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Low cost geothermal energy indicators and exploration methods in Kenya

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Geothermal power is one of the safest and environment friendly energy worldwide. It has been harvested in Kenya since 1956 with most potential sites being along the Rift Valley. There are surface manifestations such as hot springs and mudpools that are visible. Different methods of exploration are usually applied, including geophysical, geochemical and geological methods. This paper highlights different geothermal exploration techniques with emphasis on low cost methods that can be used in developing countries to map geothermal potential areas highlighting methods used in Kenya. A comparable cost analysis is done for Olkaria field in Kenya which has been explored using different methodologies and the results show that ground survey methods are more expensive than remote sensing though the two methods have unique advantages. Ground data collection method is three times expensive as compared to the remote sensing methodology. It also reviews the geothermal indicators that can be mapped by remote sensing techniques, and especially those using satellite imagery.

Key words: Geothermal indicators, exploration, geographical information systems (GIS), remote sensing.

INTRODUCTION

Energy usage worldwide is increasing and use of alternatives such as geothermal energy is set to increase, since the world has only a finite supply of fossil fuels (Bertani, 2015; GEA, 2012).

Geothermal power is one of the safest and environment friendly energy harvested in Kenya since 1956 (Omenda, 1998). Although Kenya has substantial renewable energy resources such as hydropower, solar, geothermal and wind, only about 18% households in Kenya are connected to the national electricity grid, and over 60% (Table 1) of the energy consumption is based on non-commercial biomass (Gloporis, 2012; Kiruja, 2011; Kiplagat et al., 2011).

According to GEA 2012, global geothermal industry has sustained a growth rate of 5% since 2012 and is projected to reach 2765 MW by 2020. Kenya and Ethiopia are endowed with significant geothermal resources as part of the East African Rift System (Pürschel et al., 2013). The main source of electricity in Kenya is hydroelectric power but due to climate change with prolonged dry spells in Kenya water has reduced in the rivers and dams such that the proportion of

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Table 1. Energy types in Kenya.

Source of energy	Percentage
Biomass	75
Petroleum	19
Electricity	6

Source: Kiplagat et al. (2011).

hydroelectric power is expected to fall to 20% by 2022 thus the country shifting focus to increasing wind and geothermal energy by 45% according to Gil-Alana et al., 2017.

Kenya is one of the leading countries globally with significant geothermal resources with rich geothermal potential sites being along the Rift Valley (Figure1), and a few outside the rift (Mibei, 2012). According to geothermal power generation report, Kenya has installed capacity of 700 MW against total potential of about 10,000 MW with Olkaria geothermal field being the largest producing site (Omenda and Simiyu, 2015). The Olkaria geothermal field is inside a major volcanic complex associated with Quaternary volcanism. The field is a high-temperature geothermal system located within the Kenya Rift Valley with numerous volcanic domes (Omenda, 1998). Geothermal energy in Kenya has been used for direct use and in direct use (Figure 1).

With the ever-increasing demand for energy in the country there is need for exploration of cost effective ways of locating geothermal potential areas. The Kenyan Government has recognized geothermal energy as important source of electricity and has supported the Kenya Electricity Generating Company (KenGen) accounting for about 75% of the total installed capacity (Othieno and Awange, 2016; Kiplagat et al.,2011).

One of the main challenges associated with geothermal harvest is the large upfront cost of geothermal exploration and development in addition to high risks associated with resource exploration (Omenda, 2012). This study aims to;

(1) Summarize geothermal indicators in Kenya section 2 and 3
(2) Review methodologies of delivery of the indicators and
(3) Show how geographical information systems (GIS) and remote sensing (RS) has been used in exploration of geothermal energy by reducing the cost of exploration. One of the objectives of this study is to show which indicators could be mapped using GIS and RS clarifying on the strengths and limitations.

Physical geothermal manifestations

Geothermal energy manifests itself on the surface as hot-springs (Figure 2a and b), boiling springs steam jets, geysers, mudpools, seeps altered grounds, sulphur deposit, silica sinters, travertine, geothermal grass, young lava flows caldera and fumaroles along the Kenyan Rift after which geophysics, geochemistry and geological exploration methods are used for citing the wells for drilling (Njue, 2012).

