determination. This is because the other two factors give information about the earth's interior as opposed to geochemistry, which relays information about the contents of the earth's interior.

When carrying out geological studies however, field work should be supplemented where possible by satellite imagery and aerial photography. These leads to identification of hidden geological structures especially faults and lineation which may otherwise be unnoticeable by use of the naked eye. Figure 4.1 shows a geologically suitable area, the figure takes the shape of a caldera as it is the biggest geological structure and other factors lie within it.

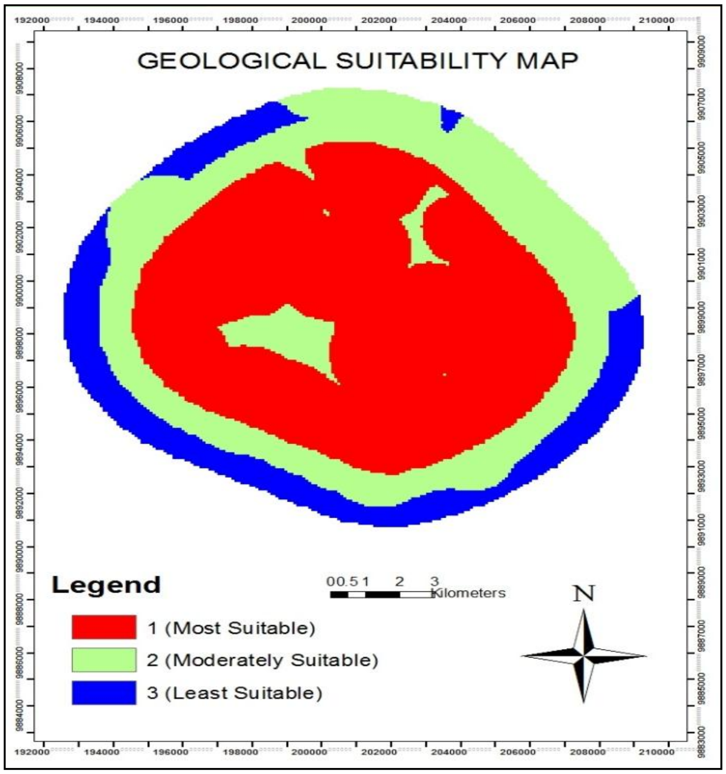


Figure 4.1: Map showing the Geological Suitability of the study area

4.3.2 Final Geophysical Suitability Map

Results obtained from the analysis and interpretations of the iso-resistivity maps indicate that a large percentage of the study area is geo-physically suitable for geothermal power generation. A huge part of the study area is found to have low to average resistivity values at different heights of measurement hence the study area may be termed as generally conducive for geothermal power generation. Figure 4.2 shows the final geophysical suitability map of the study area.

