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Geothermal Well Site Suitability Selection Using Geographic Information Systems (GIS) and Remote Sensing: Case Study of the Eburru Geothermal Field

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ABSTRACT

Conventional geothermal site selection process comprises a multi-disciplinary field approach that involves the integration of several surface exploration methods such as geological, geochemical, geophysical and environmental baseline surveys. Geographic Information Systems (GIS) multi-criteria analysis and remote sensing image analysis are emerging technologies used in the establishment of favorable areas for geothermal well siting and targeting. They are convenient, relatively cost-effective methods useful in feasibility and actual field stages of geothermal resource exploration. For this study, the aforementioned geospatial were used to establish favorable areas for geothermal well sites within the Eburru high-temperature geothermal field. Supervised image classification was used to isolate unsuitable areas at preliminary stages of the study. GIS raster overlays analysis methods such as logic, math operators and decision tables were used for final suitability selection. Three suitability zones namely; most suitable area, moderately suitable area and the least suitable area were established. Areas near Eburru trading centre, Thome (Northern region) and Badlands rift axis were found to be most suitable. The central and western regions of the study area were deemed to be moderately suitable. North Eastern zones near Gilgil and Kikopey towns were found to be the least suitable.

1. INTRODUCTION

Geothermal well site selection is a multidisciplinary approach done by integrating field data acquired by geophysical, geological, and geochemical, among techniques. Geochemical methods allows the estimation of the origin, temperature and recharge within the geothermal reservoir, thereby indicating the degree of permeability within the reservoir rock structure. Interpretation of geological samples allows the estimation of the location of heat source. Geophysical techniques allows estimation of subsurface geology structures. The aforementioned techniques are the mostly used in optimal selection and targeting of geothermal wells.

Remote sensing method has been used as a cost-effective tool for geothermal exploration over large areas enabling the succeeding assortment of targets for additional exploration using ground-based studies (Haselwimmer & Prakash, 2013). The basic principle of this technology is to use the 8-14 µm region of the spectral radiant to observe changes in temperature of objects on the earth's surface. The tone of thermal imagery shows the surface radiance temperature. Remotely sensed thermal infrared (TIR) images have been used for years to detect geothermal activity. High-resolution Thermal Infrared sensors (<5m) are ideal for mapping and monitoring geothermal surface anomalies (Varghese, 2016). GIS functionality, such as vector and raster spatial analysis and overlay, can be employed for structural mapping and analysis using powerful software programs (Abdullah, et al., 2013). The success of GIS in sitting problems is attributed to its ability to perform deterministic overlay and buffer operations (Al-Amri & Eldrandaly, 2014). This is usually achieved through organizing, visualization, querying, combining, or analyzing geospatial data. For this study, GIS and remote sensing was used to identify geothermal anomalies by modelling surface manifestation indicators (fumaroles, altered grounds, open faults, fractures, eruption centers, dykes) in the Eburru prospect area.

For ease of classification, the geothermal surface manifestation features have been categorized as follow: (1) Geological factors, characterized by open faults, hydrothermal veins, dykes and volcanic centers; (2) Geochemical factors, fumaroles, hot (steaming) grounds, altered grounds and (3) thermal factors, characterized by heat loss survey and satellite land surface temperature measurements.

1.1 Study Objectives

i. To identify the criteria for selecting suitable sites for geothermal wells.
ii. To establish the relative weights of the identified criteria.
iii. To perform a multi-criteria evaluation analysis to generate the final suitability.
iv. To compare the final suitability map with the existing maps generated using different geoscientific approaches.

2. EVIDENCE LAYERS

The evidence layers have been categorized as follow: (1) Geological factors, characterized by open faults, hydrothermal veins, dykes and volcanic centers; (2) Geochemical factors, fumaroles, hot (steaming) grounds, altered grounds and (3) thermal factors, characterized by heat loss survey and satellite land surface temperature measurements.

2.1 Geological Factors

These are important surface manifestation features in geothermal systems. Faults, fractures network zones are depositional sites for hydrothermal fluids. The faults may facilitate geothermal fluid flow by providing channels of high permeability or might create barriers to flow by offsetting areas of high permeability (Munyiri, 2016). These features appear in a linear pattern, resembling drainage features. This makes them suitable for detection using satellite remote sensing. Craters are depressions, commonly deep and precipitous, that mark the eruptive vents of volcanoes. They are indicators of underground heat sources. Most of the craters and calderas in the Eburru geothermal complex coexist alongside eruption of silicic rocks like trachyte, rhyolite, and basalts (KENGEN, 2018).