The rift valley is a volcanic area and surface manifestations features stimulate exploration. Fluids and gases leak to the surface along faults and fissures or through permeable rock, which are a clear indication of existing geothermal reservoir in the ground. These manifestations may overlie a geothermal system while some may discharge after flowing some distance down gradient from a hydrothermal area (Muhagaze, 1984).

According to White and Williams (1975), low temperature systems have <90°C, intermediate temperature systems 90 to 150°C and high temperature systems range from 150 to 240°C. Kenya has high temperature prospects located within the Kenya Rift Valley (Omenda and Simiyu, 2015).

Renner (1975) defines the salinity of hot water systems as ranging between 0.1 and 3%. Vapor dominated reservoirs are good geothermal resources and occur where there is very high heat flow but low water recharge. Near-surface gases leach rocks in the spring area as they condense to form acids. According to Fournier and Rowe (1966), siliceous sinter deposits are indicators of the presence of hydrothermal reservoirs with temperatures higher than 175°C.

METHODOLOGY

Geophysical methods

Geophysical measurements in geothermal involve measuring various parameters connected to geological structure and properties of geothermal systems with the aim of detecting and delineating geothermal resource as well as locating exploitable reservoirs and the siting of drill-holes through which hot fluids at depth can be detected (Mariita, 2010; Hersir and Bjornsson,1991). Parameters that characterize geothermal systems are

(1) High temperature
(2) High porosity
(3) High permeability
(4) Pressure and
(5) Chemical composition of the fluid (Wanjohi, 2012).

Aretouyap et al. (2016) has discussed various geophysical methods used in Africa highlighting their strength and limitations. Direct methods measure parameters that are directly influenced by geothermal activity while indirect method explores the physical parameters of the host rock. Some of the geophysical methods (Table 2) include;

(1) Thermal methods
(2) Electrical methods
(3) Gravity method
(4) Magnetic method and seismic methods (Domra Kana, 2015).

Table 2 summarises the various geophysical methods employed in geothermal exploration. In their review paper, Domra-Kana et al. (2015) have summarised the geophysical methods of geothermal