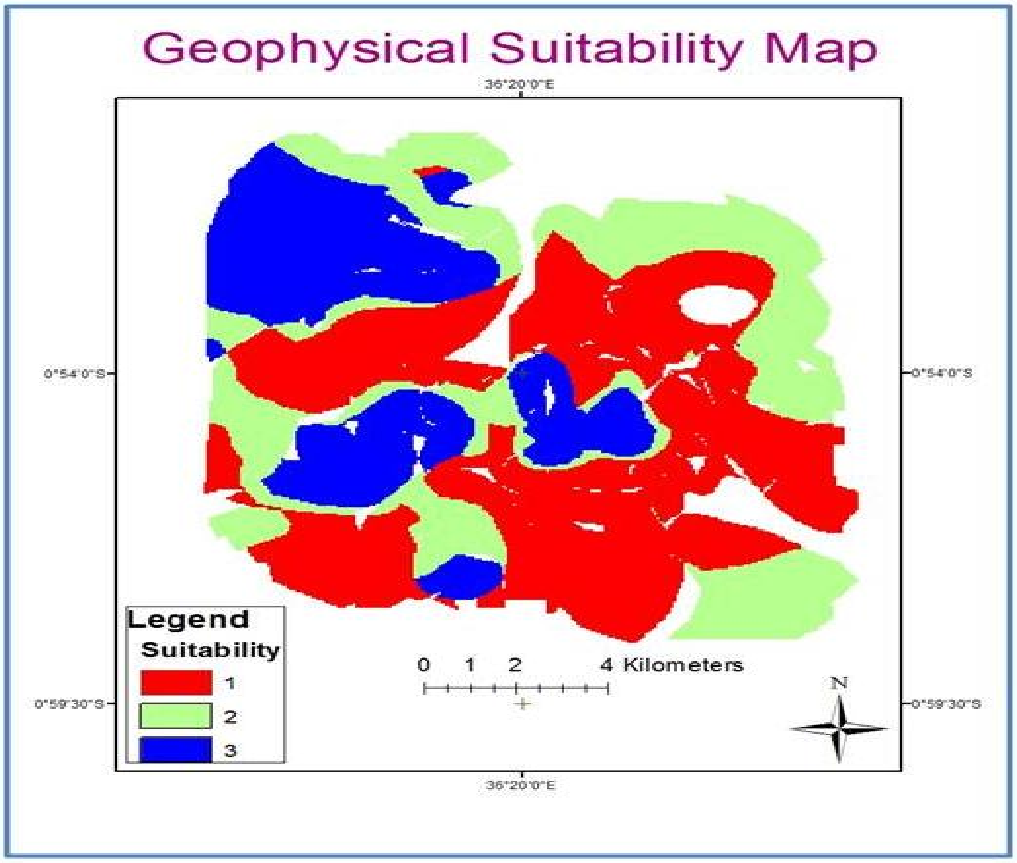


Figure 4.2: Showing the Geophysical Suitability of the study area

When the results of the geophysical analysis as shown on the geophysical suitability map are overlain with a layer containing the spatial locations of the Olkaria geothermal fields, results indicate that the resistivity is lower around Olkaria North-West Field than the area around South-East and the central part of the study area. The near surface difference in resistivity as observed in the iso-resistivity map at 0m a.s.l is caused by contrasts in the subsurface geology. An altered thick surficial layer of pyroclastics occurring in the Olkaria East field is the cause of the near surface low resistivity around this area (Omenda, 1994).

The Olkaria East Field lies exactly within the caldera hence the presence of the pyroclastic rocks, usually formed through massive volcanic activities. Areas of low to average resistivityôs of 10 ɋ m -80 ɋ m are found to lie in regions characterised by high geological formations. A series of fault lines and lineationôs are evident in the south-eastern low resistivity regions. It is worth noting that a huge part of the caldera covers the central part of the study area as well. The concurrence of the results provides further evidence of the existence of a geothermal resource in the south-eastern part of the study area (Omenda1998).

4.3.2.1 Interpretation of Results of the Iso-resistivity Maps

Resistivity data interpretation from the Olkaria geothermal field shows that the low resistivity (less than 20 ɋ m) anomalies at depths of 1000m a.s.l that define the geothermal resource boundaries are controlled by a series of lineation and fault lines present in the study area. The near surface difference in resistivity is because of the contrasts in the subsurface geology. Drilled wells show that the low resistivity anomalies at 1000m a.s.l define a geothermal system with temperatures in excess of 240^{0}C (Keller et. al. 1994).

4.3.3 Final Geochemical Suitability Map

Results obtained on analysis of the three geochemical indicators in ArcMap shows that the reservoir temperature increases from the north west to the Eastern part of the study area. The temperature range is from 77ºC to 284ºC and a larger part of the study area is suitable for geothermal power generation as over 70% of the sampled points met the required 200^{0}C threshold required for an area to be classified as thermally suitable. In the study area therefore, there exists a suitable temperature for development in most of the prospect areas but the high priority area is in the western part area. Figure 4.3 shows the final geochemical suitability map.

