UNIVERSITY OF NAIROBI

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REMOTE SENSING AND GIS APPLICATION IN SELECTION OF OPTIMAL LOCATIONS FOR PHOTOVOLTAIC SOLAR POWER PLANTS. A CASE OF ISIOLO COUNTY

BY

NDIRITU HUDSON KIMUNYI

F56/34275/2019

A project report submitted to the Department of Geospatial and Space Technology in partial fulfilment of the requirements for the award of the degree of:
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DECLARATION OF ORIGINALITY

Name of student: NDIRITU HUDSON KIMUNYI

Registration: F56/34275/2019

College: ARCHITECTURE AND ENGINEERING

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Department: GEOSPATIAL AND SPACE TECHNOLOGY

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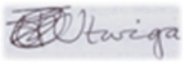
SIGNATURE:  DATE 2^{nd} September 2021

DEDICATION

To the people who made significant contribution in my academic voyage-

My parents and siblings

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My debts of gratitude to people and institutions that have helped me complete this research are enormous in both number and degree.

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ABSTRACT

Renewable sources of energy present a significant opportunity as they are free, readily available and have minimal negative impact to the environment compared to the non-renewable sources such as fossil fuels. The shift towards clean energy is essential for Kenya as it enable diversification of the energy portfolio, attainment of a green economy and sustainable development. The aim of this study was to use remote sensing data and GIS techniques to identify potential sites for optimal placement of photovoltaic solar power plants in Isiolo which is one of the marginalized Counties in Kenya. In this County, few people have access to electricity for lighting and many rely mainly on firewood and fossil fuels for cooking which contributes immensely to the reduction of tree cover.

The approach for delineating potential sites included multi criteria GIS analysis using a set of metrics categorized into technical, economic and environmental including solar irradiance, topography, population density, accessibility and proximity to spatial features influencing suitability and land use land cover. Analytical Hierarchical process (AHP) was used to determine the corresponding weight of each criterion. The weighted criteria were overlaid to determine the suitable areas and a sensitivity analysis conducted in order to test the robustness of the model. Finally the potential electric power that can be generated from the most suitable site was evaluated. The results showed 2% of the study area to have the highest suitability index, 76% to have moderate suitability, 2% to have marginal suitability and 20% to be unsuitable. First ten of the most suitable sites were evaluated to have a potential of 1443 GWh/year.

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ACRONYMS

AHP	Analytical Hierarchical Process
GIS	Geographic Information Systems
GHI	Global Horizontal Irradiance
SDGs	Sustainable Development Goals
GW	Giga Watts
PV	Photovoltaic
KWH	Kilo Watt Hour
IPP	Independent Power Providers
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984
DNI	Direct Normal Irradiance
CSP	Concentrating Solar Power
MCDA	Multi-criteria decision analysis
ERB	Electricity Regulatory Board
DC	Direct Current
AC	Alternating Current
MoE	Ministry of Energy

CHAPTER 1: INTRODUCTION

1.1 Background

One of the sustainable development goals (SDGs) is to ensure that everyone has access to safe, sustainable, and modern energy. The development of Kenya's energy sector is critical to the realization of Vision 2030 (Gathu et al., 2017). Kenya has a lot of potential when it comes to renewable energy sources. Despite its strategic location in the equatorial region, solar energy is the least used renewable energy source in Kenya. As of October 2019, Kenya had 2.6GW of installed electricity capacity, with 29.3 percent hydro, 25.54 percent fossil fuels, 29.4 percent geothermal, 11.88 percent wind, 1.77 percent solar, and 2.13 percent other sources. The current electricity demand is approximately 1.9GW. This demand has been growing at a 3% annual rate. Kenya's expected capacity and demand for electricity are 19GW and 15GW, respectively, by 2030.

Kenya's electricity access rate was 56 percent in May 2016. The government's numerous national electrification programs, such as the Last Mile connectivity project, increased the access rate to 73 percent by April 2018 (World Bank, 2019). For a long time, Kenya has relied heavily on hydropower. The reliability of hydropower has been greatly impacted by changes in climatic conditions, primarily due to a drop in water level capacity in hydro dams. To address this issue, efforts have been made to increase the capacity of other renewable energy sources, such as geothermal and wind power.

Solar energy is the radiant light or heat from the sun that can be captured using a variety of technologies including photovoltaic, solar thermal energy, solar heating, and solar architecture. Every day, the sun radiates huge amounts of energy than the world can consume in one year and thus can be deemed as the most abundant and promising renewable energy source as tapping this potential can provide reliable and sustainable energy. It’s due to this fact that solar energy is considered a renewable energy source. In the development of Solar Power Plant systems geospatial techniques are applied to determine the most suitable site for installation. This is done through analysis of various criteria that a particular site must poses.

1.2 Problem Statement

Kenya predominantly relies on hydropower as the main source of electricity. Hydropower is greatly affected by the ever changing climatic patterns and therefore it is not reliable. Diversification into other energy sources is thus necessary. Solar energy despite being an abundant source is not economically utilised in Kenya as its contribution to the national grid is approximately 2%. The Vision 2030 development blueprint envisions a ten percent annual economic growth rate and the country achieving middle-income status by 2030. This would be difficult to achieve with the current capacity of 2.6GW because the projected electricity demand needed to fuel economic growth by 2030 is 15GW. Kenya has a great potential for solar energy use all year due to its strategic location on the equatorial region, which receives 4-6 KWH/m2/day levels of solar insolation suitable for economic exploitation (Tisza, 2014). This should serve as a strong motivator for the use of solar energy.

The expansion of electronic technology applications and system automation in Kenya, as well as increased electricity connectivity in the country, has resulted in increased electricity consumption. To meet this demand, stable and sustainable supply is needed. The world today is currently confronted with the challenge of climate change and global warming. This can be attributed in part to the power generated by fossil fuels. Adoption of clean and renewable energy sources is unavoidable in order to meet this challenge. Solar power is an excellent alternative source of clean energy.

1.3 Objectives

1.3.1 General

- The primary goal of this research study is to identify suitable locations for the placement of Photovoltaic solar power plants.

1.3.2 Specific

- To investigate indicators that characterizes a suitable location for the installation of PV solar power plants.
- To conduct analysis to identify optimal locations for PV solar power plants.
- To estimate the potential electric power that can be generated at optimal sites.

1.4 Justification

The sun radiates enormous amount of solar energy each and every day. Due to this fact, solar energy qualifies as a renewable source. These sources unlike non-renewable ones are more environmental friendly, less expensive to exploit and abundant. These qualities make them sustainable. The demand for power continues to increase with increase in electricity connectivity, industrial and technological advancements. In order to meet this demand, it's prudent to diversify on the sources of energy. Solar energy presents itself as a feasible alternative energy source.

This study aimed to provide both government institutions in the energy sector and independent power providers (IPP) with suitable sites for establishing Off-Grid or Grid-Connected Solar Power Plants. This information can be used to guide the planning of power transmission infrastructure and also in making investment decisions. The study area was chosen as it lags behind in electricity connection with only 29 per cent of the total households having access. Being an arid county strategically located on the equatorial region, it receives reliable sunshine throughout the year hence it has high potential for harnessing of Solar Energy.

1.5 Scope and Limitation of the Study

This research study aimed to identify suitable locations for the establishment of photovoltaic solar power plants in Isiolo County to address low electricity connectivity through the exploitation of solar energy resource.

The study registered some limitations: Firstly, the Global Horizontal Irradiance dataset collected using remote sensing techniques was not augmented with field measurements to enhance its accuracy. Secondly, in the study methodology, the site suitability factors were weighted jointly as opposed to discretely. Thirdly, the study only considered technical, economic and environmental factors for site suitability analysis and did not include cultural factors.

1.6 Organization of the Project

The project report is organized into five chapters: Introduction which covers a brief background of the research topic as well as the objectives, Literature review which discusses essential concepts as well as case studies related to the research topic, Methodology which outlines the data and procedures used in the execution of the project, Results and discussion where the results from the data analysis are presented and discussed and finally Conclusion and Recommendations where a summary of the research findings is highlighted and recommendations given to enhance subsequent research related to the topic.

1.7 Study Area

Isiolo is a county in Kenya located on the upper Eastern region between Longitudes 36^0 51' and 39^0 27' East and Latitude 00^0 05' South and 2^0 05' North. Its capital and largest town is Isiolo. It covers an area of 25,337 square kilometres and has a population of 268,002 persons as of 2019 census. The county is mainly arid and relies on Livestock as its main economic activity.

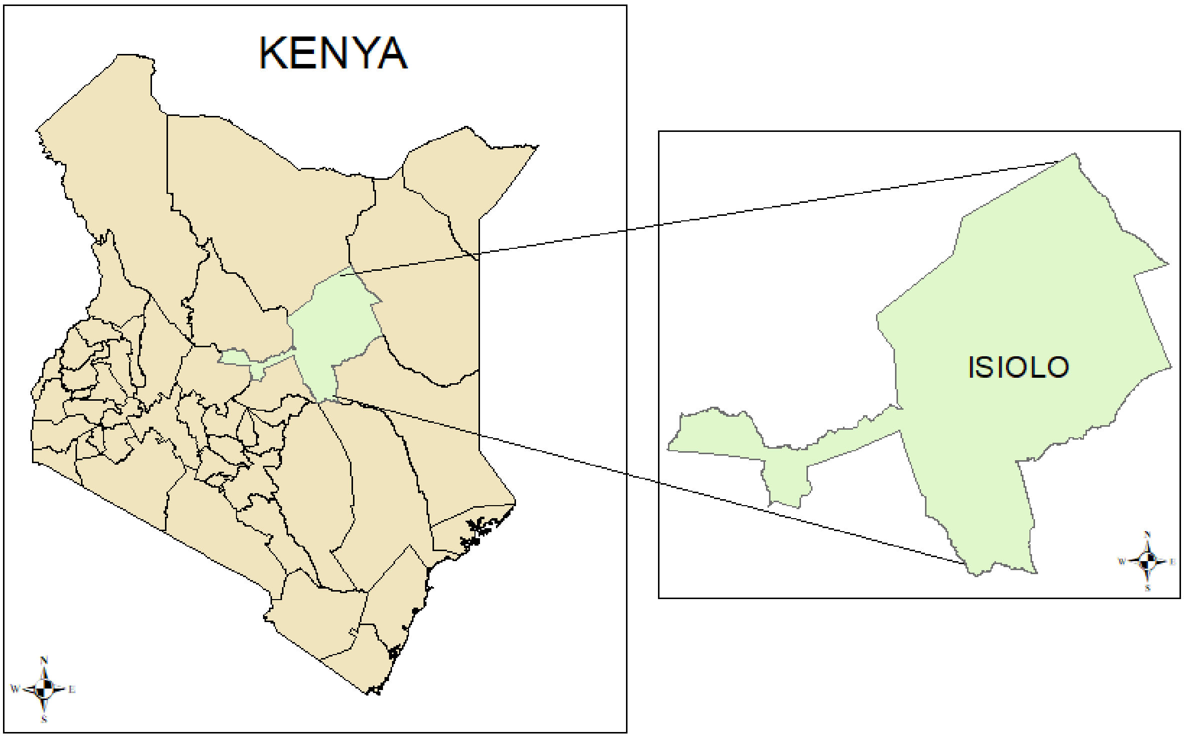

Figure 1.1: The Study Area

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Renewable energy sources are widely and freely available, with little impact on environmental degradation and global warming. They are thus a viable alternative for countries to adopt in order to meet rising energy demand, transition to a green economy, and achieve sustainable development.

The sun emits enormous amounts of energy on a daily basis; this energy is known as solar energy. Solar energy is thus abundant, free, and clean in this regard. When properly tapped, it has the potential to meet the growing demand for power in many countries around the world. Global Horizontal Irradiance (GHI) is the total amount of radiation received from the sun on the ground, which includes Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) (Hassan et al., 2020). Electricity is generated using Concentrating Solar Power (CSP), which collects and converts DNI into electrical power, or a solar Photovoltaic (PV) system, which collects and converts DNI and DHI into electric energy.

The efficiency with which solar energy is collected and converted into electric energy is determined by a number of spatial parameters. These include the amount of solar irradiation received per square meter, relative surface temperature and humidity, land topography—most notably slope and aspect—all of which influence solar radiation distribution on the Earth's surface. The importance of spatial parameters in the effectiveness of solar power systems emphasizes the value of Geographic Information Systems (GIS) in determining suitable locations for installing such systems. GIS has the ability not only to capture, process, analyze, and visualize spatial data that is critical for the planning and implementation of solar systems, but also to estimate the potential electric power that can be generated. In multi-parameter analysis, GIS applications typically employ a variety of data analysis models, such as fuzzy overlay analysis, ranked overlay analysis, weighted overlay analysis, suitability composite indices, and Boolean overlay analysis.

In this review, some basic principles, concepts and terminologies critical in the determination of optimal locations for establishment of solar power plants have been discussed.

2.2 Energy Sector in Kenya

The Kenyan energy sector is overseen by the Ministry of Energy (MoE). The Energy Regulatory Commission (ERC), which replaced the Electricity Regulatory Board (ERB) following the repeal of the Electric Power Act of 1997 and the subsequent enactment of the Energy Act of 2006, regulates the entire energy sector.

Other key players in the energy sector include the Kenya Electricity Transmission Company (KETRACO), which is in charge of developing the transmission grid, the Rural Electrification Authority (REA), which is in charge of the government's Rural Electrification Programme, Geothermal Development Company (GDC), which is in charge of geothermal resource assessment and steam production drilling, Kenya Power and Lighting Company (KPLC) which is in charge of distributing and retailing electricity to customers all over Kenya, Kenya Electricity Generating Company (KenGen) which is in charge of producing electric power and Independent Power Providers (IPP) who are majorly investors producing and selling electric power to KPLC under the Feed-in-Tariffs Policy.

2.3 Photovoltaic Systems

PV systems are composed of solar panels installed on rooftop or mounted on posts erected on the ground. When the sunlight hits a PV cell, an electric current is generated by displacement of negatively charged electrons which are concentrated to produce a charge that can power the load (Li, 2013). According to Foster et al, (2010), PV systems require little or no maintenance as PV cells are solid state devices with no moving parts. No additional energy source is required to run these systems hence they are very economical particularly for remote areas (Linder, 2012). They can also be scaled to meet future demand and also exhibit a high life cycle; these advantages makes PV power a sustainable energy alternative to conventional sources of energy (Li, 2013).

There are two main types of PV systems, these include off-grid and grid-connected systems. Off-grid systems operate as stand-alone mostly in remote areas that are not connected to an electric grid. They consist of PV modules, batteries for storing energy for use when there is no sunshine, charge controller for controlling battery charging and inverter for converting DC current to AC current.