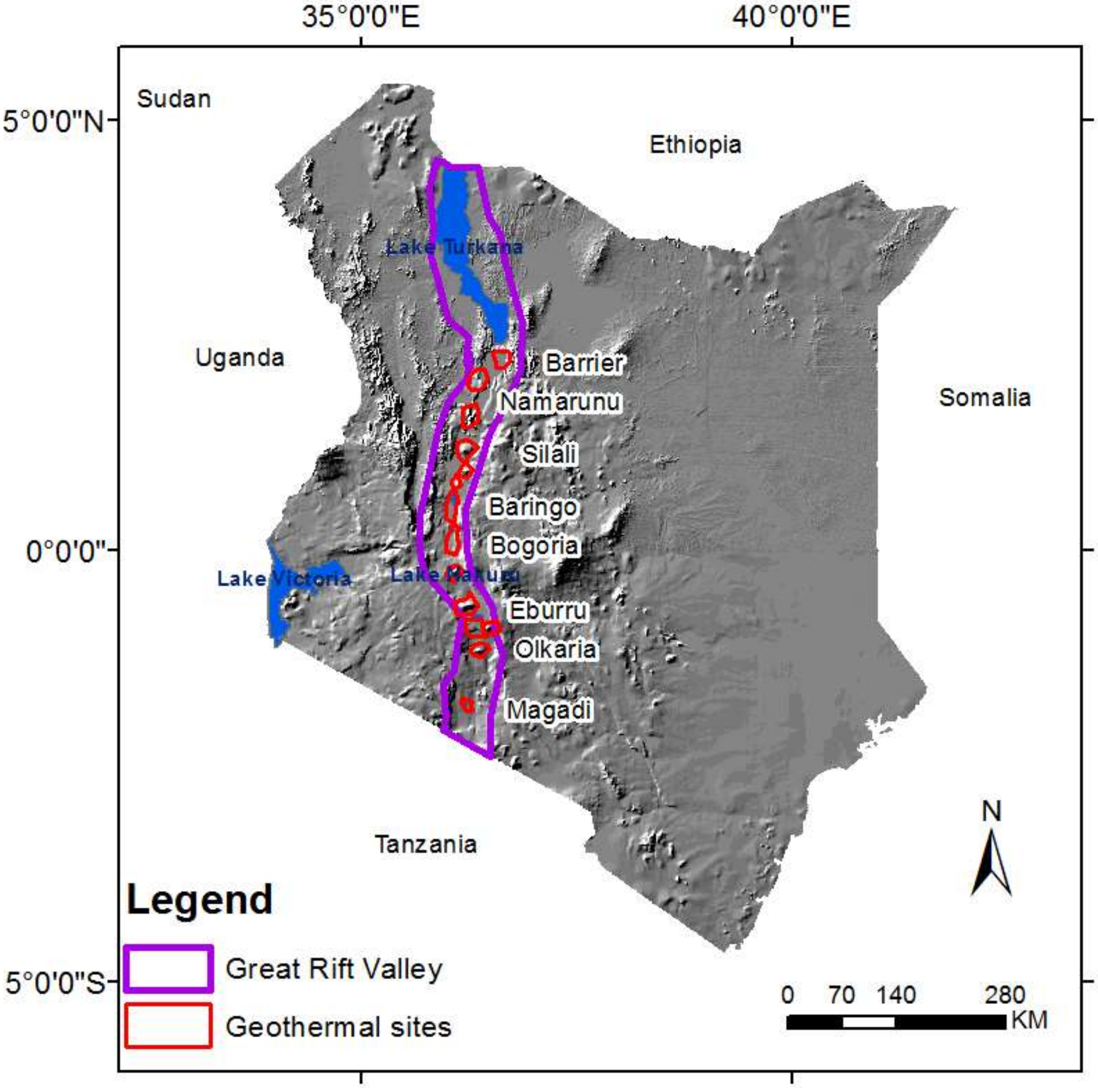

Figure 1. Kenya geothermal sites.

Figure 2. Hotspring at L. Bogoria (a) and Geothermal grass at Olkaria (b).

Table 2. Geophysical methods for geothermal exploration.

Geophysics methods		**Strength**	**Limitations**	**Indicator and unit of measure**
Direct methods				
Electrical methods DC resistivity – direct method	Depth sounding (Schlumberger)	Resistivity provides information on ground conductivity (Sircar et al., 2015)	Affected by changes in surface relief and lateral changes in resistivity. (Mariita, 2010)	Electrical resistivity / Conductivity. Unit of measure (Ohm-m)
	profiling	Can be used to map contaminated groundwater plumes (Mariita, 2010)	Depth limitation. Resistivity profiling is slower and more expensive than EM surveying. (Hersir and Bjornsson,1991)	
Electrical methods AC-resistivity- direct method	Transient electromagnetic (TEM)	Non-invasive, rapid and economical, making them well-suited for hydro-geologic studies. Expensive (Domra Kana et al., 2015.)	Controlled source of energy. Measurements are affected by utilities and metals. When used to detect fracture it may be affected by thickness, soil conductivity expensive (Domra Kana et al., 2015)	Electrical resistivity / Conductivity. Unit of measure (Ohm-m)
	Audio-frequency MT (AMT) and Magnetotelluric (MT).	Great depth of penetration to the surface. Natural source of energy used in the diagnosis of low-resistance zones under layers with strong seismic wave energy screening. AMT acquisition is faster than traditional MT(Sircar et al., 2015; Lichoro et al., 2017)	AMT frequency band is limited to the audio range. Signal availability depends on the season, time of day, and weather. Data quality may be affected by power lines and other features expensive (Kana et al., 2015.)	
Thermal methods	Heat flow	Direct measurement of temperature is done leading to better correlation of with properties of geothermal systems (Hersir&Bjornsson, 1991). The rate of heat transfer depends on the temperature gradient and thermal conductivity of the material	Requires drilling of shallow or slim holes which is fairly expensive (Domra Kana et al., 2015.)	Thermal conductivity. Unit of measure is Watts/Meter Kelvin (W/mK)
Indirect methods				
Gravity method- indirect method		Where seismic refraction is limited, gravity could be used in mapping bedrock topography under a landfill. Map lateral lithologic changes, and faults. Useful for shallow reservoirs (Mariita, 2010; Hersir and Bjornsson,1991)	Detectability varies with target size, depth and density contrast Interpretation of data often requires ancillary data from other sources like drilling (Mariita 2010; Hersir&Bjornsson, 1991).	Rock density. Unit of measure is Milligals or gravity unit (1 mGal =10 g.u.)
Magnetic method	Induced Magnetizitation and permanent magnetization	Useful for identifying infrastructure hazardous to drilling or excavation. Can delineate hydrogeology features (Mariita, 2010)	Does not give good resolution for deep targets. (Mariita, 2010)	Magnetic susceptibility Unit of measure is nanoteslas (nT), or gammas
Seismic method	wave velocity, seismicity incombination with geological structures	Used to detect lateral and vertical variations in velocity. Maps stratigraphic units (Mariita, 2010).	Depth penetration not high and its difficult to interpret the large quantity of data collected. Not cost effective (DomraKana et al., 2015.)	Wave velocity (V)and density of rock (ρ).Unit of measure is meters/second, (m/s)