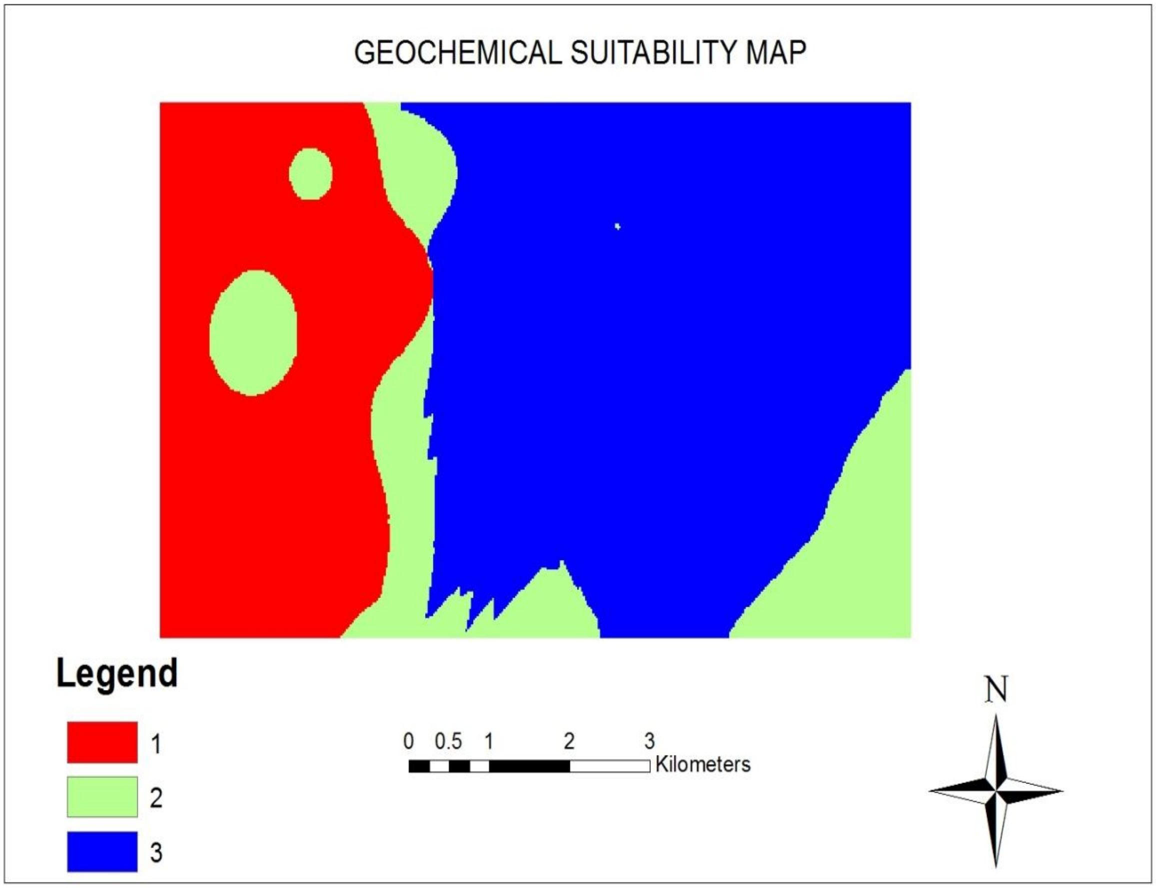


Figure 4.3: Shows the suitability of the area based on Geochemical Layer

Final Geothermal suitability map

Using spatial analyst tools in ArcMap, the final suitability assessment map is derived based upon the results of the three suitability maps obtained for the geophysical, geochemical and geological data layers. The final suitability map is shown below;

4.2 Final Geothermal Suitability Map

The final aim of all exploratory work in geothermal exploration is to select the most promising sites for exploratory drilling as well as final drilling sites. From the combined evidence provided by all the different geo-scientific disciplines involved in the exploration, the promising well site areas were selected, divided into three areas depending on their suitability levels. The purpose of this work is to provide a method by using the GIS-based decision support system to combine all exploration and environmental data and information to select optimum geothermal well sites for exploration drilling in order to reach to the deep geothermal resources.

To develop a decision support model for sustainable development of geothermal resources, the exploration work (geological, geochemical and geophysical investigations) have to be carried out and their results integrated in a GIS environment. The process of delineating which area is suitable for well targeting can often be a huge task for exploration scientists and decision makers. However, the decision process can be simplified if it is broken down into a stepwise procedure as described in this study.

For finding the optimum area for well sites, the first decision-making process is used on all exploration survey results to find out the suitability. Secondly, the study area is classified based on environmental suitability. Finally, by combining exploration suitability and environmental suitability with special assigned weighting for each layer the promising area for exploration drilling is selected. For purposes of this study however, only the first decision-making process is put into perspective with emphasis put in for Geological, Geophysical and Geological data layers.As noted in Figure 3.4, the highest priority is assigned to the geophysical layer followed by geological and finally the geochemical data layers.

From Figure 4.4, it is observed that the final suitability map shows that the highest priority areas are characterized by the positive results of the three factors. This is the area indicated by the red colour. The optimal sites lie along zones of geological significance as evidenced by the presence of the crater zone, the caldera and lava domes in areas classified as having highest potential for geothermal power generation. This is further supported by the concurring results obtained from Iso-resistivity maps and the geochemical results of the study area.