2.2 Geochemical Factors (Fumaroles and steaming grounds)

Fumaroles are vents in the Earth's surface from which steam and volcanic gases are emitted. Fumaroles offer an important window into the processes at work beneath the surface of some volcano (Braddock et al., 2017). Fumarole activities usually follow the structural configuration of faults and fractures in areas of recent volcanism. The manifestations have are used as indicators of the existence of geothermal systems associated with shallow magma chambers (Omenda et al., 1993).

Hydrothermal alteration is caused by the processes acting within volcanic systems such as fluid-rock interaction, boiling and mixing are considered the primary cause of various surface waters and steam vents as well as the observed secondary mineralogy (Bjorke, 2010). Hydrothermally altered zones are in the study area are found along faults. By mapping alteration zones at the surface, it is possible to locate the zones with highest temperatures, pressures, or permeability, all of which are important in geothermal exploration.

2.3 Thermal Factors

Heat loss temperature data collected at shallow holes (50cm-1m) was interpolated to establish and predict spatial distribution in the study area. Satellite temperature data established via NDVI threshold method was integrated with heat loss survey data to autocorrelate thermal distribution in the study area.

2.4 Environmental Constraints

Constraints are areas that limit or make expansion and investment impractical according to Best Management Practices and development guidelines. Constraints analysis is based on the Boolean criteria, which limit the alternatives under consideration to specific regions (Sarpong & Baffoe, 2016). They are expressed in the form of a Boolean (logical) map where areas excluded from the consideration (i.e. unsuitable areas) are coded with the value 0 and those open for consideration (i.e. suitable areas) are coded 1 (Sarpong & Baffoe, 2016; Chaudhry, 2008).

The following are the set constraints for this study:

i. Siting is restricted to regions 1000m away from residential areas (Yousefi et al., 2007). This is to reduce pollution arising from drilling of geothermal wells or any modification to the landscape.
ii. Geothermal wells cannot be sited in protected areas such as forest and game reserves, tourist sites, (Noorollahi, 2005).
iii. Siting in lakes or any water body is restricted (Chaudhry, 2008) to avoid pollution resulting from injection of brine into the water source. Sarpong & Baffoe (2016) proposed a 250m buffer of streams and water bodies.

3. METHODOLOGY

This study incorporated the results of two main data integration models; exploration data modeling and environmental suitability analysis. In exploration data modeling different exploration data including geological, geochemical and geophysical data are integrated and suitable area which presents the location of geothermal resources is defined. The environmental suitability analyses were performed by overlaying environmentally important data layers and a suitable area was selected. The result of two integration models is overlaid and suitable area for geothermal well sites is selected.

Sites that satisfy the screening criteria were subjected to more detailed evaluation and are compared as possible alternative sites for the proposed facility. Usually, the selection criteria would include economics, social, and environmental measures/factors (also known as constraints). Normalization of the proxy criteria. The involved criteria are often multiple and incommensurable because they have different objectives measured along quantitative, qualitative, discrete or continuous measurement scales. To make the different criteria proxies comparable along a common measurement scale, they must be normalized using a scale function (Hannssen et al., 2018). Standardization for most of the factor maps was done using a linear function, which converted the original factor scores (each expressed in its own unit of measurement) into dimensionless scores in the range 1 (Least suitable) to 3 (Most Suitable) in increasing suitability. The proposed approach consists of four main steps as shown in Figure ().