exploration as being very useful in detecting geothermal anomalies. They rank the thermal and electrical methods as the best in comparison to seismic, magnetic and gravimetric, though a combination of different methods is recommended. However, they note that all geophysical methods are expensive but powerful tools in geothermal exploration. Detailed discussions on geophysical methods for geothermal exploration have been done by Aretouyap et al. (2016), Domra Kana et al. (2015), Wanjohi (2012), Mariita (2010), Hersir and Bjornsson (1991), and Abiye and Tigistu (2008).

Geochemical methods

Geochemical sampling and chemical analysis provide information used to:

(1) Delineate geothermal fields
(2) Locate aquifers, and
(3) Site wells.

The geochemist looks for parameters that would give an indication of trace of geothermal fluids and prediction of subsurface temperature. Trace of metal in the fluid such as Mercury and Lithium could be an indicator of geothermal area s (Bowen, 1989).

Borehole and springs chemical properties that are measured are temperature, pH, total dissolved solids (TDS), Carbon dioxide (CO_2), sulphates (SO_4), Chloride (Cl), Fluoride (F), Hydrogen (H_2)Sodium (Na), Silica (SiO_2), Randon gas (Rn-222) among others (Libbey and Williams-Jones, 2016; Mwangi, 2013; Pürschel, 2013; Karingithi and Opondo, 2012; Bowen, 1989). There are three main steps in geochemical processes:

Table 3. Geochemical methods for geothermal exploration.

Geochemical analysis	Strengths	Limitations	Indicator and unit of measure(ppm)
Sampling and chemical analysis of hot water springs. Water is collected from natural springs or drilled boreholes	Determination of properties of subsurface water from the chemical composition of water which has been collected at the earth's surface(Pürschel 2013)	Require uncontaminated tools during sampling (Bowen, 1989; Karingithi and Opondo,2012)	Hydrogen sulphide (H_2S), Carbon Dioxide (CO_2), pH, Conductivity, and total dissolved solids (TDS), Chloride (Cl) and Fluoride (F), Silica (SiO_2), sulphates (SO_4)
Fumarole steam and condensate sampling	Can be used to compute reservoir temperature at depth (Mwangi, 2013; Libbey and Williams-Jones, 2016)	Require different analysis techniques in order to get good results (Bowen, 1989)	Hydrogen, Oxygen, Nitrogen and Methane
Soil gas survey (for Rn-222, CO_2 and temperature)	Indicators of permeability and possible location of reservoir. (Pürschel 2013)	Interferences due to different sources(Mwangi, 2013; Karingithi& Opondo,2012)	CO_2, Radon-222 and Radon – 220, Temperature (°C)

(1) Sampling - care should be taken to avoid contamination of the samples
(2) Analysis- Isotopic analyses, enthalpy of the different fluids, and
(3) Interpretation of data.