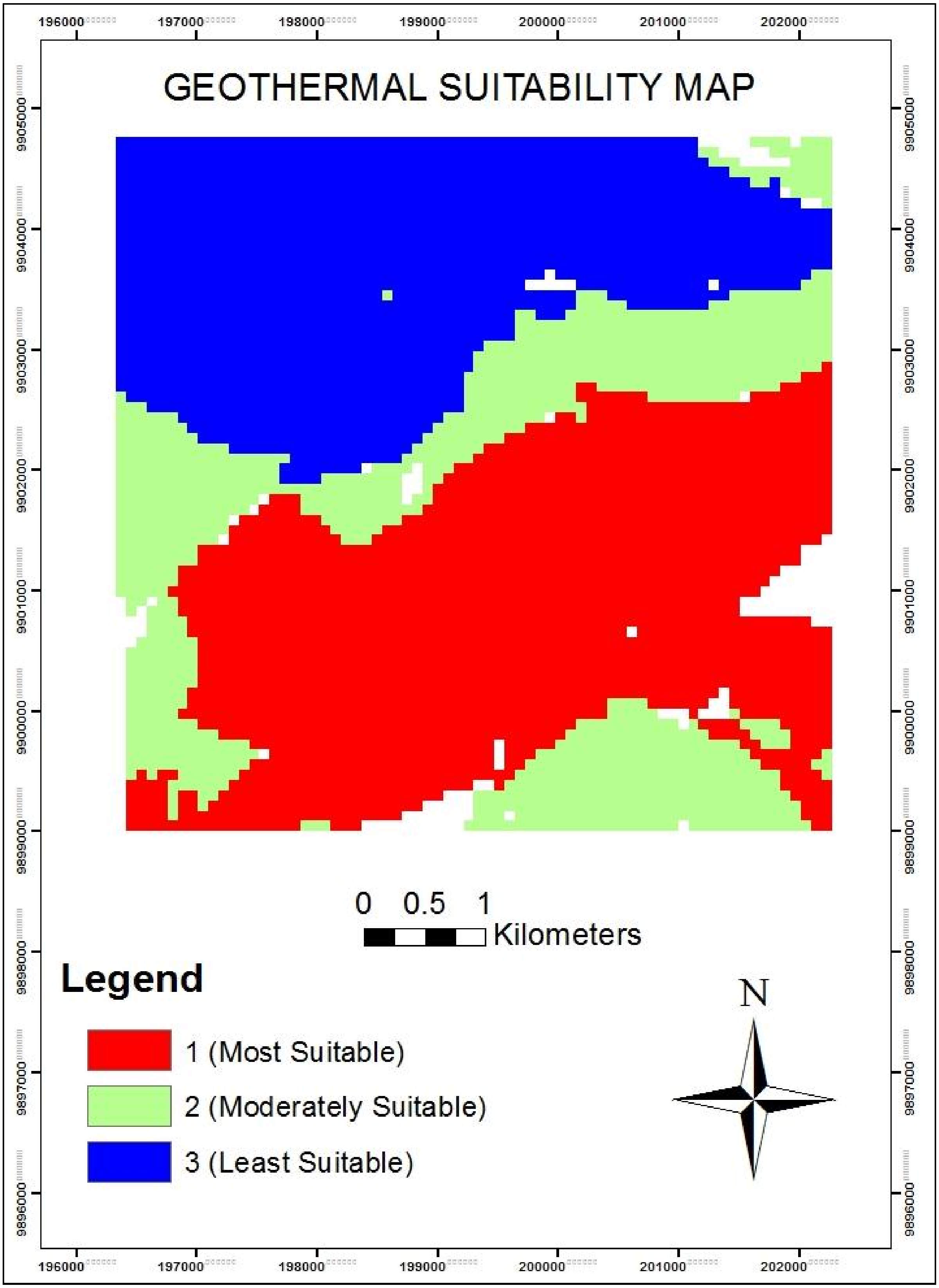


Figure 4.4: Map Showing the Final Geothermal Suitability Map

From Figure 4.4, the moderately suitable area is marked by the green color and marks the smallest part of the study area in terms of areal extent. This may be attributed to the high weighting values assigned to the Geophysical and geological layers as opposed to the less influential geochemical layer. It is worth noting that the most suitable area agrees with the results of both the geophysical and geological data layers. Overlaying these two layers on the final suitability map provides evidence to this.

The area assigned the last priority is least suitable for geothermal well-site selection. This area is observed to be less suitable because it satisfies the required criteria only on one factor, geological, geophysical or geochemical. It is indeed true as the final suitability map when overlaid with the applied geological structures indicate that the area falls outside the area.