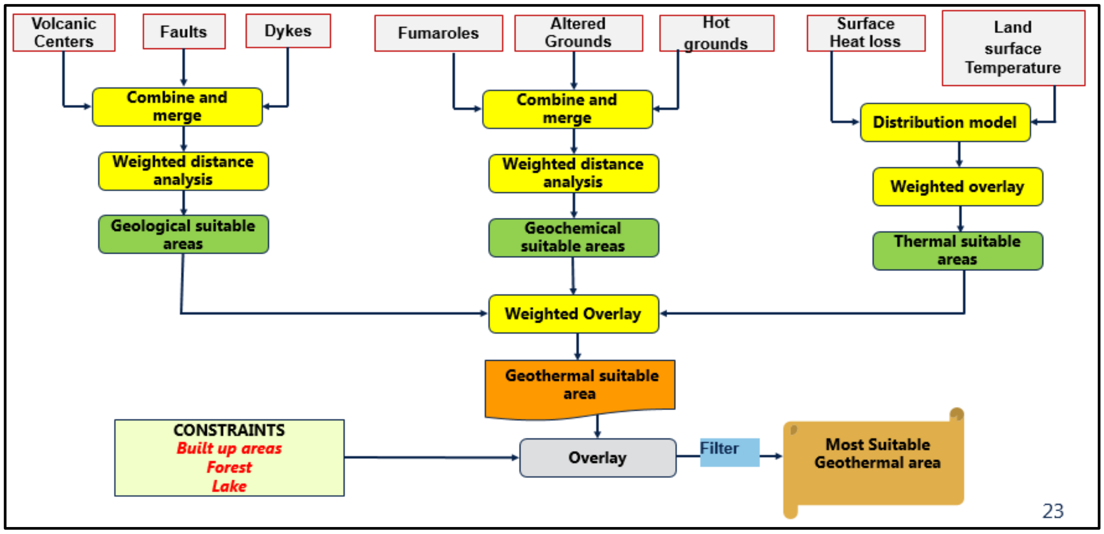

Figure 1: Study methodology workflow

4. RESULTS AND DISCUSSION

4.1 Environmental Constraints map

Based on the aforementioned criteria, a restriction map was created as represented in Figure 1.

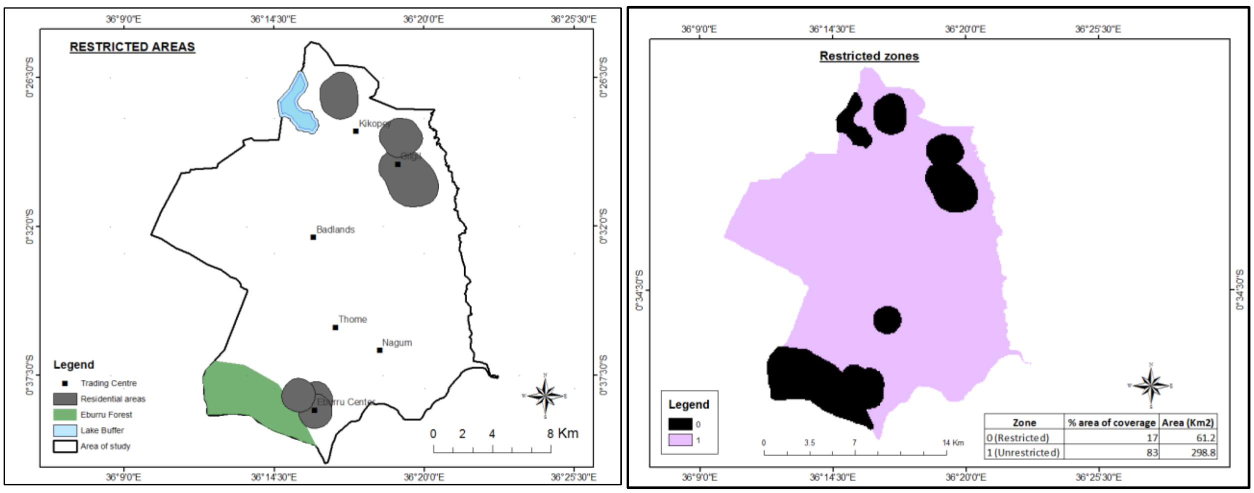

Figure 2: Environmental constraint map of Eburru prospect

From the constraint map, the purple colored areas (coded 1) are considered suitable while the black areas (coded 0) are unsuitable.

4.2 Criteria weights

The weighting criteria used multicriteria overlay analysis based on the relative influence of the geothermal factors that were discussed in the previous chapter are as shown in Tables 1.

Table 1: Criteria weights and influence for suitability selection

Final Suitability criteria		
Factor	**% influence**	**Score**
Geological	50	3-Most suitable
Geochemical	30	2-Moderate Suitable
Thermal	20	1-Least suitable

4.3 Final suitability map

A final suitability map was developed by integrating the three geothermal factor evidence layers and filtering the restricted areas as shown in Figure 2.