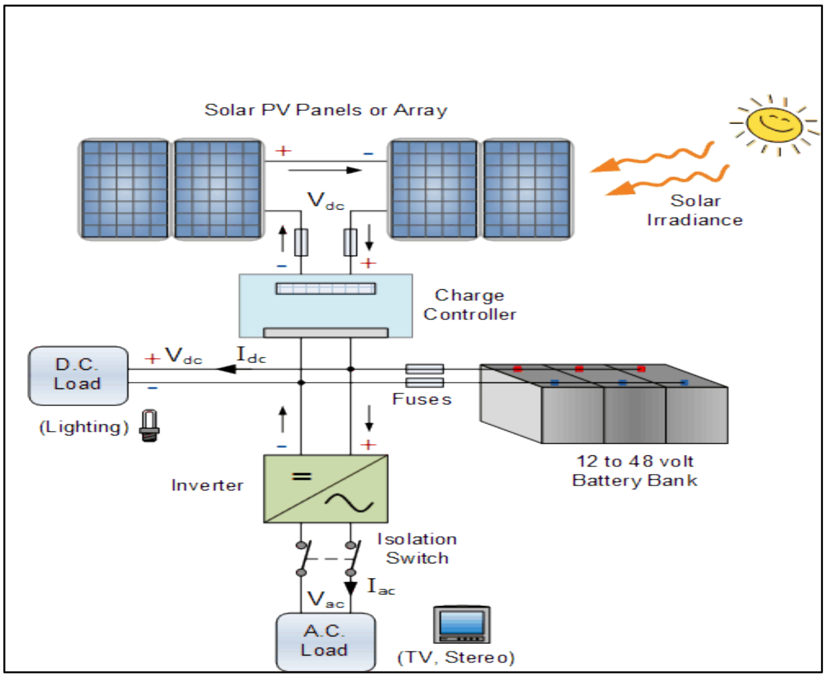

Figure 2.1: Off Grid System (Alternative Energy Tutorials 2021)

Grid-connected systems are connected to the electricity grid network. Electricity can therefor flow to and from the grid. Excess electricity is usually fed back into the grid and sold, when the system experience an energy drawdown, power can be bought back from the grid. The grid therefore acts as an energy system, thus battery storage is not mandatory.

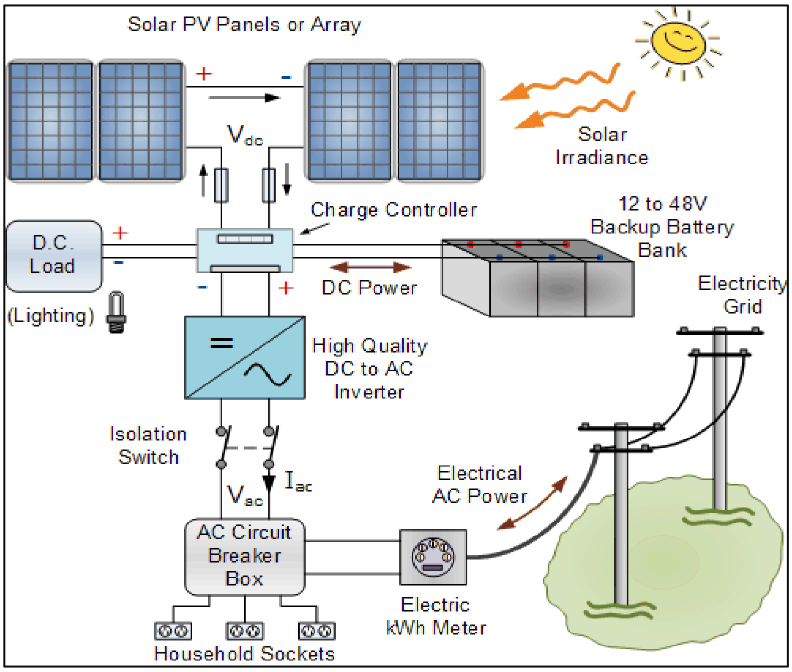

Figure 2.2: Grid connected System (Alternative Energy Tutorials 2021)

2.4 Multi-criteria Decision Analysis (MCDA)

Multi-criteria decision analysis (MCDA) is a decision-support tool that is frequently used when making choices that involve multiple conflicting criteria. It allows for the maximization of all benefits over the course of a project, making it an important planning and decision-making tool (Tisza, 2014).

Different techniques having distinct characteristics and calculation criteria are applied in MCDA. The most common evaluation approaches include Boolean variables referred to as constraints (true/false) and fully continuous variable called factors. Constraints define areas that are deemed unsuitable, whereas factors are used in expressing varying degrees of suitability in a numeric scale (Piirisaar, 2019).

Multi-criteria decision analysis is predominantly valuable for PV systems assessment, where a compromise solution must be found that minimizes the cost of the structure design and maintenance while optimizing electricity production. The coupling of GIS with MCDA techniques enhances decision making in all stages such as system design, choice and visualization.

2.5 Analytical Hierarchical Process (AHP)

This is a multi-criteria decision making approach introduced by Thomas Saaty in 1970's. It's used as a decision support tool to solve complex decision problems. It constitutes different multi-level hierarchical structures that place the goal on the top, the criteria in the middle and the alternatives at the bottom. The input of experts is a pair-wise comparison of the criteria values; used to obtain the weights of significance of the decision criteria and relative performance measures of alternatives in relation to each particular decision criteria (Kousalya et al., 2012).

The methodology of AHP comprise of:

- Establishment of structural hierarchy

  A complex decision is structured in to a hierarchy descending from an overall objective to various criteria and sub criteria to reach the lowest level. At the top of the hierarchy is the overall goal of the decision. The representation of the criteria and sub criteria is usually in the intermediate levels where as the decision alternative are usually highlighted at the lowest level of the hierarchy. The facets of designing the hierarchy include; creative thinking, recollection and the use of people's perspectives (Kousalya et al., 2012).

- Establishment of comparative judgments

This includes determination of priorities of the components at each level of the hierarchy. Each element in a particular level is compared with an element of the immediate higher level and a comparison matrix developed. The pairwise comparison is given using a nine point scale showing the level of importance of particular criteria in relation to another.

- Synthesis of priorities and measurement of consistency

Priorities are derived from the comparison matrix as its principal eigenvector defining a ratio scale. Eigenvector is thus an intrinsic concept of correct prioritization process which allows measurement of inconsistency in judgement (Saaty, 1980).

Table 2.1: Saaty Ration for Pair Wise Comparison

Intensity of Importance	Definition	Explanation
1	Equal importance	Two elements contribue equally to the property
3	Moderate importance of one over another	Experience and judgement slightly favor one over the other
5	Essential of strong importance	Experience and judgement strongly favor one over the other
7	Very strong importance	An element is strongly favored and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is one of the highest possible order of
2,3,6,8	Intermediate values between two adjacent judgments	Compromise is needed between two judgment
Reciprocals	Whe activity i compared to j is assigned on of the above numbers, the activity j compared to i is assigned its reciprocal	
Rational	Ratios arising from forcing consistency of judgments	

2.6 PV Systems Siting Criterion

Several factors impact the site selection process of PV plants sites. These factors can be categorized into efficiency factors which influence the technical performance of the system, economic factors which influence the cost of construction and return of investment and environmental factors for conservation purposes.

2.6.1 Efficiency/Technical Factors

- Solar Radiation

  This is the radiant energy from the sun. It is considered the most dominant factor when siting solar power plants. Areas receiving 5KWh/m^2/day are considered suitable for economic exploitation (Olufemi et al., 2015).

- Aspect

  This is the direction which a slope faces. Sites located in the northern hemisphere should be on southerly facing slopes, those in the equatorial region on flat slopes where as those in the southern hemisphere should be on northerly facing slopes to enhance optimal contact of the PV cells with the solar radiation.

- Slope

  In general, areas with lower gradient receive higher radiation than areas with low gradient. Terrain with a slope of less than 3% is therefore considered more suitable for the placement of PV plants (Khemiri et al., 2018).

- Temperature

  Most PV cells are designed and tested for optimal efficiency at a temperature of 27^0 centigrade, thus efficiency of the system reduces per one degree increase or decrease from this optimal temperature.

2.6.2 Economic Factors

- Accessibility factors

  Proximity to roads is a preferable economic factor which ensures avoidance of additional cost for infrastructural development (Khemiri et al., 2018), operational supports, equipment loading and personnel transport. Areas with no road access are therefore considered unsuitable for PV siting.

  Other factors such as proximity to towns, schools, hospitals are also considered as close proximity may cause environmental problems and negative impacts on future expansion developments (Yousefi et al., 2018).

- Soil characteristics

  Soil affects the cost of construction of the PV structures in that different models are adopted for different soil types. Loamy soils are generally considered best for construction followed by sandy and finally clay soil is the least favourable because of its tendency to expand and contract in large amounts.

- Population density

  Population is used in the estimation of current and future demand of electricity. It therefore guides on the generation capacity to be adopted for the system. Population density of a particular location is also considered as areas with >500 people per square kilometre are considered to begin to transition to urban setting (Olufemi et al., 2015).

2.6.3 Environmental factors

- Protected areas

  These include areas such as national parks, wildlife sanctuaries and historic sites. The cells located in these regions are excluded for the purposes of environmental conservation and cultural preservation.

- Wetlands

  Areas in close proximity to water bodies such as lakes, dams and rivers are excluded when locating potential PV sites because of conservation, safety and health reasons ensuring environmentally safe and economically favourable power generation.

- Land Use Land Cover (LULC)

  LULC is a critical component as distribution of diverse land use types leads to considerable constraints in the planning process. It therefore helps in identification of locations that have no potential for siting such as agricultural lands, forests, wetlands and urban areas (Yousefi et al., 2018).

2.7 GIS Multi-Criteria Models

2.7.1 Boolean Overlay Analysis

This analysis treats all factors considered as limiting criteria via predefined threshold limits. It does not produce varying levels of suitability by categorizing the study area into two main categories: suitable or unsuitable. As such, it should be considered for conjunctive screening in cases where suitable sites have attributes that meet all of the criteria under consideration. To generate different levels of suitability, ranked overlay analysis can be used to generate suitable sites with a high score on at least one of the considered criterion.

2.7.2 Weighted Overlay Analysis

Only integer raster surfaces are supported by Weighted Overlay Analysis. Before they can be analyzed, the continuous raster surface representing the various criteria under consideration should be reclassified into integers. The reality is represented in a discrete space model in weighted overlay, which necessitates prior knowledge of the considered criteria threshold limits and associated indicators identifying discrete suitability levels.

2.7.3 Fuzzy Overlay Analysis

In cases where there is uncertainty, a large number of criterion, and continuous suitability levels, fuzzy overlay analysis is used. When compared to weighted overlay analysis, it is more effective in multi-criteria suitability analysis, despite requiring significantly more computational effort.

2.8 GIS related solar power siting studies

1. Combined approach of multi criteria analysis and geographic information system for optimal placement of solar photovoltaic farms in Mekkah region, Saudi Arabia (Khemiri et al., 2018). In this study AHP was adopted to determine weight of each criteria under investigation.
2. GIS-based suitability analysis for siting solar power plants in Kuwait (Hassaan et al., 2020). In this study, a four step methodology which included; identifying siting criterion, data preparation, developing a composite suitability index and delineating suitable sites was adopted. The use of GIS not only in delineating suitable sites but also in the estimation of electric potential was demonstrated. The need for further studies investigating the impact of high temperature on the efficiency of the PV systems was also highlighted.
3. Mapping suitability areas for concentrated solar power plants using remote sensing data (Olufemi et al., 2015). The approach included use of satellite data to estimate the global

solar radiation and development of computational model built on GIS for estimation of site suitability.

4. Site suitability analysis of solar PV power generation in South Gondar, Amhara region, Ethiopia (Nebey et al., 2020). In this study factors affecting suitability were weighted using AHP. The weighted and reclassified values were multiplied together to produce the final suitability map. The nature of the topography was noted as a key factor as it affects the solar irradiance incident of the PV panel surface. The study advocated to use of solar energy to bridge the energy gap between the rural and urban communities.
5. Spatial site selection for solar power plants using GIS based Boolean-fuzzy logic model in Markazi province of Iran (Yousefi et al., 2018). This study proposed a comprehensive model for spatial site selection of solar power plants in semi-arid regions design to utilize effective spatial factors taking economic, environmental and technical factors into consideration. Boolean and fuzzy logic was applied for site selection noting that the use of fuzzy logic as an efficient method for evaluation of the score of map pixels based on the selected criterion; using different fuzzy operators to overlay raster layers leads to accurate results. The use of this approach was suggested for future studies to develop models for site selection of hybrid renewable energy plants for diverse climates.