The final priority map is meant for decision-making therefore the user would be making decisions based upon all available information and data. The study therefore proposes a multi criterion approach that may be adopted by KenGen in identification of suitable geothermal well sites. This method if adopted is sure to increase the success rates of drilled wells than it is currently with the application of the geophysical methods alone.

4.3 Justification of Results

The results obtained for the three suitability areas were compared to the locations of existing wells within the area of study. A sample of 18 wells was used for this purpose by overlaying their spatial locations on the geothermal suitability map. Figure 4.5 shows the spatial locations of existing wells on the final geothermal suitability map.

Out of the eighteen existing wells, twelve wells were found to be located in the area found to be most suitable, three on the area found to be moderately suitable and three were located on the area found to be least suitable for geothermal well location. This represented a near 70% of the wells being located on the area found to be most suitable. The results hence are justifiable since they are comparable to KenGenôs current exploration methods.

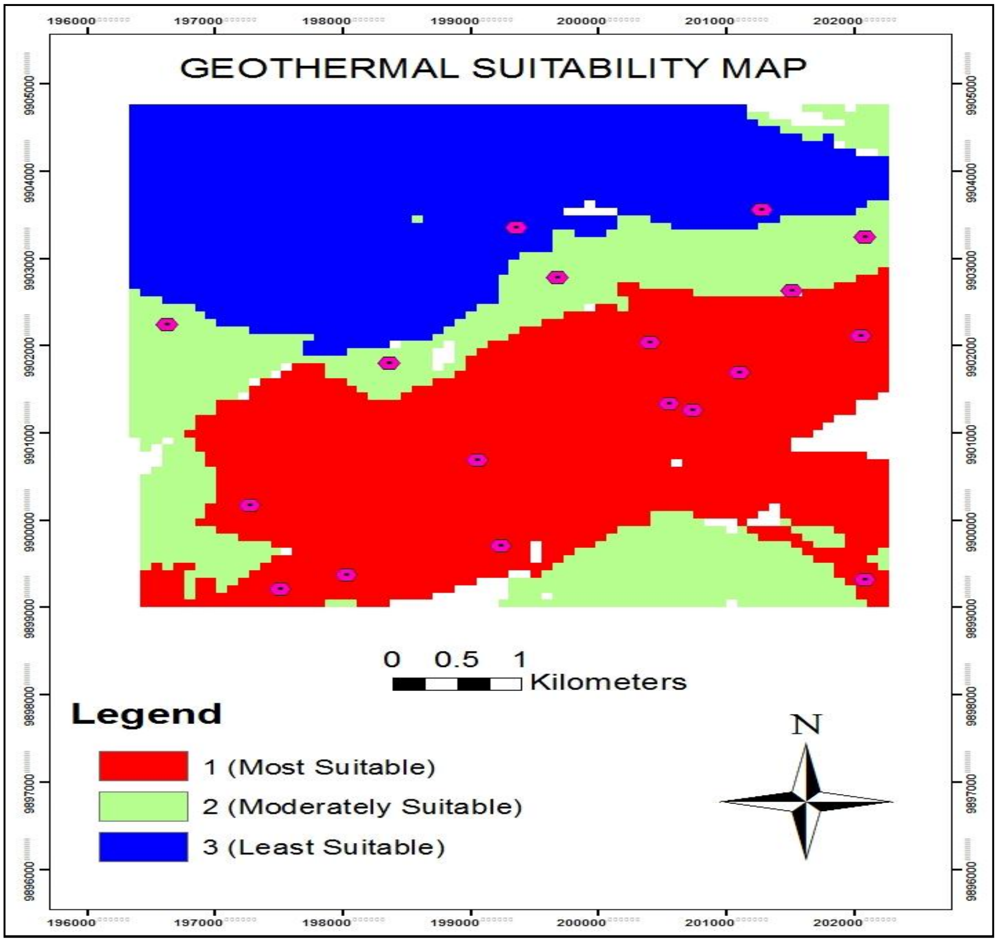


Figure 4.5: Map Showing Location of existing wells on the suitability Map

4.4 Current Exploration Levels at the Great Olkaria Geothermal Field

The Olkaria geothermal resource can be divided into two regions; a heavily explored part where extensive drilling has delineated the resource and a long-term utilization plan exists, and a less explored part where most of this research focused on. Drilling in this part has been limited and mainly indirect indications of an exploitable resource exist, as evidenced by the findings of this study. The conceptual model for the former part is accurately defined from previous research while the model for the latter part is very speculative.