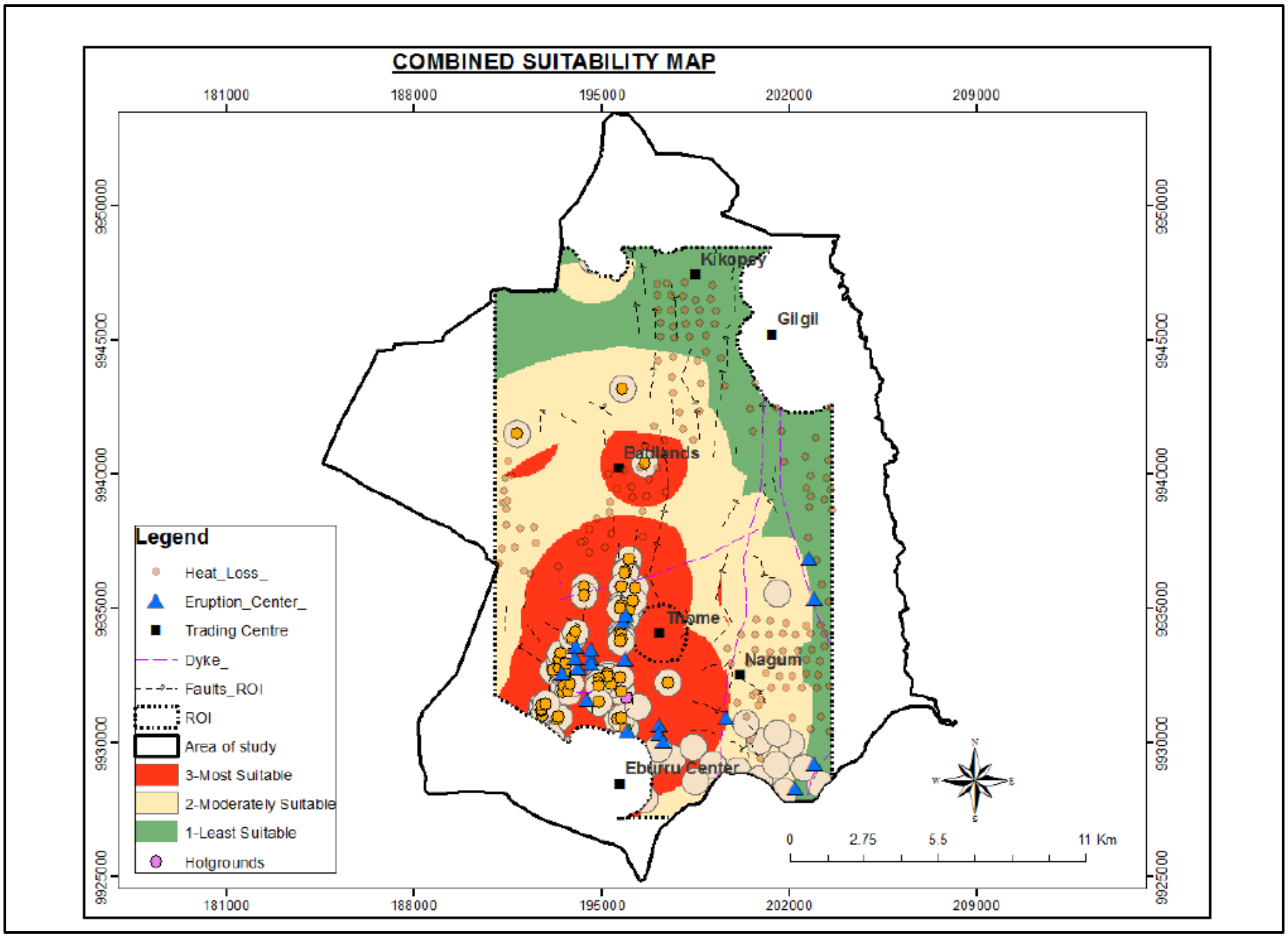

Figure 2: Integrated suitability map of Eburru prospect area

From the suitability map, areas around Eburru, Thome trading centers and Badlands Rift axis are the most promising sites for geothermal well siting. These areas are flanked by numerous geothermal manifestation features as evidenced by field data. The six wells drilled by KenGen were sited in this area. The Badlands area is also adjacent to the Badlands basaltic flow that postulated to be in near the magmatic heat source located along the Elementaita-Eburru rift axis. Areas that are North of Badlands area, Lake Elementaita buffer area and Nagum have medium geothermal energy potential. The Eastern areas near Gilgil and North Eastern regions near Kikopey trading centers have low potential. The area's suitability classes are presented in Table 2.