CHAPTER 3: METHODOLOGY

3.1 Overview

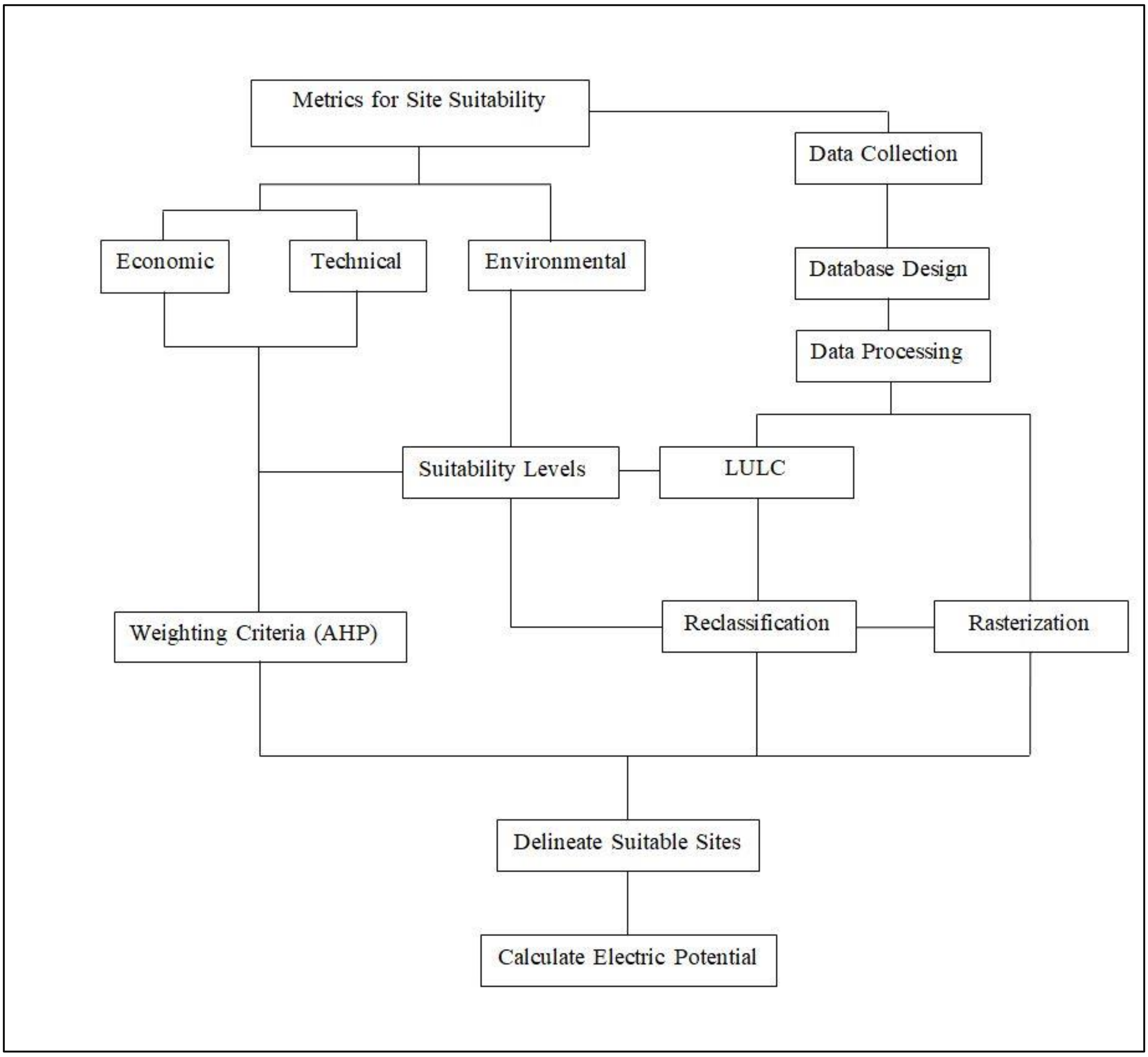

Figure 3.1: The Workflow Diagram

The methodology included identification of metrics for PV site suitability where twelve criteria (listed in table 2) categorized as technical, economic and environmental were identified. The technical and economic criteria were weighted together using the Analytical Hierarchical process. Data processing included creation of rasters of the vector data layers under consideration and terrain analysis to develop slope and aspect of the study area. From the literature review and expert advice, suitability levels for each criteria were developed and used to reclassify the rasters. Finally, the rasters were overlaid to come up with the final suitable locations and estimation of the electric potential was calculated.

3.2 Data and Sources

The summary of the data used is shown in the table below. Global horizontal Irradiance data of 30m spatial resolution was sourced from the World Bank and used for extraction of annual solar radiation of the area of study. The digital elevation model was obtained from USGS Earth explorer portal and used for the derivation of slope and aspect for the study area. The temperature data was obtained from the World Bank in raster format. The soil data was acquired from the Kenya Soil and Terrain database (KENSOTER) and was of 1KM spatial resolution. Population density data was obtained from the World Bank archives was of $1KM^2$ spatial resolution. The road data was obtained for the Kenya Roads Board (KRB) which comprised class A, B, C, D and E; it was used to generate raster of distances from the roads. Rivers, protected areas and land use land cover datasets were obtained from the National Environmental Management Authority (NEMA); these were used to generate exclusion rasters. Towns, schools and hospitals datasets were acquired from open data sources and used for the creation of rasters of suitable distances from these locations.

Table 3.1: Data and Data Sources

S/NO	DATA	SOURCE	RESOLUTION
1	GHI	World Bank	1km
2	DEM	USGS	90m
3	Temperature	World Bank	1km
4	Soil	KENSOTER	1:1000000
5	Roads	KRB	N/a
6	Population density	World Bank	1km2
7	Rivers	NEMA	N/a
8	Prot. Area	NEMA	N/a
9	LULC	NEMA	N/a
10	Towns	Open Sources	N/a
11	Schools	Open Sources	N/a
12	Hospitals	Open Sources	N/a

3.3 Data Processing

This involved coordinate transformations where all the datasets were projected and assigned a uniform coordinate system. WGS 84, UTM zone 37N was selected in conformance with the location of the study area. Projected coordinate system was used to enable calculation of proper distances. Rasters were created out of the vector data to enable uniformity for data analysis; terrain analysis was conducted to generate slope and aspect data. These raster datasets were extracted using the study area as the mask. Suitability levels were generated using expert advice and literature review and used to reclassify the rasters.

Analytical hierarchical process was used to weight the technical and economic criteria under investigation. These weights were applied in the overlay analysis to come up with the potential locations for PV sites.

3.3.1 Rasterization of vector data

Euclidean distance tool was used to generate rasters of buffer distances as shown below:

a. Distances from Roads

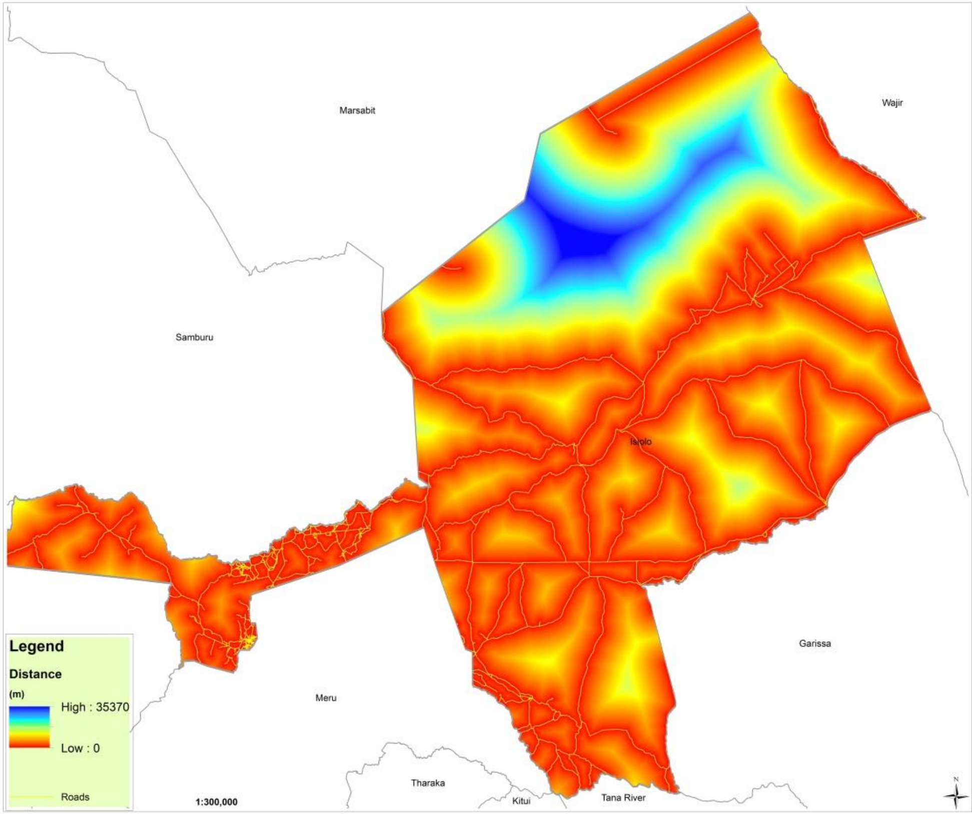

Figure 3.2: Buffer Distances from roads

b. Distances from Schools

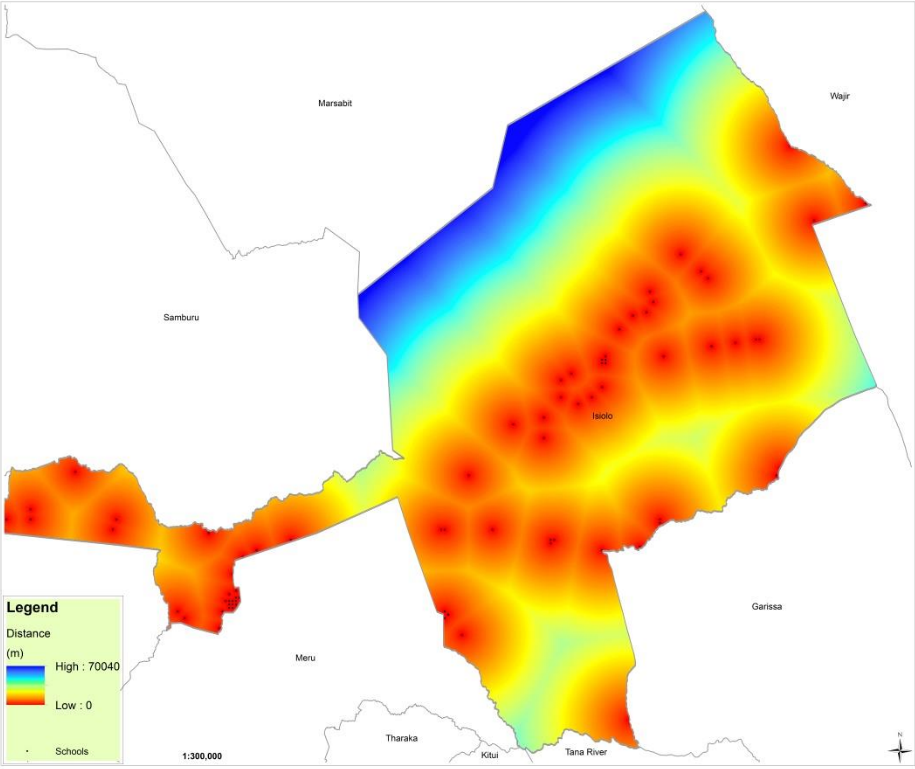

Figure 3.3: Buffer Distances from Schools

c. Distances from Hospitals

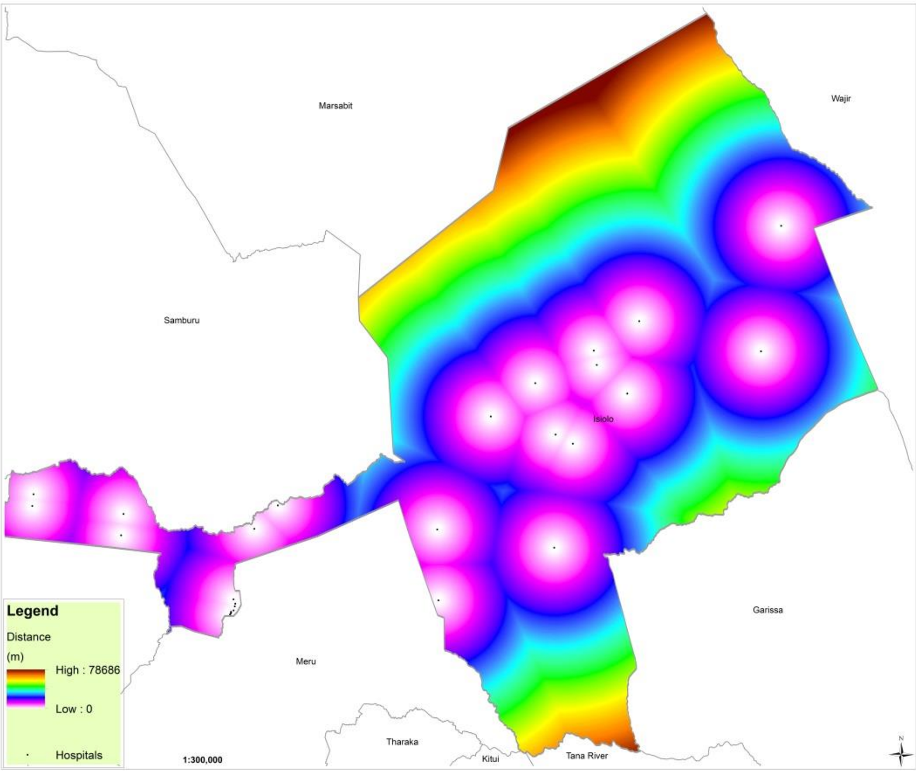

Figure 3.4: Buffer Distances from Hospitals

d. Distances from Towns

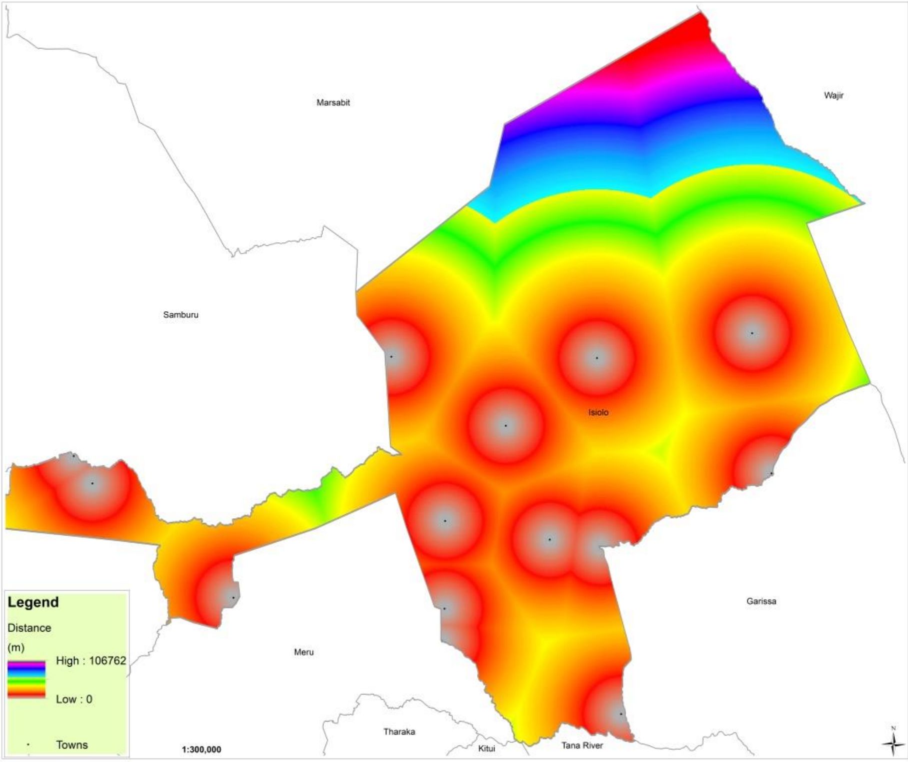

Figure 3.5: Buffer Distances from Towns

e. Distances from Rivers

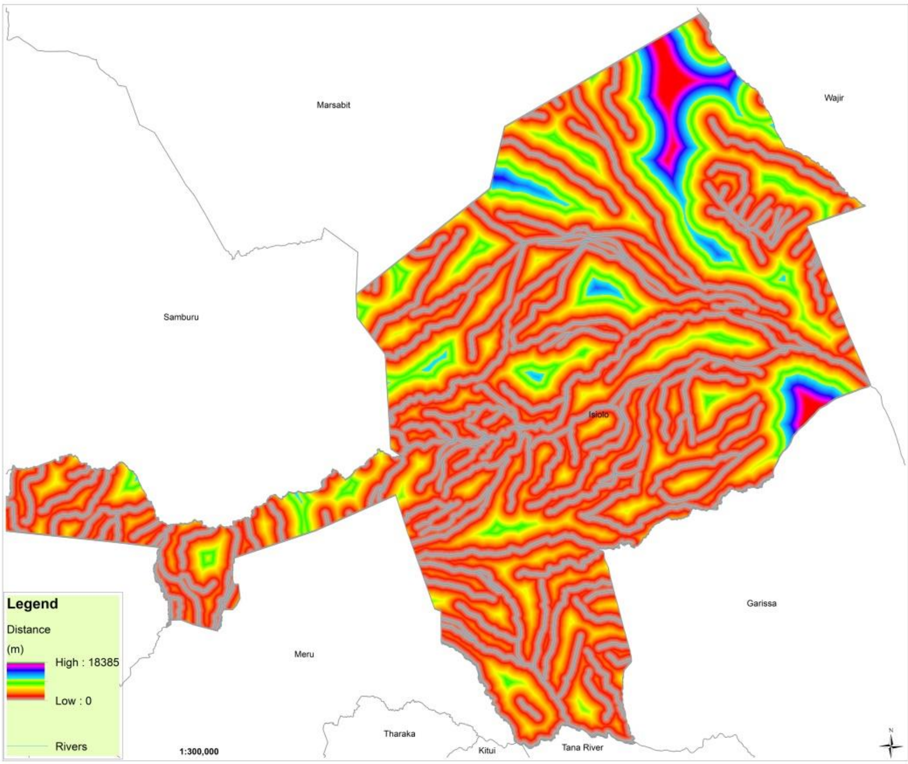

Figure 3.6: Buffer Distances from Rivers

f. Distances from Protected areas

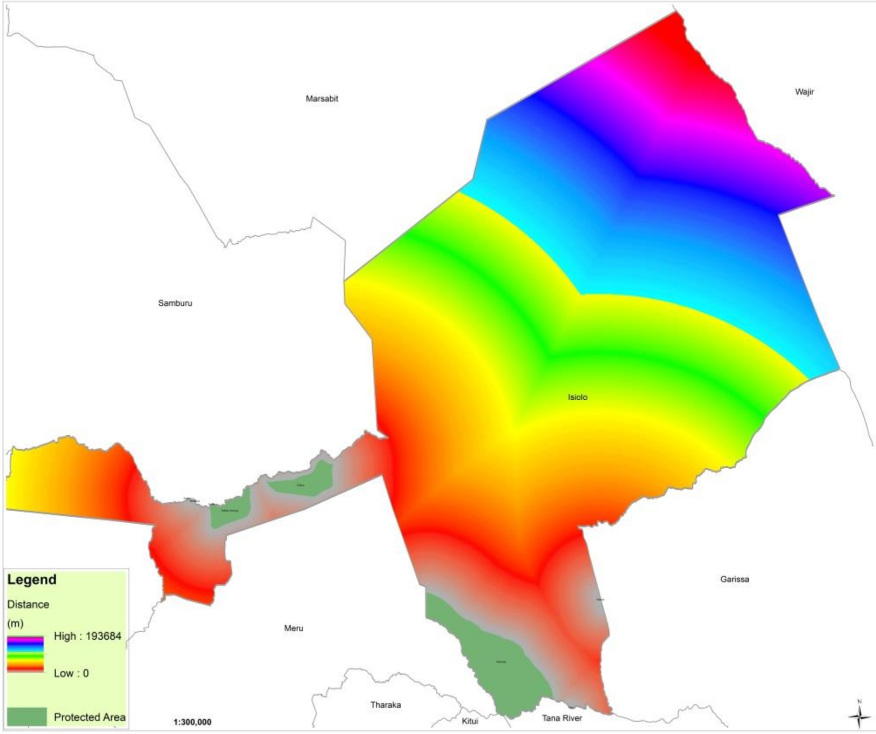

Figure 3.7: Buffer Distances from Protected Areas

3.3.2 Terrain Analysis

Slope and Aspect were generated from the digital elevation model as shown below:

a. Slope

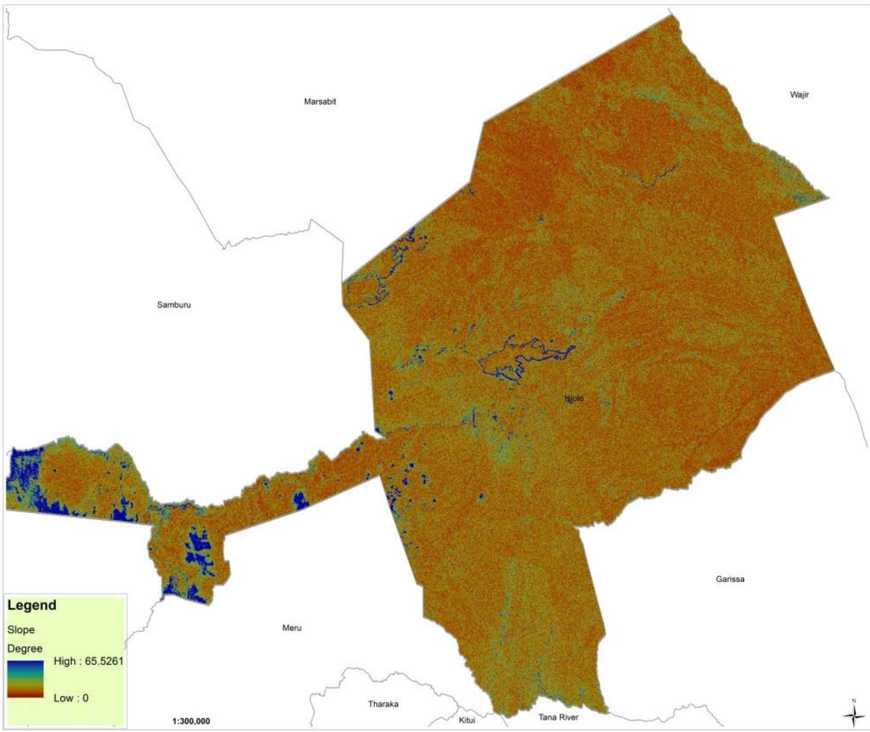

Figure 3: Slope

b. Aspect

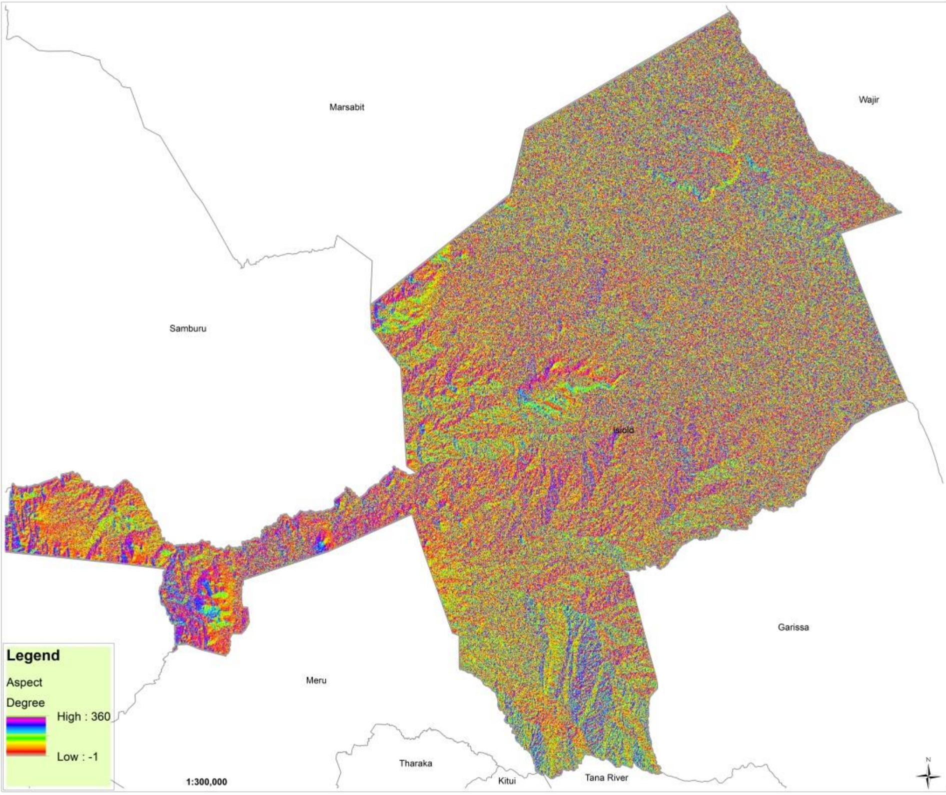

Figure 3.9: Aspect

3.3.3 Reclassification of Data

On the basis of suitability levels for each criteria influencing PV power generation, the raster datasets were reclassified using a one to nine scale where one represented least suitable, five represented moderately suitable and ten represented highly suitable.

a. Reclassified GHI

GHI between 2100 and 2200 was classified as least suitable, 2200 and 2300 as moderately suitable and that above 2300 as highly suitable.

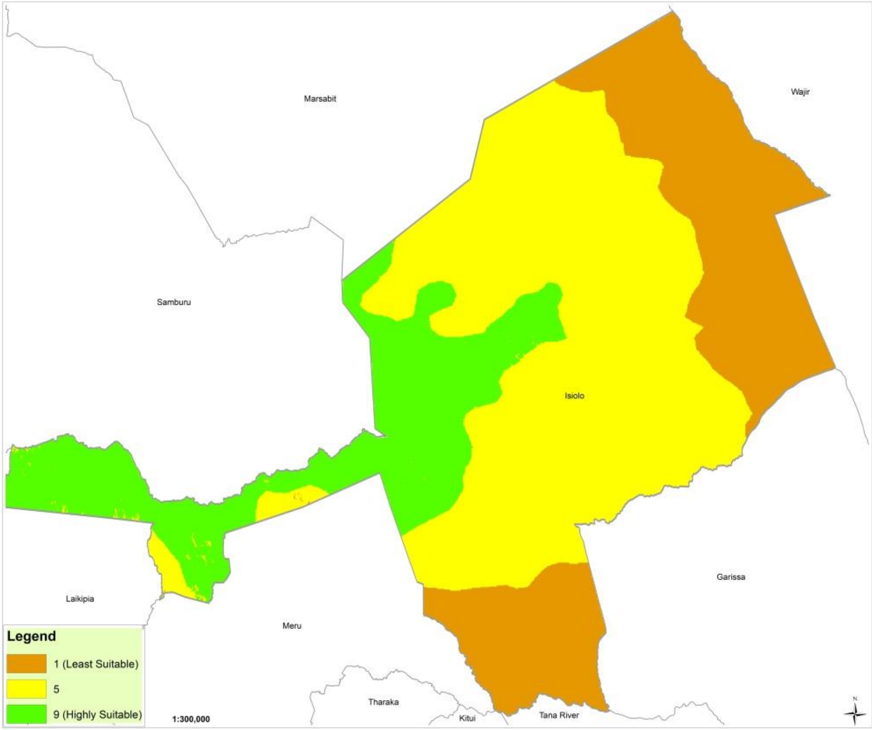

Figure 3.10: Reclassified GHI

b. Reclassified Aspect

Aspect between 120 and 160, 200 and 240 degrees were classified as least suitable, between 160 and 200 was classified as moderately suitable and that between -1 and 0 was classified as highly suitable.

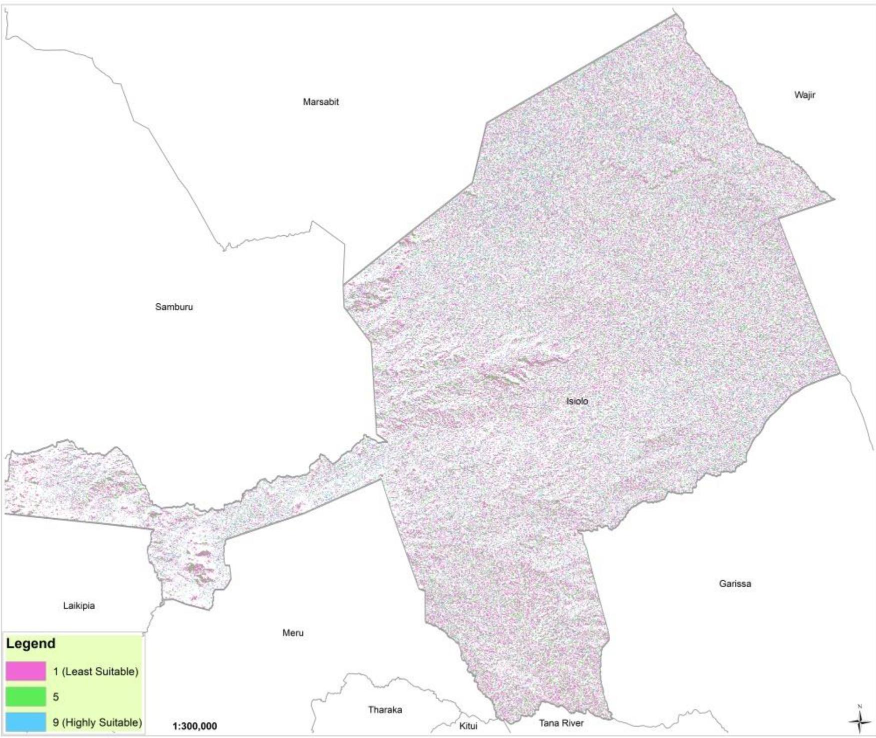

Figure 3.11: Reclassified Aspect

c. Reclassified Slope

Slope between 6 and 10 degrees was classified as least suitable, that between 3 and 6 degrees as moderately suitable and that between 0 and 3 degrees was classified as highly suitable

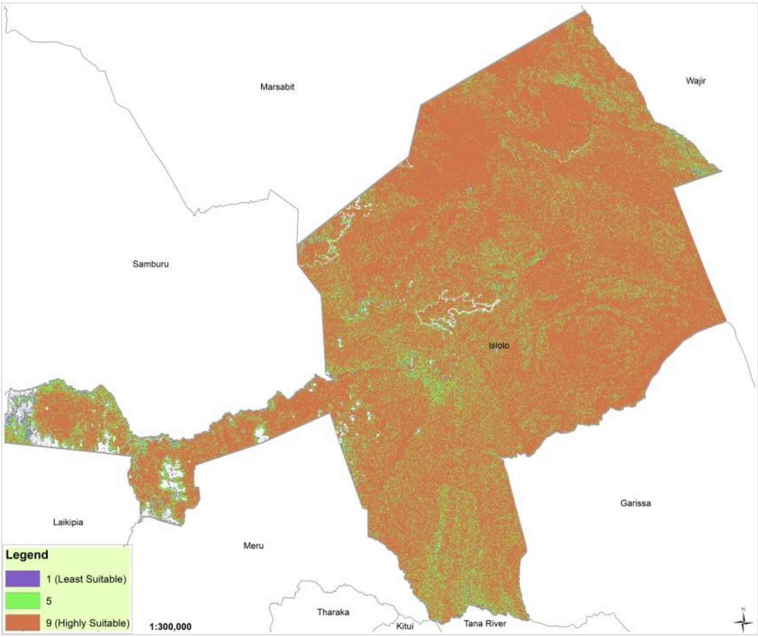

Figure 3.12: Reclassified Slope

d. Reclassified Temperature

Temperature between 18 and 21 degrees Celsius was classified as least suitable, between 21 and 25 degrees Celsius as moderately suitable and that between 25 and 27 as highly suitable.