4.4.1 Future Plans for the un-explored areas

The resources anticipated in the less explored part require exploration through comprehensive surveying and exploration criteria. It is highly recommended that the Kenya Electricity Generating Company adopt the findings of this research with further inclusion of suggested factors and application of GIS in analysis and interpretation of the results obtained from the integration of the results of the three data layers.

The results of the three different evidence layers are quite comparable, which adds confidence to the results. The electrical generation capacity of the less explored part is estimated to be about 300 MWe based on a volumetric assessment, an estimate that needs to be confirmed through comprehensive exploration and drilling. The area has massive potential for generation of further geothermal energy and this can be accurately determined if the steps proposed by the findings of this project report are adopted.

4.5 Proposed Layers for consideration for further studies

i). Access Roads

One of the important parts of every geothermal well siting study is the condition of the road network in the project area. The location of roads can play a significant role in reducing costs and limiting environmental impacts during construction and utilization of geothermal energy. Siting a geothermal well near existing road networks will minimize the creation of new roads during construction and for maintenance thus leading to reduced infrastructural development costs. In the geothermal power well-site selection project, a 500m buffer size is created around the road features to define the restricted areas termed as inaccessible areas.

ii). Rivers

River limitations refer to the location of rivers and potential for flooding by streams or rivers around geothermal resource potential areas. Areas without river, stream or big tributary drainage within their buffer can be assumed as suitable areas for geothermal resource generation as opposed to areas falling within buffered zones in rivers, streams and tributaries.

iii). Population of the area

The location and distribution of villages, single buildings, nomadic camping-sites, sheep farming, stadium and sport centres, burial grounds, mosque etc are considered as population centre data layer. To avoid siting wells within these areas, it is recommended that a 500-meter buffer zone be generated around these features to delineate suitable from unsuitable data layers. It is particularly important for KenGen to carry out further studies and demarcate such areas to avoid conflicts with the neighbouring local communities.

CHAPTER 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study applied GIS in a multi-criterion approach to produce a suitability map for optimal well siting. This was enabled through the application of various spatial analysis tools. The tools are applied on data from three key data sources, the geology, geochemistry and geophysical data sources of the study area. The project outlines a systematic guideline to help scientists and engineers define the optimal geothermal prospect locations.

Digital data layers and factor maps are the products of the analysis of the three geo-scientific data sources applied in this project and are used in a GIS environment to develop a suitability map for each of the geo-scientific disciplines. The intermediate products are then integrated into a single suitability map. The procedure for data integration involves use of statistical tools to combine all information of positive areas. A measurement from a given method may be giving a higher confident on interpretation of a geothermal system than another.

The derived ópositive areasô for all the three Geo-scientific are put through weighted overlays and a reclassification process undertaken. The results demonstrate that the vast majority of suitable sites from the 40 sampled points lie on the area found to be geo-physically suitable as compared to the other two factors, the geological and geochemical factors, hence geophysics is a more reliable exploration method than the two. A higher weight is assigned to such an area as opposed to areas considered as geologically/geochemically suitable. However, sites that fall within areas common to the three suitability maps are classified as the best sites for geothermal well location.

The results of this study illustrate how GIS as a tool can be used in an exploration of geothermal energy in a scientific approach hence making the process of decision making easier and accurate. Multi criteria approach employs the inclusion of the three-geoscientific exploration methods and this is necessary as it leads to realization of accurate results as compared to adopting a single method approach.

In comparison to the current methods employed at KenGen, this method was found to give almost similar results. However, the area found to be suitable is smaller as compared to the area considered more suitable by geophysical methods currently employed in the study area. This is because the multi criteria approach factors in two extra methods of exploration which may render some areas unsuitable. It is hence a more strict method and guarantees accuracy in well siting.

From Figure 4.2, the calculated areal coverage for the three classes is 28.46 km^2, 14.66 km^2 and 22.81 km^2 for the most suitable, moderately suitable and least suitable areas respectively. This represents 43% for the most suitable area, 22% for the moderately suitable area and 35% for the least suitable area.

From the study, it is noted that to define the classes of suitability for each factor under consideration, expert knowledge in the subject of interest is required. In this case, expert input from the three geo-scientific fields was required to realize accurate results. The methodology undertaken in this study was carried out in close consultation with geologists, geochemists and geophysicists at KenGen. Their input was important especially in assigning weights and ratings.

5.2 Recommendations

The following is a set of recommendations based on the findings of this research project.