Where geothermal reservoirs have relatively high permeability and rather long residence times for fluid water, water and rock should attain chemical equilibrium if the temperatures exceed 200°C (Bowen, 1989). Chemical geothermometers are used to determine subsurface conditions. Increase in Carbon Dioxide level indicates increase in reservoir temperature (Pürschel, 2013). Table 3 lists the various geochemical analysis methods. Examples of geochemical analysis of three fumaroles in Suswa are shown in Table 4.

Geological mapping

Geological analyses involve mapping parameters such as geological structures, volcanic centers and intrusive, geothermal manifestation, drainage pattern and rock type by either using geological maps or field visits. Geological maps provide information on distribution of rocks at surface, stratigraphy, geological structure which is useful in mapping geothermal potential areas. Figure 3 shows geological map of part of Kenya rift valley from Menengai to Suswa.

During the field visits, areas which give good exposure of outcrops and structures are located by making traverses across the geological grain (Bowen, 1989). Table 5 shows the various geological analyses methods.

Environmental baseline studies

Environmental baseline studies outline existing environmental conditions to understand changes that may occur after proposed development like geothermal harvesting. The main aims of the environmental studies are to check

(1) Compliance with regulatory requirements
(2) Sustainable development and environmental impacts
(3) Implementation of monitoring, mitigation
(4) Biodiversity conservation
(5) Preservation of endangered species
(6) Community development projects and
(7) Safety.

Table 6 lists the various environmental indices that are associated with geothermal harvest.

DISCUSSION

Application of GIS and RS in deriving geothermal indicators

Many geoscientists have used RS data for mapping geothermal indicators since the advent of the technology. Remote sensing and GIS have been used to manage different geo scientific datasets associated with geothermal exploration (Knox-Robinson and Wyborn, 1997; Noorollahi et al., 2008; Prol-Ledesma, 2000).

In Russia, GIS has been used to integrate data on geothermal power plant location and characteristics of geothermal fields. The data has been shared publicly to enable users to carry out preliminary assessments of the geothermal potential areas (Teterina et al., 2015).

Calvin et al. (2002) have combined optical, near-infrared and thermal infrared imagery to identify geothermal resources and map geologic structures based on their surface expression. They used both multispectral (ASTER, MASTER)

Table 4. Geochemical results of Suswa fumaroles. Data courtesy of KenGEn, GDC, UNU 2012.

Condensate; component concentrations in ppm			
Suswa	**f2**	**f3**	**f4**
Outlet Temp (°C)	92	92	88
pH/20(°C)	5.8	6.1	5.12
SiO_2	0.67	1.08	0.85
Na	3.31	1.83	-
K	0.68	1.22	0.71
Li	<0.01	<0.01	<0.01
Ca	0.59	0.93	2.61
Mg	<0.001	<0.001	0.13
NH_3	0.6	0.3	2.5
SO_4	0.21	0.82	0.12
Cl	2.28	3.5	0.63
F	<0.01	<0.1	<0.01
B	0.02	0.08	<0.01

Table 5. Geological analysis.