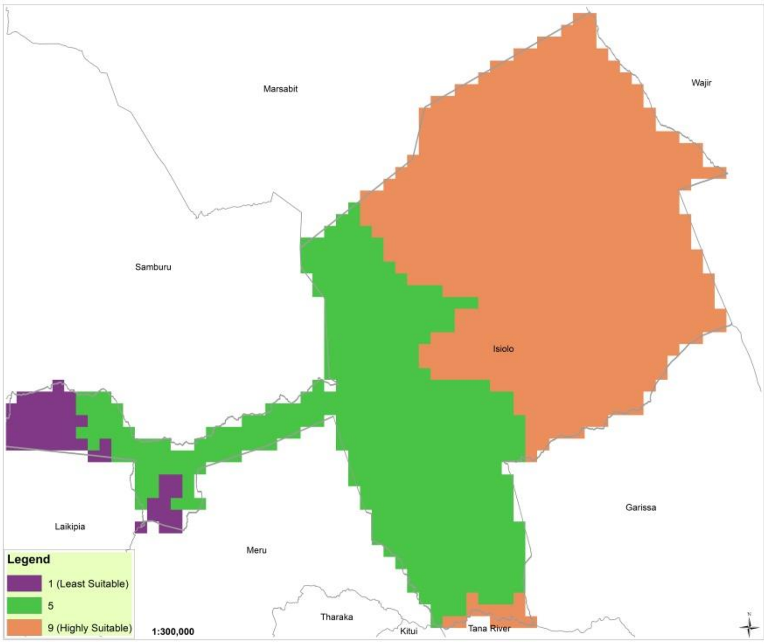

Figure 3.13: Reclassified Temperature

e. Reclassified Roads buffer distance raster

The buffer distances from roads of between 2000 and 3000 meters were classified as least suitable, those between 1000 and 2000 meters as moderately suitable and those in the range of 0 to 1000 meters as highly suitable.

Figure 3.14: Reclassified Buffer Distances from Roads

f. Reclassified Soils

The soil dataset was classified assigning clay soil the least suitability, sandy soil moderate suitability and loamy soil highest suitability.

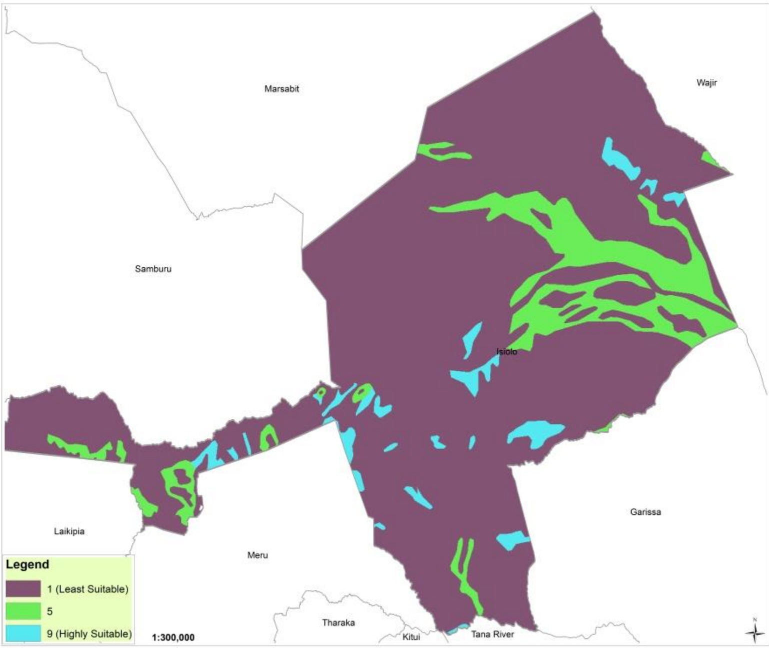

Figure 3.15: Reclassified Soil Data

g. Reclassified Population

Population density of between 300 and 500 people per square kilometre was classified as least suitable, that of between 100 and 300 as moderately suitable and finally that of between 0 and 100 as highly suitable.

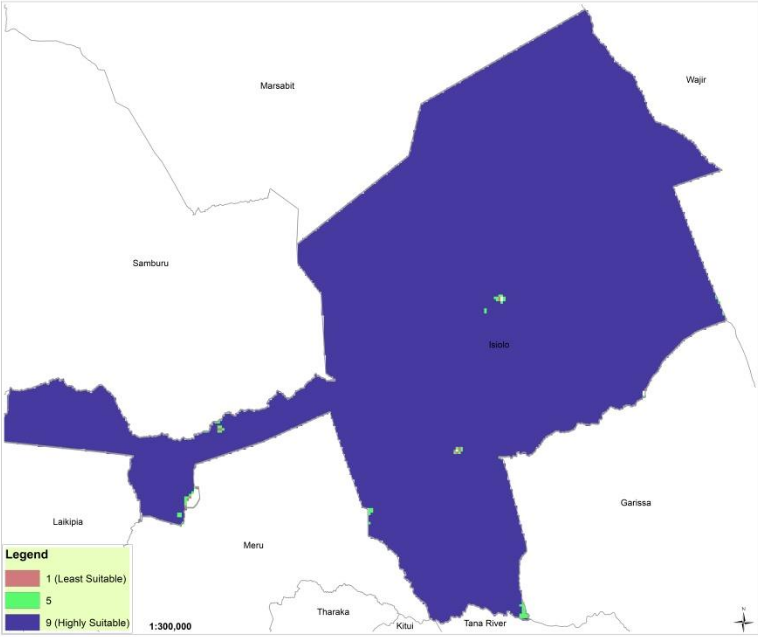

Figure 3.16: Reclassified Population Data

h. Reclassified Towns buffer distances raster

Buffer distances from town centres of between 2000 and 3000 meters were classified as least suitable, those between 3000 and 4000 as moderately suitable and those greater than 4000 meters as highly suitable.

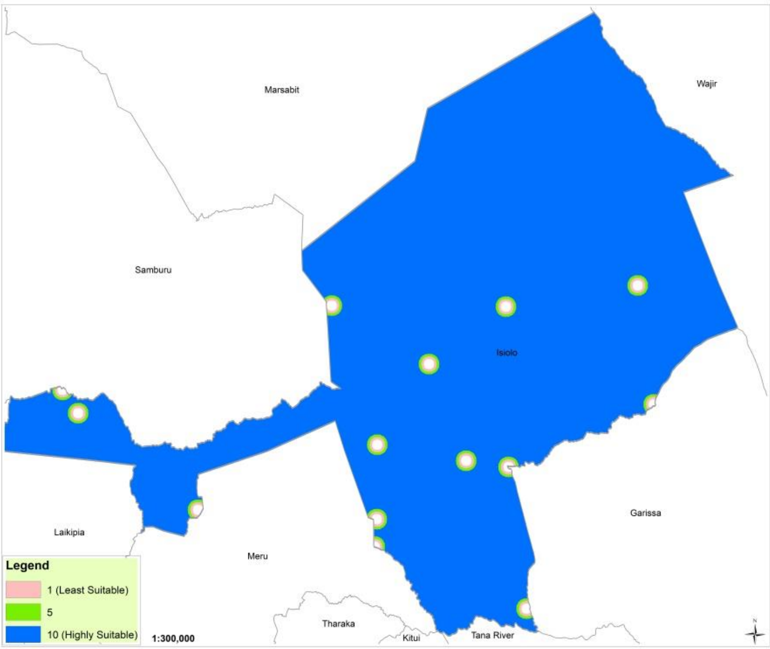

Figure 3.17: Reclassified Buffer Distances from Towns

i. Reclassified Schools buffer distances raster

Buffer distances from schools of between 500 and 1000 meters were classified as least suitable, those between 1000 and 2000 as moderately suitable and those greater than 2000 meters as highly suitable.

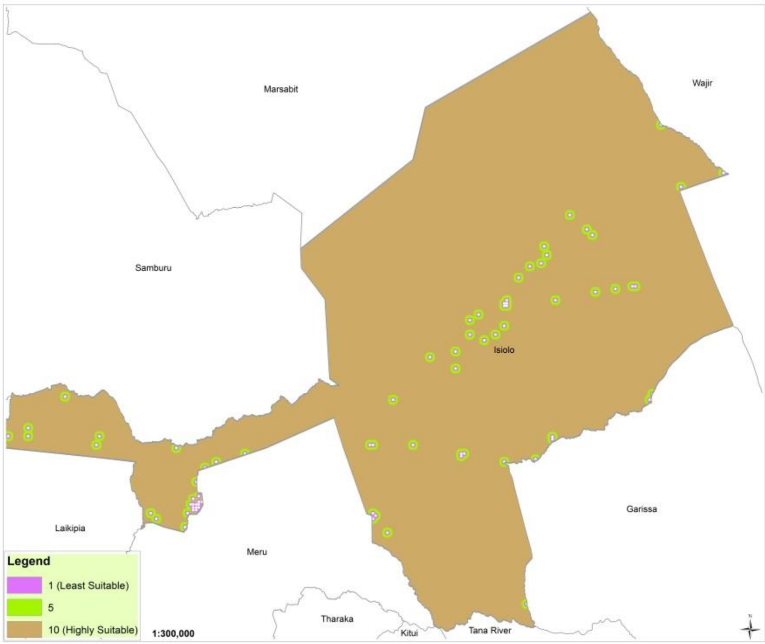

Figure 3.18: Reclassified Buffer Distances from Schools

j. Reclassified Hospitals buffer distances raster

Buffer distances from schools of between 500 and 1000 meters were classified as least suitable, those between 1000 and 2000 as moderately suitable and those greater than 2000 meters as highly suitable.

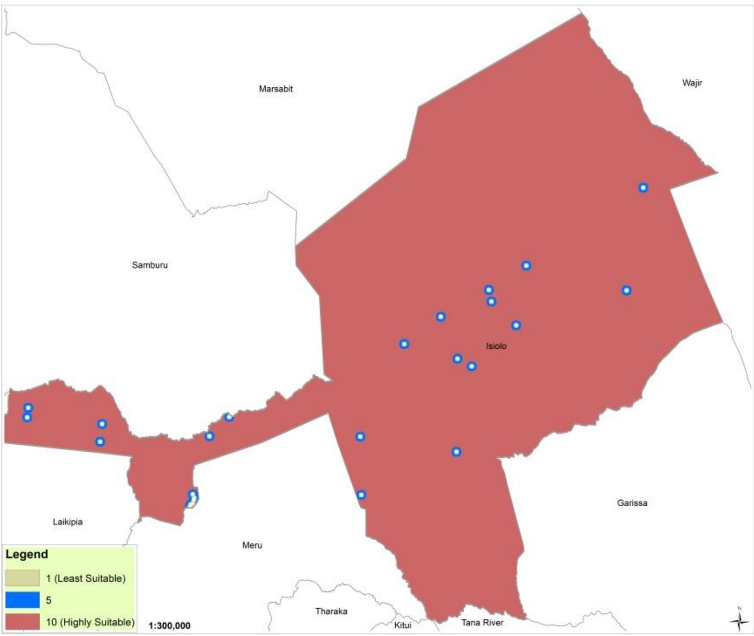

Figure 3.19: Reclassified Buffer Distances from Hospitals

k. Reclassified Protected Areas buffer distances raster

Areas falling between 0 and 500 meters of the protected areas were classified as unsuitable, between 500 and 1000 meters as marginally suitable, between 1000 and 2000 meters as moderately suitable and those greater than 2000 meters as highly suitable.

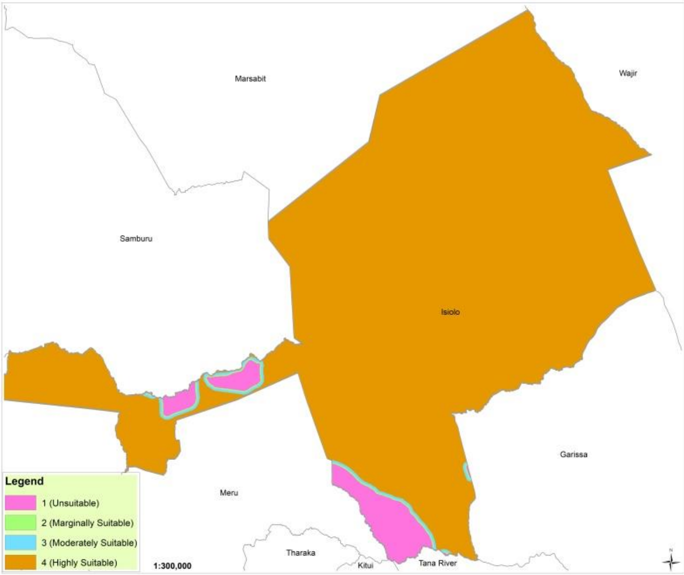

Figure 3.20: Reclassified Buffer Distances from Protected Areas

l. Reclassified Rivers buffer distances raster

Areas falling between 0 and 500 meters of the streams were classified as unsuitable, between 500 and 1000 meters as marginally suitable, between 1000 and 2000 meters as moderately suitable and those greater than 2000 meters as highly suitable.