(i) It is recommended that KenGen adopts the multi-criterion approach in the suitability analysis for siting of Geothermal wells within Olkaria Geothermal Station. The adoption of this method will lead to accuracy in the suitability analysis of well fields hence minimizing on losses that may be incurred where dry wells are drilled.

(ii) While using the multi-criterion approach, it is necessary to strictly observe all the parameters vis a vis their criteria for geothermal power exploration. For example, for an area to be described as geologically suitable for geothermal energy, it must satisfy all the requirements that make the area geologically suitable. e.g. presence of lava domes, calderas and craters in an area with a 3000m buffer zone.

(iii) Apart from the studied geo-scientific criteria, other influential factors must be considered while siting a geothermal well. This includes proximity to roads and water sources, steepness of the area for easy mobilization of equipment and drainage characteristics of the area. These factors are recommended for further study in order as to decipher suitable areas by application of all necessary data sets. It is highly recommended that a further study of these factors be carried out.

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APPENDICES

Appendix A: Locations of Co_2 and H_2s Sample Points in the Study Area

SAMPLE NO.	EASTINGS (m)	NORTHINGS (m)	ELEVATION	CO2(ppm)	H2S (ppm)	LOCATION
SA-1	200254.75	9901606.24	1933.29	142	7.87	Olkaria East
SA-2	200599.5	9901306.39	1925.92	103	9.62	Olkaria East
SA-3	200623.59	9901079.7	1929.31	111	11.16	Olkaria East
SA-4	200769.97	9901221.72	1931.88	165	15.51	Olkaria East
SA-5	201118.18	9901664.8	1942.28	146	13.13	Olkaria East
SA-6	200438.6	9902034.8	1941.58	141	10.08	Olkaria East
SA-7	196530.605	9903783.84	2025.81	280	1.11	Olkaria West
SA-8	193973.93	9902392.87	2065.73	675	6.41	Olkaria West
SA-9	195750	9902962	2204.12	662	1.99	Olkaria West
SA-10	194802.042	9903952.402	2026.53	748	5.23	Olkaria West
SA-11	194640.454	9900114.304	2013.43	627	4.82	Olkaria West
SA-12	192909.44	9902906.883	2046.63	712	0.91	Olkaria West
SA-13	198634.649	9903716.557	2123.14	101	2.64	Olkaria N-E
SA-14	200457.713	9904509.769	2155.95	146	7.89	Olkaria N-E
SA-15	199646	9903813	2044.01	280	9.57	Olkaria N-E
SA-16	201857.874	9900842.945	1891.86	336	8.91	Olkaria Domes
SA-17	201683	9899016	1952.22	322	0.85	Olkaria Domes
SA-18	202844	9899771	2045.32	501	1.87	Olkaria Domes
SA-19	200757.326	9904718.619	2169.47	90	3.98	Olkaria N-E
SA-20	200016.939	9903768.621	2097.57	159	2.87	Olkaria N-E
SA-21	199830	9903543	2073.98	212	9.87	Olkaria N-E
SA-22	199646	9903813	2044.09	165	4.59	Olkaria N-E
SA-23	198956.158	9903778.072	2087.83	195	5.98	Olkaria N-E
SA-24	198757.778	9903381.326	2162.73	173	2.54	Olkaria N-E
SA-25	199338.225	9903658.392	2021.85	117	8.78	Olkaria N-E
SA-26	200581	9904178	2165.87	117	3.99	Olkaria N-E
SA-27	200816	9904398	2177.12	307	3.87	Olkaria N-E
SA-28	200254	9904223	2137.09	95	4.82	Olkaria N-E
SA-29	199620	9904118	2027.22	132	6.89	Olkaria N-E
SA-30	199252	9901760.722	2019.12	90	3.99	Olkaria N-E
SA-31	199335	9903691	2021.19	198	3.44	Olkaria N-E
SA-32	199364.177	9903310.236	2032.66	60	4.75	Olkaria N-E
SA-33	200457.713	9904611.439	2135.45	94	7.88	Olkaria N-E
SA-34	199451.079	9904233.514	2014.35	77.1	8.9	Olkaria N-E
SA-35	200757.326	9904618.569	2165.57	81.2	3.34	Olkaria N-E
SA-36	200016.939	9903758.621	2101.57	86.1	4.9	Olkaria N-E
SA-37	199830	9903549	2069.19	84.6	5.65	Olkaria N-E
SA-38	199646	9903799	2039.2	73.5	7.82	Olkaria N-E
SA-39	198956.158	9903783.072	2084.83	90.1	8.82	Olkaria N-E