Geological analysis	Indicator
Rock samples	Record porosity and permeability, weathering patterns, depositional or magmatic flow feature (Kandie, 2012; Njue, 2012)
Structural	Faults: Extent, trend, location, displacement, a fault gouge; Folds: Dip, strike deformation, orientation of grains; Joints: Attitude, size, open or closed, alignment (Norini et al., 2015; Omenda, 1998)
Sedimentary terrain	The geologist maps depositional structures such as bedding planes, cross bending, fossil contents, unconformities, grain size and type, turbidity currents among others (Kandie, 2012)
Volcanic terrain	Lava flow surface patterns should be mapped as well as colour and mineral composition, nature of the lava flow and thickness, presence of the intrusive and pyroclastic rocks composition, size of the clasts and thickness of the beds (Stelling et al., 2016)
Metamorphic terrain	Foliation planes, colour and mineral composition, nature and grade of metamorphism, microstructures such micro folds should be noted (Calvin et al, 2015)
Hydrothermal deposits and features	Areas with silica sinter, travertine, metallic deposits, sulphides are geothermal manifestation areas. Craters if visible; their sizes, orientation, location, depth,and shape. Nature of the erupted products; distribution, composition, thickness, shape of clasts, altered materials. Age and frequency of eruptions by use of tephrochronology. Surface alteration and stunted vegetation (Eldosouky et al., 2017; Neale et al., 2016)

and hyperspectral (HyMap, AVIRIS and SEBASS) data sets with field-based geologic maps to determine thermal anomalies. Pickles et al. (2001) used geobotanical hyperspectral airborne remote sensing to improve detection of geothermal anomalies. ASTER has been used to map Silica in La Pacana caldera (der Meer et al., 2014). Multispectral remote sensing have been used to map broad cases of surface minerals while hyperspectral optical remote sensing has been used to map surface mineralogy according to der Meer et al., (2012).

Other researchers have shown a negative correlation between the vegetation stress and changes of plant properties such as reduction in chlorophyll due to increase in ground temperatures could indicate geothermal anomalies and can be mapped using infrared bands (Haselwimmer and Prakash, 2013).

Thermal imagery has been used to assist exploration of geothermal prospects because the tone of the imagery shows the surface radiance temperature (Prakash et al., 1995). Thermal Infra-Red (TIR) remote sensing has been successfully used in geothermal exploration in the past (Babita and Sailesh, 2012; Zhou, 1998; Qin et al., 2011; Prakash et al., 1995).

Land Surface Temperature (LST) from Landsat-7 Enhanced Thematic Mapper Plus (ETM+) sensor has proved to be useful in geothermal exploration when combined with good understanding of geothermal mechanism of the area. LST has been integrated with

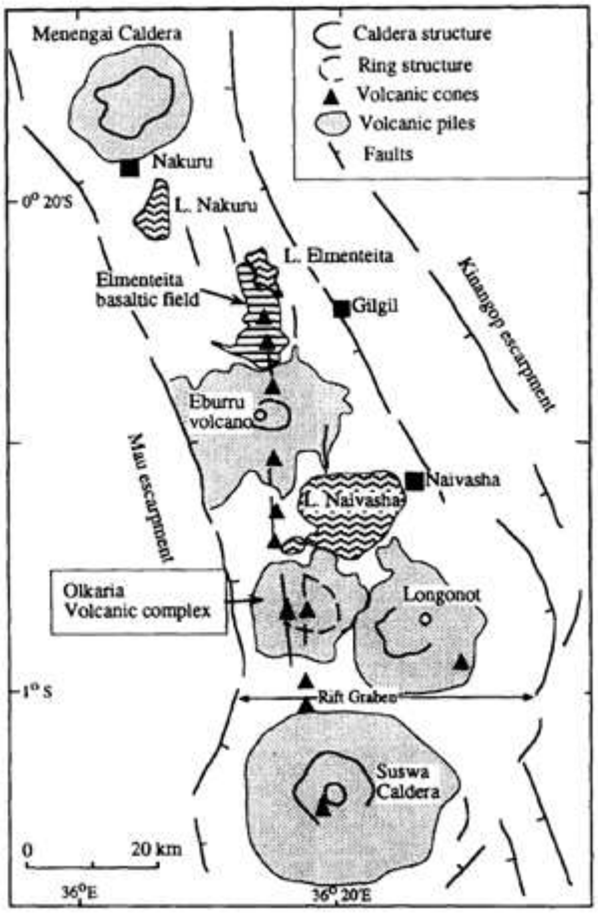

Figure 3. Geological map of segment of the Kenya rift valley (Source: Omenda, 1998).