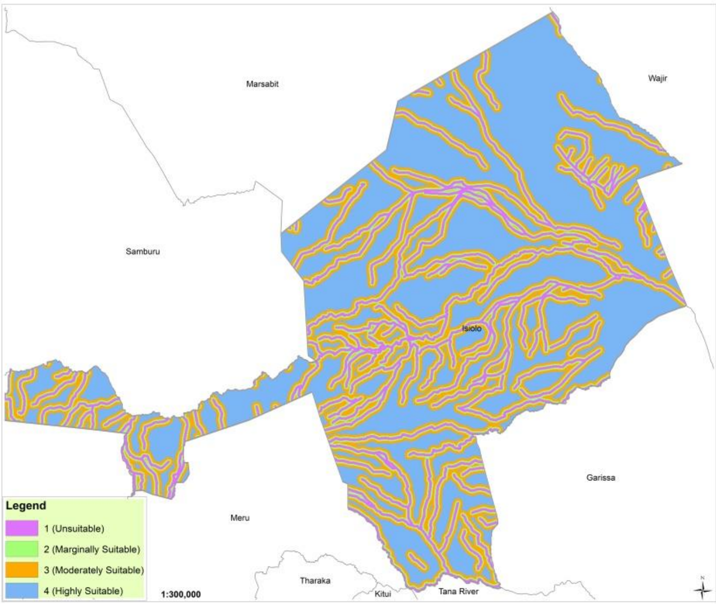

Figure 3.21: Reclassified Buffer Distances from Rivers

m. Reclassified Land Use Land Cover

The study area was mapped into seven land use classes; barren land which was classified as the highly suitable, grass lands and shrub lands which were classified as moderately suitable, wood lands which were classified as marginally suitable and swamp lands, agricultural land and urban areas which were classified as unsuitable.

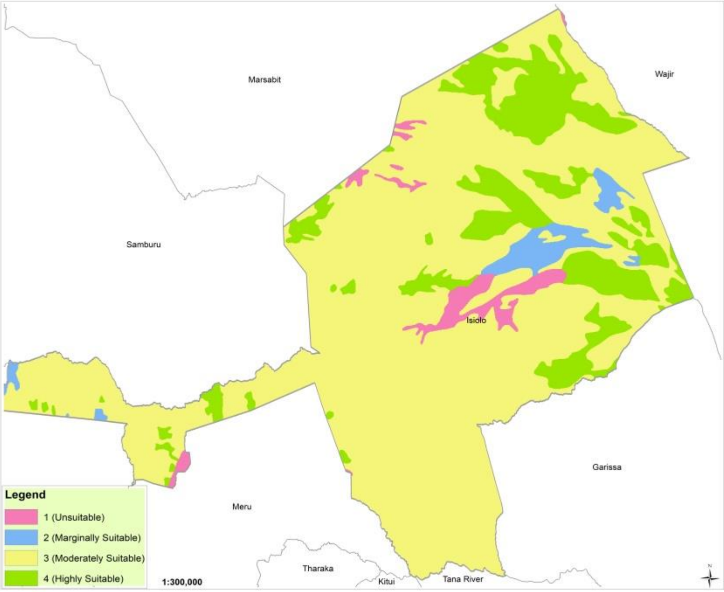

Figure 3.22: Land Use Land Cover Reclassified

3.4 Multi – Criteria Analysis

3.4.1 Analytical Hierarchical Process

The metrics for site suitability were compared against each other using the Saaty scale to determine particular level of influence for each. This resulted into a pairwise comparison matrix.

Table 3.2: Pairwise Comparison Matrix

		Pairwise Comparison Matrix									
		GHI	Temp	Aspect	Pop.	Slope	Roads	Soil	Towns	Schools	Health F.
1	GHI	1.00	6.00	6.00	5.00	8.00	9.00	9.00	9.00	9.00	9.00
2	Temp	0.17	1.00	0.50	4.00	7.00	7.00	7.00	7.00	8.00	8.00
3	Aspect	0.17	2.00	1.00	5.00	4.00	6.00	6.00	6.00	8.00	8.00
4	Pop	0.20	0.25	0.20	1.00	6.00	5.00	6.00	7.00	5.00	6.00
5	Slope	0.13	0.14	0.25	0.17	1.00	5.00	5.00	5.00	7.00	7.00
6	Roads	0.11	0.14	0.17	0.20	0.20	1.00	1.00	5.00	5.00	6.00
7	Soil	0.11	0.14	0.17	0.17	0.20	1.00	1.00	3.00	3.00	3.00
8	Towns	0.11	0.14	0.17	0.14	0.20	0.20	0.33	1.00	3.00	3.00
9	Schools	0.11	0.13	0.13	0.20	0.14	0.20	0.33	0.33	1.00	1.00
10	Health F.	0.11	0.13	0.13	0.17	0.14	0.17	0.33	0.33	1.00	1.00

The table 3.2 was normalized to enable determination of the respective weights for the criterion. The technical factors were observed to have high influence as compared to the economic factors – GHI had the highest weight of 34 per cent where as Health facilities had the lowest weight of 2 per cent

Table 3.3: Normalized Pairwise Comparison Matrix

			Normalized Pairwise Comparison Matrix									
		GHI	Temp	Aspect	Pop.	Slope	Roads	Soil	Towns	Schools	Health F.	Weight
1	GHI	0.45	0.60	0.69	0.31	0.30	0.26	0.25	0.21	0.18	0.17	0.34
2	Temp	0.08	0.10	0.06	0.25	0.26	0.20	0.19	0.16	0.16	0.15	0.16
3	Aspect	0.08	0.20	0.11	0.31	0.15	0.17	0.17	0.14	0.16	0.15	0.16
4	Pop	0.09	0.02	0.02	0.06	0.22	0.14	0.17	0.16	0.10	0.12	0.10
5	Slope	0.06	0.01	0.03	0.01	0.04	0.14	0.14	0.11	0.14	0.13	0.08
6	Roads	0.05	0.01	0.02	0.01	0.01	0.03	0.03	0.11	0.10	0.12	0.05
7	Soil	0.05	0.01	0.02	0.01	0.01	0.03	0.03	0.07	0.06	0.06	0.03
8	Towns	0.05	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.06	0.06	0.03
9	Schools	0.05	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.06	0.06	0.03
10	Health F.	0.05	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.02	0.02	0.02

3.4.2 Delineating Suitable Sites

The reclassified rasters of technical and economic criteria were overlaid together applying the respective weights for each criterion. This resulted into an eight suitability class raster denoting least to highest suitability. This raster was reclassified into three classes of highly suitable, moderately suitable and marginally suitable. Overlay analysis was conducted with the reclassified environmental criteria and the land use land cover rasters while restricting the unsuitable areas to generate the final suitability map. The highly suitable sites were considered as potential PV solar installation sites.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

In this chapter the metrics for photovoltaic solar site suitability, map of delineated suitable sites and the estimated electric potential of the delineated sites in the study area have been presented and discussed.

4.2 PV site suitability factors of Influence

The Global Horizontal Irradiance (GHI) was considered the main factor influencing site suitability as it's a measure of solar radiation. The study area was observed to have high solar irradiance in the range of 2100 to 2400 kWh/m^2 per annum – the highest being to the west, the moderate at the central region and the lowest to the east of the study area.

The slope of land was identified to also contribute to the PV site suitability. The slope of the study area was found to be in the range of 0 to 75 degrees with majority of the locations having a low slope, hence higher suitability. Aspect, the direction in which the slope faces was also found to be a significant factor. The study area being in the equatorial region, the flat slopes were deemed to have the highest suitability index.

The temperature of the study area was in the range of 18 to 27 degrees Celsius. Regions with the temperature range of 25 to 27 degrees were assigned the highest suitability index while those in the range of 18 to 21 degrees were assigned the lowest suitability index. This was so because the optimal operating temperature of PV solar is 27 degree Celsius.

The distances from roads were considered to have a direct relationship to the construction cost of the sites, therefore area in optimal distances closer to the roads were considered highly suitable than those further away. The distances from hospitals, schools and towns were considered as safety measures from settlements and also consideration for future expansion. Distances close to these facilities were therefore considered unsuitable where as far distances were considered as highly suitable.

The distances from rivers and protected areas were considered as an environmental conservation measure. Areas closer to these features were therefore considered unsuitable where as those far away were considered suitable for PV solar sites installations.

4.3 Overlay Analysis Results

The weighted overlay analysis tool was used with the GHI, slope, aspect, temperature and the proximity reclassified raster inputs. The degree of influence for each raster was derived using the analytical hierarchical process as shown in table 4. The output of this analysis resulted into a three class's raster showing marginally suitable, moderately suitable and the highly suitable PV solar areas.

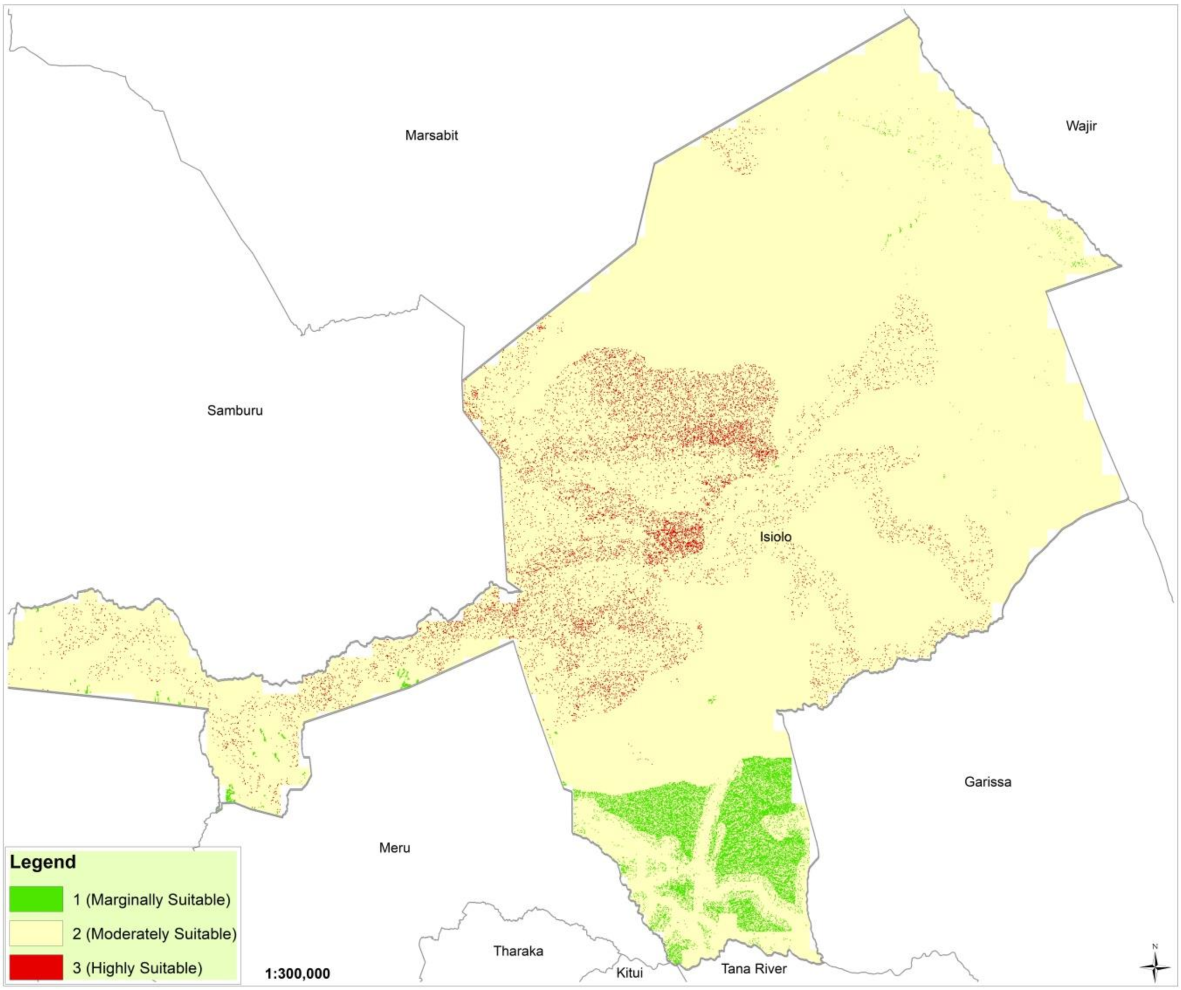

Figure 4.1: Weighted Overlay Analysis Results

4.4 Final Suitability Map

In order to come up with the final suitability map, the raster output of the overlay analysis above was overlaid assigning with the reclassified environmental factors and land use land cover rasters. The highest weight was assigned to the overlay analysis raster followed by the land use land cover raster while environmental factors were assigned the least but equal weights. The unsuitable areas in the environmental and land use land cover rasters were assigned the restricted scale value. This resulted into a four class raster showing the highest suitable which accounted for 2%, moderately suitable which accounted for 76%, marginally suitable which accounted for 2% and restricted area which accounted for 20% of the total land area.