Appendix B: Location of Temperature Sampling Points in the Study Area

SAMPLE NO.	EASTINGS (m)	NORTHINGS (m)	ELEVATION (m)	TEMP. (^oC)
OW 35	200896.75	9901206.14	1933.29	260
OW 43	200824.55	9901806.39	1925.92	265
OW 38 B	200333.59	9901479.37	1929.31	240
OW 44A	200169.97	9901721.72	1931.88	255
OW 44B	201298.18	9901164.38	1942.28	265
OW732A	200458.66	9902734.58	1941.58	265
OW 730B	196190.62	9903983.84	2025.81	220
OW 47	193298.93	9902692.87	2065.73	270
OW 41A	195240.15	9902462.98	2204.12	255
OW 916 A	194922.42	9903352.02	2026.53	260
OW-906A	194240.44	9900514.04	2013.43	235
OW-907A	192609.44	9903106.83	2046.63	200
OW-908	198594.69	9903416.57	2123.14	205
OW-908A	200297.13	9904109.79	2155.95	180
OW-909	199646.43	9904813.98	2044.01	175
OW-909A	201297.74	9901342.95	1891.86	270
OW-910	201283.83	9899016.62	1952.22	285
OW-910A	202244.38	9899771.96	2045.32	230
OW-911A	200797.26	9904718.69	2169.47	75
OW-912	200286.39	9903768.61	2097.57	90
OW-913A	199309.94	9904543.65	2073.98	182
OW-914	199346.39	9903813.47	2044.09	90
OW 914A	198476.18	9903278.02	2087.83	192
OW-201	198397.78	9903781.36	2162.73	86
OW-202	199168.25	9903358.32	2021.85	86
OW-203	200581.25	9901178.45	2165.87	89
OW-204	200816.39	9904698.75	2177.12	92
OW-301	200754.45	9904723.58	2137.09	126
OW-302	199120.98	9904118.28	2027.22	81
OW-303	198952.98	9901360.72	2019.12	171
OW-303A	199935.38	9903391.47	2021.19	82
OW-304	199364.17	9903610.36	2032.66	160
OW-304D	200157.13	9903911.49	2135.45	94
OW-305	199951.79	9903733.14	2014.35	77
OW-306	200157.26	9904918.59	2165.57	181
OW 802	200516.99	9903758.61	2101.57	86
OW 6 A	199230.39	9903149.44	2069.19	77
OW 731	199146.55	9903299.11	2039.2	184
OW 46	198356.18	9903383.72	2084.83	81
OW 45	200180.11	9904265.65	2171.12	98

Appendix C: Locations of Sampled Wells in the Study Area

WELL No.	EASTINGS (m)	NORTHINGS (m)	Elevation (m)
WELL-1	199364.177	9903360.986	2036.000
WELL-2	199218.543	990751.908	2155.000
WELL-3	200407.786	9902035.965	2010.000
WELL-4	200562.876	9901337.675	2169.000
WELL-5	200743.939	9901260.621	2097.000
WELL-6	201105.324	9901699.435	2073.000
WELL-7	199192.278	989941.239	2044.000
WELL-8	199683.158	9902785.072	2087.000
WELL-9	198365.983	9901802.000	2090.000
WELL-10	202087.165	9903250.435	2005.000
WELL-11	197512.328	9899218.387	2034.000
WELL-12	197279.239	9900174.494	2045.000
WELL-13	198029.409	9899373.508	2022.000
WELL-14	199243.289	9899709.328	2028.000
WELL-15	199063.234	9900691.546	2037.000
WELL-16	202061.278	9902113.098	2084.000
WELL-17	202087.238	9899321.450	2059.000
WELL-18	201518.000	9902629.905	2071.000
WELL-19	201285.289	9903560.290	1995.000
WELL-20	196633.390	9902242.000	1992.000

Appendix D: Locations of Sampled Fumaroles within the Study Area

Fumarole No.	Eastings (m)	Northings (m)
F-1	199364.770	9903360.986
F-2	200457.730	9904509.769
F-3	199451.790	9904453.514
F-4	200757.360	9904718.619
F-5	200016.939	9903768.621
F-6	199830.000	9903543.000
F-7	199646.000	9903813.000
F-8	198956.158	9903778.072
F-9	197748.000	9898599.000
F-10	200067.600	9901153.970
F-11	199894.110	9901283.820
F-12	199912.770	9901099.870
F-13	200259.650	9901205.660
F-14	200374.810	9901052.070
F-15	200101.440	9901326.420
F-16	200019.210	9901495.720