Table 2: Suitable areas for geothermal well siting in the study area

Suitability index	Location
Most suitable	1000m North of Eburru Trading Centre
	Badlands Rift axis (Preferable the Eastern part close to the basaltic lava flow)
Moderately suitable	Thome area
	Nagum area and 250m South of Lake Elementaita
Least Suitable	Areas extending NE and E of the study area close to Gilgil town and Kikopey trading center

The results from the suitability map were statistically computed to establish the area of coverage based on the count of each of the three classes involved in the combined suitability map creation. The percentage suitable areas (after filtering of the constraints), are represented in Figure 3.

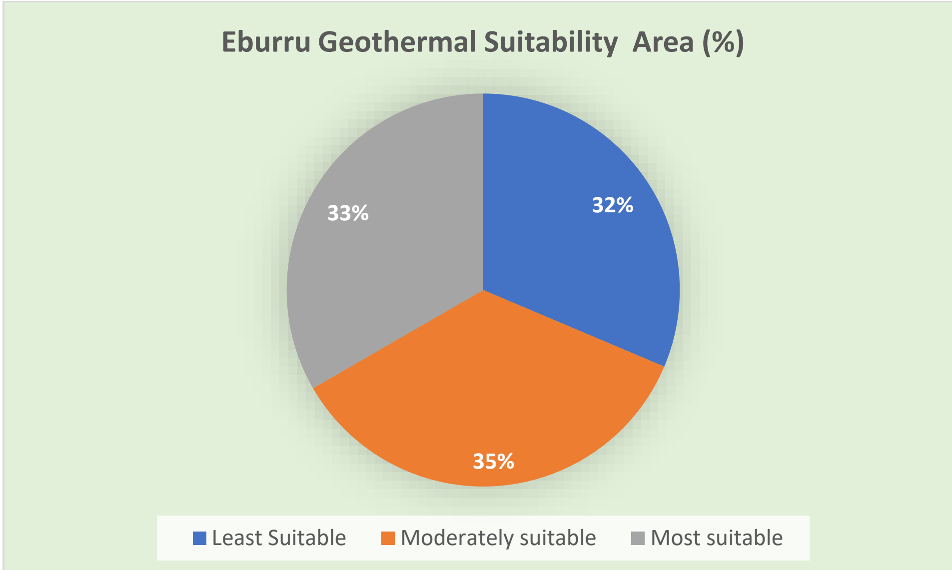

Figure 3: Area of coverage of the suitability classes, Eburru.

5.0. CONCLUSION AND RECOMMENDATIONS

The criteria weights generated using weighted overlay analysis method for the three geothermal factors confirmed the existence of geothermal energy resource in the study area. The relative influence of each individual geological factor was 40%, 35% and 25% for faults, eruption centers and dykes respectively. As for the geochemical factors, the relative influence of fumaroles, altered grounds and hot grounds was 40%, 30% and 30% respectively. The relative influence of the surface temperature distribution (thermal factor) was 50%, 35% and 15% for the ranges of >50℃, 25-50℃ and < 25℃ respectively. In general the overall relative influence of the main factors was 50%, 20% and 30% for geological, geochemical and thermal factors respectively.

From the final suitability map, areas near Eburru Trading Center, Thome village (North of study area) and areas near the Badlands rift axis were deemed most suitable for geothermal well site selection. These areas cover about 34% (about 101km^2) of the region of interest. The high geothermal suitability can be attributed to tectonic activities around these zones. Areas near Nagum, village, near the waterloo ridge and south of Lake Elementaita areas were deemed moderately suitable. They covered about 36% (108 km^2) of the area of interest. Finally, the North Eastern (Gilgil, Kikopey centers) and Western parts of the region of interest were considered least suitable. They covered about 95km^2 (30%) of the region of interest. In general, geothermal suitability decreases with increasing distance from surface manifestation feature (geothermal factors) as evidenced by the decrease of potential from Eburru shopping area towards Lake Elementaita and Gilgil area.

5.1. Recommendations

The following are the study's recommendations:

i. Carbon dioxide and radon gases distribution plus geophysical factor criteria be considered for better and more precise suitability model development.
ii. Use higher spatial resolution images to enhance digitization process.
iii. Use sensitivity analysis to validate and assess reliability of the study's findings.
iv. Consider performing a 3D multi-criteria analysis by integrating subsurface geothermal well data and surface exploration datasets. This will aid in visualization and projection of subsurface information for more accurate and precise well site selection.
v. Optimization studies to determine minimum separation distance between proposed adjacent geothermal wells and minimum number of wells in a prospect area.

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