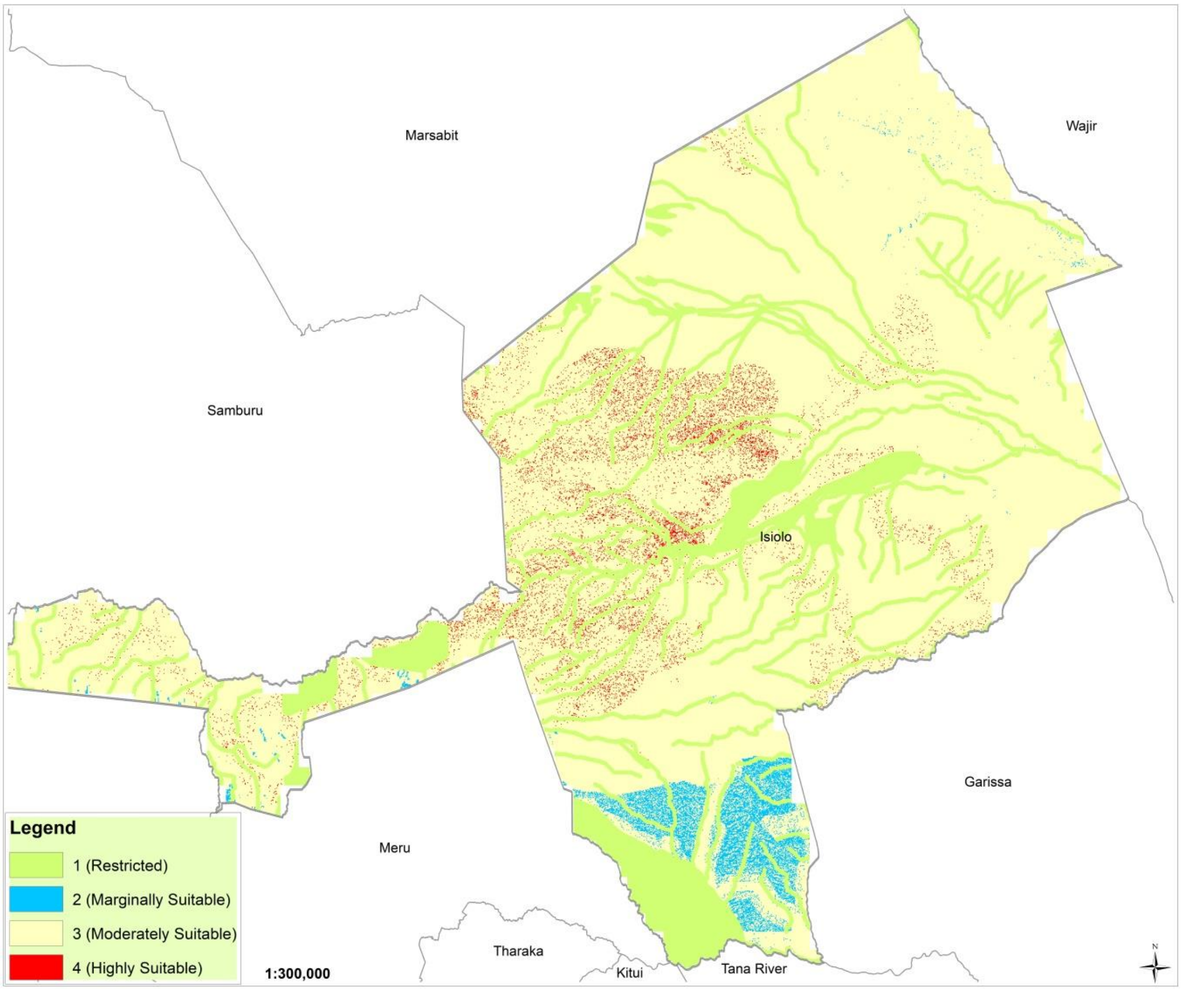

Figure 4.2: Suitability Map showing Restricted Areas

The highest suitable areas were extracted from the above raster by reclassifying to eliminate all the other classes. This resulted into the final suitability map.

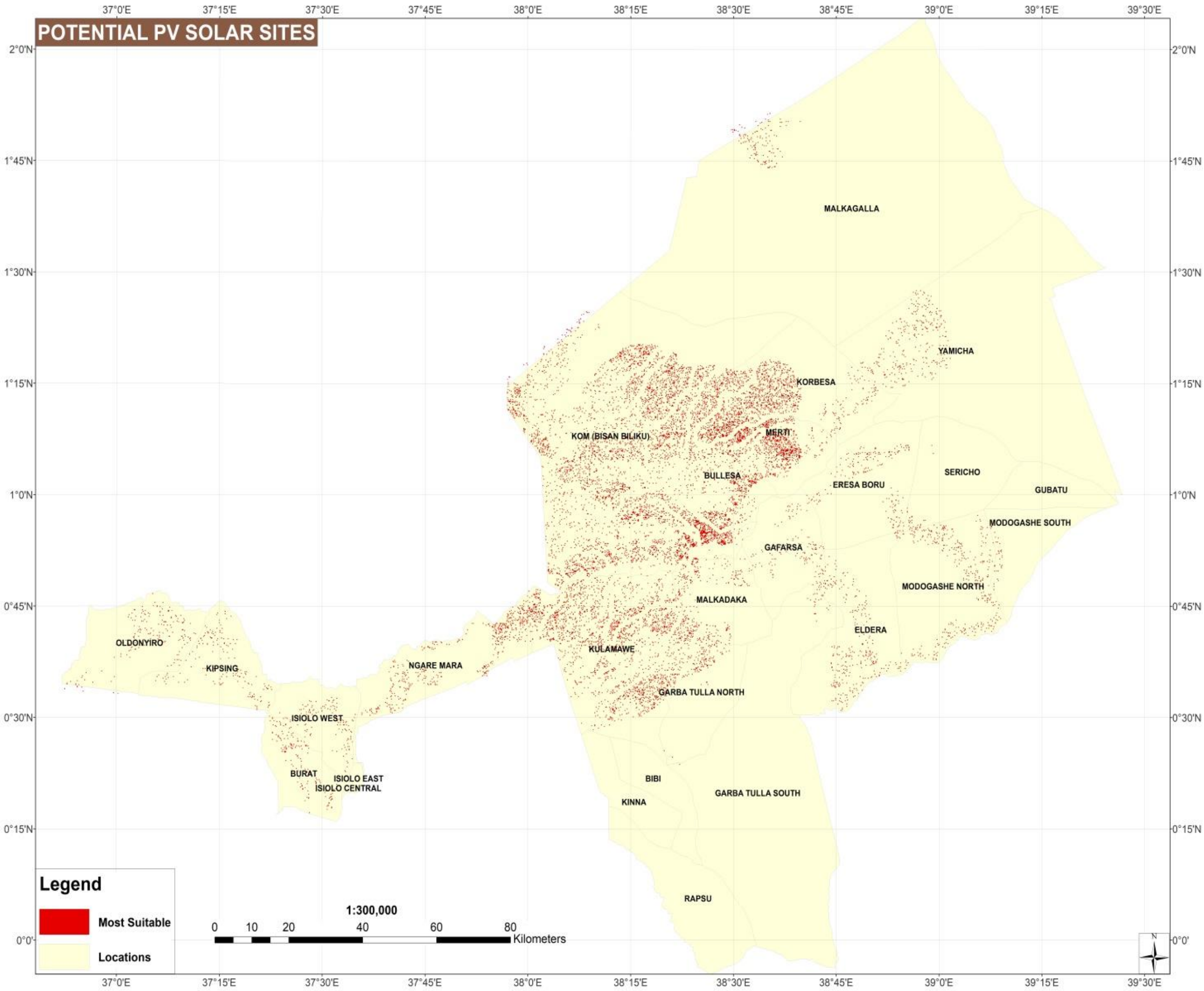

Figure 4.3: Final PV Solar Suitability Map Showing Highest Suitability Areas

4.5 Sensitivity Analysis

According to Meszaros and Rapcsak, (1996), decision models should be subjected to sensitivity analysis in order to evaluate how alterations in parameters affect the overall results the goal being elimination of subjectivity in selection of model's values and assessment of the methodology used. In this analysis, the input values are modified to generate different scenarios which are compared to the final suitability map.

Firstly, ten factors which constituted the technical and economic criteria were used to check the robustness of the model by assigning them equal weight. The results of this scenario observed visually showed a great match of trend in comparison to final suitability map thus confirming the stability of the model. The area of the highest suitable locations was calculated as 4% - slightly higher than that of the original model (2%) confirming the influence of the restricted areas.

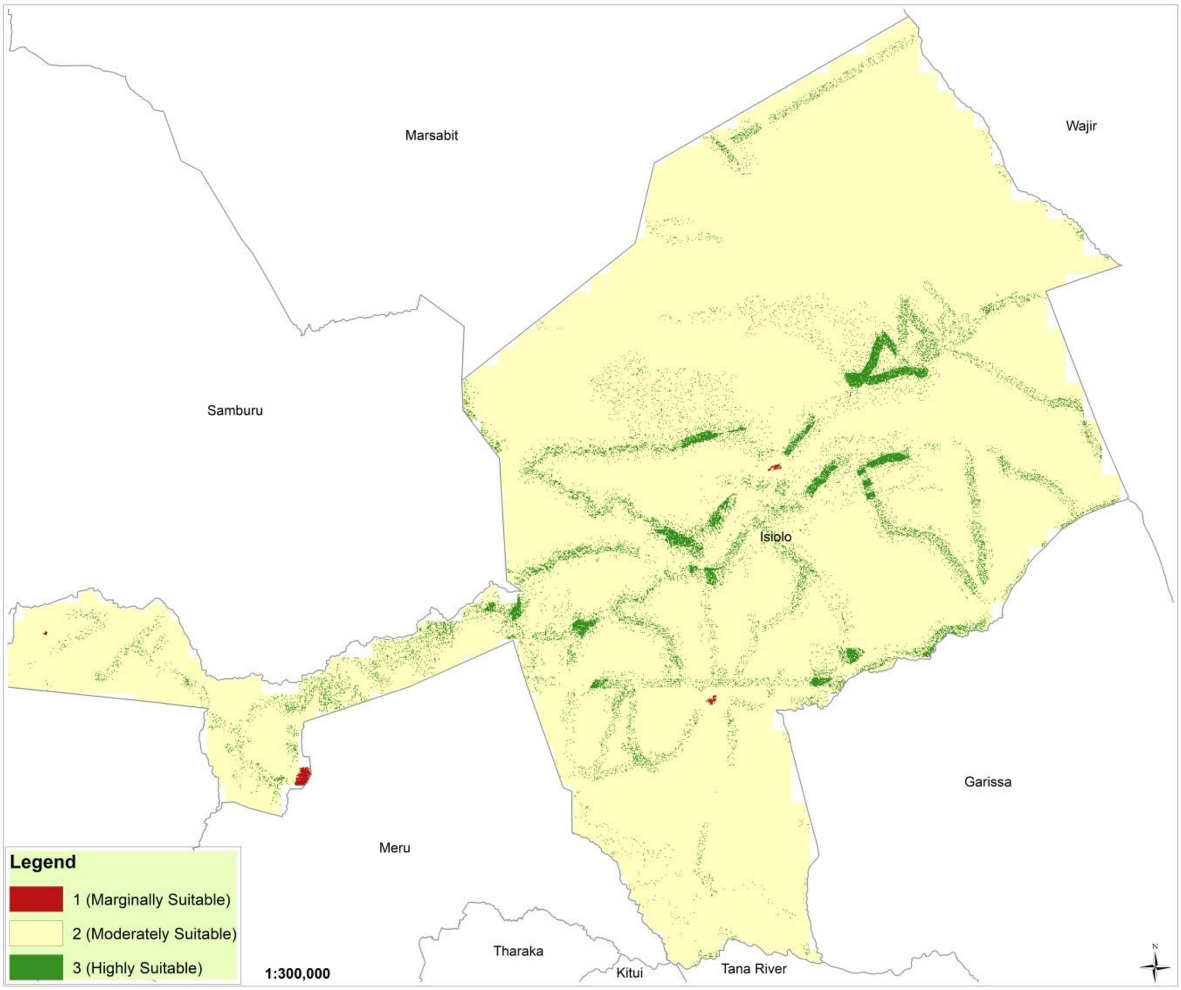

Figure 4.4: Sensitivity Analysis using Equal Weight

Secondly the stability of the model was tested without the influence of the major technical factor - Global Horizontal Irradiance and the remaining criteria still maintaining the same proportion of weight as produced by the AHP process. In this scenario, the area of the highest suitable areas resulted to 5% which was slightly but insignificantly higher than that in the first scenario confirming the influence of restricted areas and models stability. The pattern in this scenario was observed to differ from the first one as the highest suitability values were predominantly influenced by aspect and temperature.

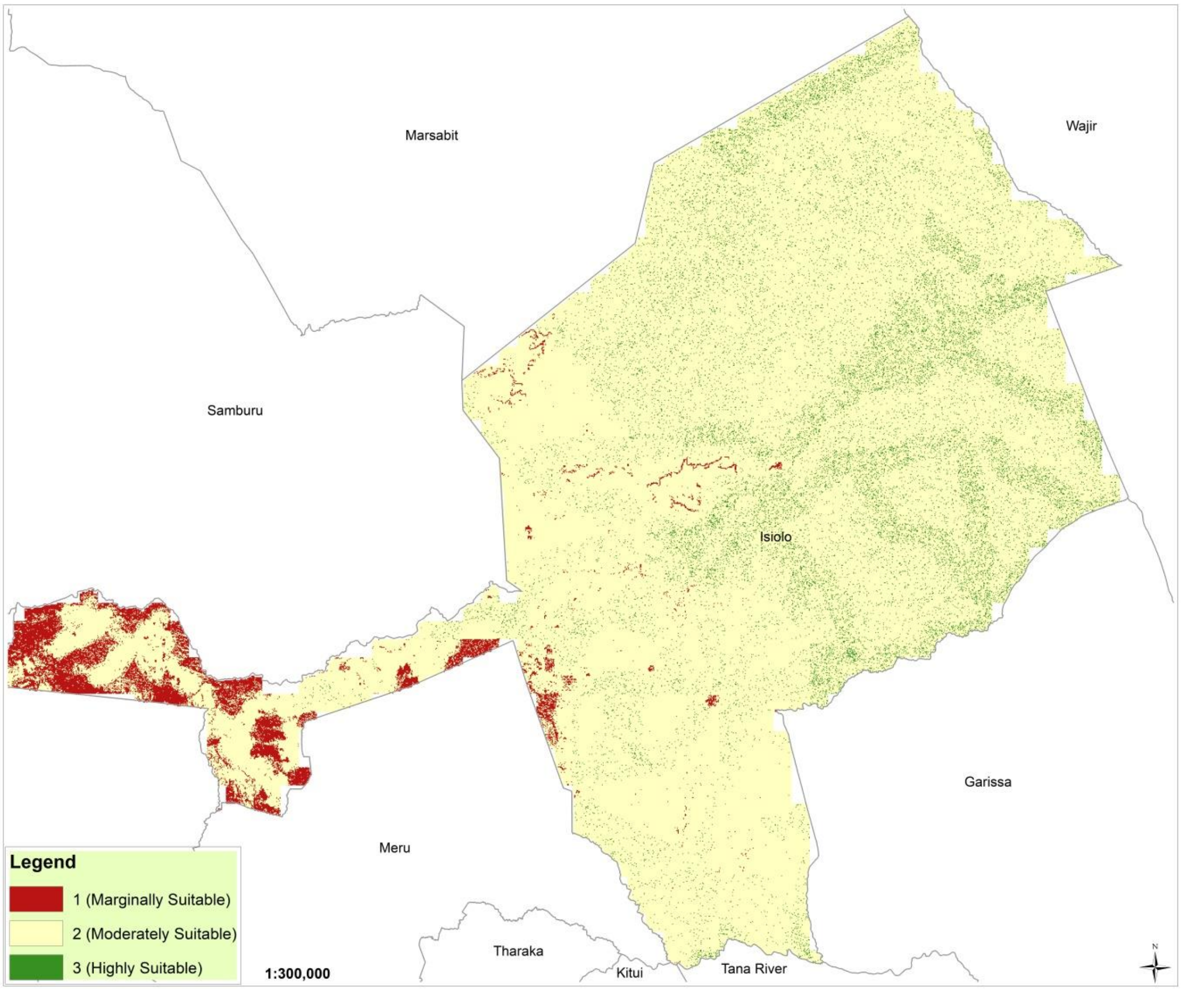

Figure 4.5: Sensitivity Analysis without GHI

4.6 Estimating Electric Potential

The highest suitability locations were extracted from the final suitability raster by reclassifying it into two classes where the highest suitable areas were reclassified as suitable; moderately suitable and unsuitable were eliminated by reclassifying them as no data.

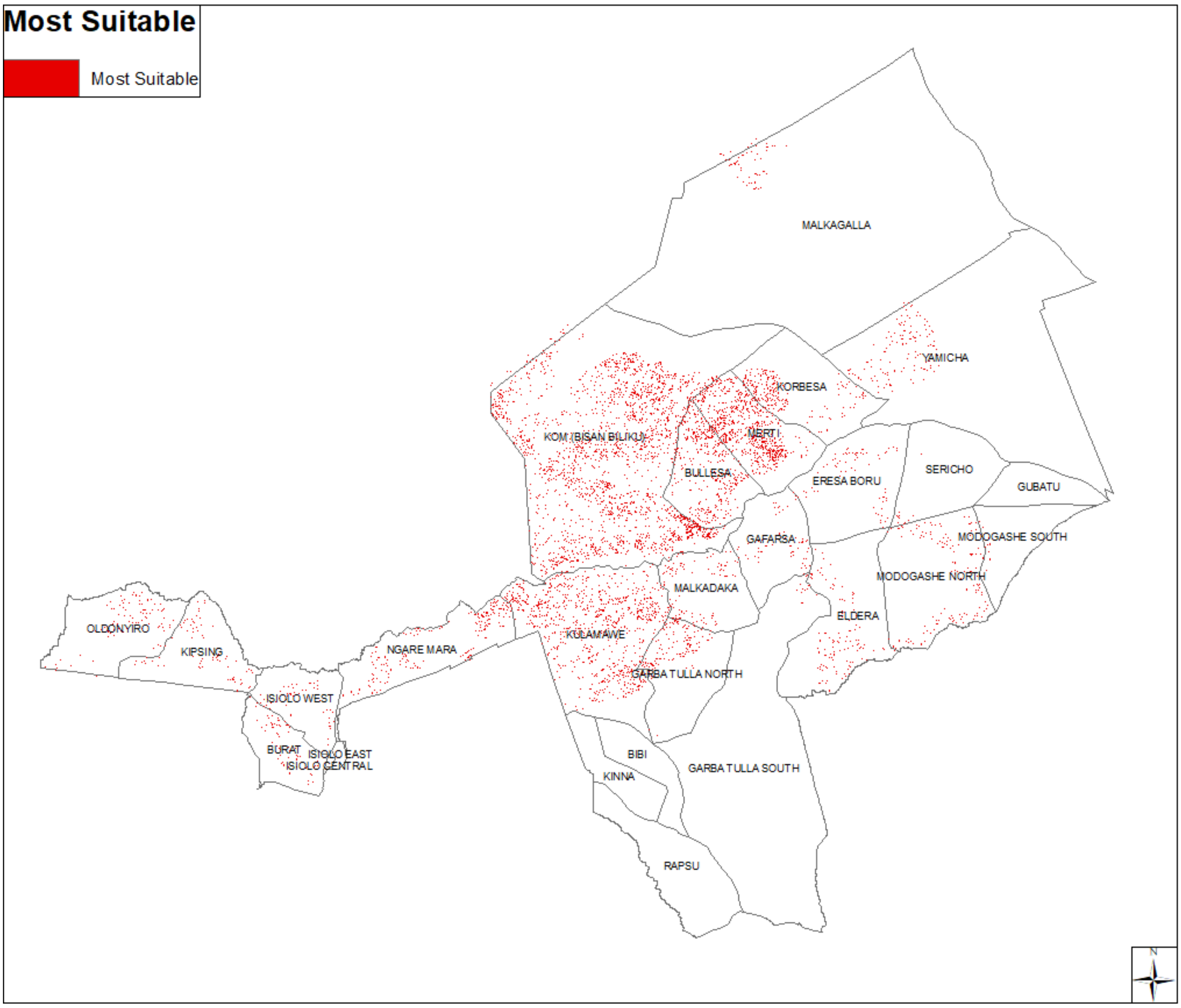

Figure 4.6: Location of most Suitable Areas

The raster to polygon tool was used to convert the suitable areas raster into a polygon. The field calculator tool was used to calculate the area in square kilometre of each polygon after which an intersection was done with the Isiolo locations administrative dataset in order to establish where each site fell. A selection of the best ten sites was used for computation of the electric potential

According to Gastli and Charabi, (2010) $GP = SR * CA * AF * \mu$

Where:

GP is the electric power generation potential in the year (GWh/year); SR is the annual solar radiation received per unit area (GWh/km^2/year); CA is the calculated total area of suitable land (km^2); AF is the area factor which indicates what fraction of the areas can be covered by solar panels – taken as 70%; μ is the efficiency with which solar system converts sunlight into electricity estimated to 0.13 for areas with abundance of solar radiation.

Table 4.1: Electric Potential of Highest Suitable Sites Extracted from Figure 4.3

Site	Name	GHI (GWh/Year/Km^2)	Suitable Area (Km^2)	Area Factor	Efficiency	Potential (GWh/Year)
1	BISAN BILIKU	2302.90	1.7097	0.7	0.13	358
2	BISAN BILIKU	2290.12	0.7916	0.7	0.13	165
3	BISAN BILIKU	2302.17	0.6830	0.7	0.13	143
4	MERTI	2311.67	0.6337	0.7	0.13	133
5	BISAN BILIKU	2306.92	0.5650	0.7	0.13	119
6	MERTI	2296.33	0.5415	0.7	0.13	113
7	BISAN BILIKU	2306.19	0.5322	0.7	0.13	112
8	MERTI	2299.98	0.5241	0.7	0.13	110
9	MERTI	2310.21	0.4751	0.7	0.13	100
10	BULLESA	2287.20	0.4341	0.7	0.13	90
Total Potential						**1443**

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In order to meet the ever rising demand of energy, it's prudent to venture into the exploitation of renewable energy sources because they are abundant in nature, self-generating and have the least negative impact on the environment compared to other sources such as fossil fuels which discharge a lot of greenhouse gases. Solar energy is one of the renewable energy sources that is very economical to exploit as it's abundant in nature, requires low initial investment and maintenance cost, has diverse applications and technological developments which are highly scalable. Particularly, it's useful in the electrification of remote areas which are not connected to the national grid where only off grid systems can be setup.

This research study aimed to identify suitable location for installation of photovoltaic solar power plants in Isiolo County. In order to achieve this objective, several metrics for site suitability analysis were identified and categorized into technical, economic and environmental criterion; these included, global horizontal irradiance, aspect, slope, temperature, population, soil, distances from roads, towns, hospitals and schools. The criteria in vector data were converted into raster data. Further, the rasters were reclassified following the derived suitability levels. The technical and economic factors were weighted together using the analytical hierarchical process and weights thereof applied in the overlay analysis which produced the suitability raster which was further overlaid with the environmental factors and land use land cover to generate the final suitability map. Sensitivity analysis of the results was conducted to determine the accuracy of the suitability model used.

The results of this study showed 2% of the study area to be highly suitable for photovoltaic solar power plants installation. The potential electric energy of the best ten sites on the basis of area coverage in kilometre square was calculated resulting to a cumulative figure of 1443 GWh/year which could not only meet the power demand for Isiolo County but also that of the neighbouring counties combined.

5.2 Recommendations

This study considered technical, economic and environmental factors as metrics for PV solar suitability analysis. Further studies could also consider social and cultural factors which would be collected through interviews and quantified using scientific methods. Incorporation of social factors would go a long way to enhance public participation.

Global horizontal irradiance data used was collected using remote sensing satellite. The possibility of using field measurements should be considered in order to enhance accuracy of this dataset as it was found to have the greatest significance among the factors considered for this analysis.

The model used in this analysis considered weighing the technical and economic factors jointly using the analytical hierarchical process. In further research, consideration for discrete weighting of these factors can be done and determination of the variations thereof determined in order to improve the accuracy of the model.

The study area was Isiolo which is one of the arid and marginalized Counties in Kenya. Future studies could consider incorporating a larger area of study covering several marginalized Counties in order to increase the overall benefit of this study by leveraging on the economies of scale.

This study further recommends that civil education be conducted to enhance knowledge and promote popularity of renewable energy and in particular solar energy in the marginalized communities. This would help reduce the reliance of fossil fuel as an energy source and thus promote conservation of the environment.

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APPENDIX

Coordinates of first 100 most suitable sites

Site	Area (KM^2)	SUB_LOCATION	LAT	LON
1	1.7097	BISAN BILIKU	38.4281	0.9151
2	0.7916	BISAN BILIKU	38.4753	0.8933
3	0.6830	BISAN BILIKU	38.4026	0.8876
4	0.6337	MERTI	38.5140	1.1232
5	0.5650	BISAN BILIKU	38.3876	0.9038
6	0.5415	MERTI	38.6412	1.0968
7	0.5322	BISAN BILIKU	38.4115	0.9405
8	0.5241	MERTI	38.6298	1.1000
9	0.4751	MERTI	38.5234	1.1298
10	0.4341	BULLESA	38.5489	1.0292
11	0.4213	MERTI	38.5162	1.1350
12	0.4195	BISAN BILIKU	38.4305	0.9068
13	0.4178	MERTI	38.6192	1.0998
14	0.4154	MERTI	38.6063	1.1213
15	0.4133	MERTI	38.6218	1.0921
16	0.3762	BULLESA	38.4744	1.1334
17	0.3530	BULLESA	38.5052	0.9797
18	0.3406	MERTI	38.6288	1.0810
19	0.3364	BISAN BILIKU	38.4540	0.9095
20	0.3308	BULLESA	38.5026	1.0274
21	0.3296	BISAN BILIKU	38.3750	0.8605
22	0.3068	BULLESA	38.4445	1.1354
23	0.3026	MERTI	38.6604	1.0862
24	0.2985	BULLESA	38.4428	0.9580
25	0.2937	MERTI	38.5799	1.1578
26	0.2788	BISAN BILIKU	38.4319	0.8941
27	0.2704	BISAN BILIKU	38.4471	0.9164
28	0.2668	BISAN BILIKU	38.4086	0.8565
29	0.2667	MERTI	38.5838	1.1325
30	0.2659	BULLESA	38.4889	0.9447
31	0.2640	BULLESA	38.4694	0.9245
32	0.2608	BISAN BILIKU	38.2669	0.9553
33	0.2607	BISAN BILIKU	38.3295	1.1328

34	0.2389	MERTI	38.6283	1.1245
35	0.2345	BISAN BILIKU	38.1149	0.8283
36	0.2295	BISAN BILIKU	38.2960	1.2399
37	0.2290	MERTI	38.5972	1.1273
38	0.2267	MERTI	38.5135	1.1816
39	0.2257	BISAN BILIKU	38.3552	1.2518
40	0.2254	MERTI	38.6519	1.1033
41	0.2224	MERTI	38.4983	1.1638
42	0.2218	BISAN BILIKU	38.4070	0.9306
43	0.2208	BISAN BILIKU	38.2933	1.3161
44	0.2203	KORBESA	38.6230	1.2468
45	0.2185	BULLESA	38.5396	1.0309
46	0.2175	BISAN BILIKU	38.3879	0.8594
47	0.2173	BISAN BILIKU	38.3499	1.2848
48	0.2172	BULLESA	38.4541	1.1512
49	0.2169	BULLESA	38.4627	1.1457
50	0.2166	BULLESA	38.4398	1.1445
51	0.2136	BULLESA	38.4770	1.1569
52	0.2123	BULLESA	38.4832	1.1334
53	0.2100	BISAN BILIKU	38.3836	0.8877
54	0.2080	KULAMAWE	38.0095	0.7383
55	0.2076	KORBESA	38.6191	1.2236
56	0.2067	KULAMAWE	38.2170	0.7050
57	0.2063	BISAN BILIKU	38.3711	0.8631
58	0.2060	MERTI	38.5322	1.1500
59	0.2051	BULLESA	38.4542	1.1291
60	0.2051	BISAN BILIKU	38.3622	1.1399
61	0.2045	MERTI	38.5129	1.1416
62	0.2040	BISAN BILIKU	38.3597	1.3140
63	0.2038	MERTI	38.6411	1.1075
64	0.2030	MERTI	38.4841	1.1575
65	0.2022	BISAN BILIKU	38.2249	1.3116
66	0.2021	BISAN BILIKU	38.2286	1.0131

67	0.2016	BISAN BILIKU	38.3432	1.2783
68	0.2012	BULLESA	38.4233	1.1288
69	0.2008	NGARE MARA	37.9348	0.6980
70	0.2000	BISAN BILIKU	38.2824	1.3218
71	0.1967	BISAN BILIKU	38.2563	0.9611
72	0.1967	BULLESA	38.4917	1.0985
73	0.1962	BISAN BILIKU	38.2009	1.0981
74	0.1950	KULAMAWE	38.1081	0.6902
75	0.1932	BISAN BILIKU	38.4809	0.9103
76	0.1931	BISAN BILIKU	38.4178	0.9363
77	0.1931	MERTI	38.5337	1.1453
78	0.1927	BISAN BILIKU	38.1978	0.8662
79	0.1922	BISAN BILIKU	38.4291	0.9298
80	0.1915	BISAN BILIKU	38.0373	1.1122
81	0.1907	BISAN BILIKU	38.1897	0.9939
82	0.1904	GARBA TULLA NORTH	38.3941	0.6897
83	0.1904	BULLESA	38.4809	0.9544
84	0.1904	BISAN BILIKU	38.2898	0.9557
85	0.1900	KULAMAWE	38.2205	0.7130
86	0.1895	KORBESA	38.6490	1.2014
87	0.1892	KULAMAWE	38.0348	0.7346
88	0.1892	MERTI	38.5721	1.1581
89	0.1839	KULAMAWE	38.1573	0.6885
90	0.1839	MERTI	38.5045	1.1340
91	0.1839	BISAN BILIKU	38.2251	1.3191
92	0.1838	KULAMAWE	38.0622	0.6766
93	0.1838	BULLESA	38.4884	1.1108
94	0.1837	BISAN BILIKU	38.4379	0.8976
95	0.1821	MALKADAKA	38.4087	0.8274
96	0.1821	BISAN BILIKU	38.3915	0.8974
97	0.1821	BISAN BILIKU	38.2495	0.9498
98	0.1819	MERTI	38.6083	1.1323
99	0.1818	KULAMAWE	38.2072	0.5181
100	0.1818	BISAN BILIKU	38.3223	1.1105