Table 6. Environmental indices associated with geothermal harvest.

Environmental baseline studies	Indicators mapped
Physical	Soil erosion, noise, visual impairments
Chemical	Chemical discharge from waste brine, non-condensable gases
Biological	Loss of sensitive habitats and interference with animal migration routes
Socio-economic	Provision of employment opportunities and constraints on available social amenities

geological analysis, geochemical, geophysics and suitability models for determination of geothermal potential areas (Qin et al., 2011; Siahaan et al., 2011; Elizabeth and Calvin, 2009).

Landsat has been shown to compute geothermal heat flux (GHF) and the results correlate well with ground data by different researchers (Savage et al., 2010; Watson et al., 2008). Unmanned Aerial Vehicle (UAV) based photogrammetric techniques have been used to map geological faults using data of rock surfaces by Vasuki, et al., (2014).

In their research, Coolbaugh et al. (2007) observed that some dark areas re-emit larger amounts of solar radiation than bright surfaces thus resulting in high terrestrial emittance that show false geothermal anomalies, thus recommends for topographic correction and effects of albedo.

In Kenya, Airborne Laser Scanning has been used at Menengai for an area of about 2000km^2 resulting into 6,236 raw images. The images having the accuracy of 3m were used to map geothermal anomalies. LST was generated and integrated to DEM and geological analysis for the conceptual model. It was noted that for small area surface manifestations (mud pools, hot springs), the

Table 7. Summary of GIS and remote sensing techniques used to map geothermal indicators.

Remote sensing imagery	Indicator measured	Strength	Limitation
A combination of compact airborne spectrographic imager Canadian (CASI-hyperspectral), airborn TM and Light Detection and Ranging LIDAR	Gaseous emissions, carbon dioxide (CO_2) (Bateson et al., 2008)	Success rate was 39%	The method located only some vents but not all
DEM, Synthetic aperture radar (SAR) and LIDAR	Structural analysis (Wang et al., 2017); Land surface deformation (Carnec and Delacourt, 2000; Heimlich et al., 2015)	Permanent day-and-night operability, overcoming the limitations due to the inaccessibility of the sites which prohibit reconnaissance work.	Require integration of other datasets.
Unmanned aerial vehicles (UAVs) based photogrammetric data	Structural analysis- (Vasuki et al., 2014; van der Meer et al., 2012)	79.8% success compared to other field methods. Useful in inaccessible or hazardous sites.	The algorithm to extract data should be chosen well
Combined multispectral and hyperspectral data. AVIRIS+ASTER+HyMap	Mineral mapping- hydroxyl and iron-oxide (Wang et al., 2017)	Different imageries reveal variety of minerals	Hyperspectral data is expensive and maybe be unavailable
ASTER	Silica anomaly and altered rocks-(Tayebi et al.,2014; Ulusoy, 2016; van der Meer et al., 2014; Wang et al., 2017)	Best to maps minerals that spread over a range of about 10 m^2	For better results require day and night imagery.
Hyperspectral; Spatially enhanced broadband array spectrograph (SEBASS)	Silicate and sulphate minerals (Reath and Ramsey, 2013; Vaughan t al., 2003; Aslett, 2010)	Improves mineral mapping compared to VNIR/SWIR	Require mineral library data for matching the spectra
Landsat 8	Hydrothermal alterations (Eldosouky et al., 2017); Monitoring hydrothermal systems (Neale et al., 2016)	Low cost and good results for larger areas.	Require additional data such as geology
ASTER, TIR- Landsat,MODIS, Airborne TIR	Temperature (Coolbaugh et al., 2007; Qin et al., 2011; Ulusoy, 2016; Vaughan et al., 2012); Heat flow from hot springs (Haselwimmer et al., 2013) SiO2	When corrected for albedo and solar radiation, shows anomalous area	Topographic correction is needed where there steep slopes

overall temperature was reducing, hence, 3 m pixel covering an 80°C hot vent of 50 cm^2 size shows an overall temperature value of 20.25°C in 10°C surface temperature environment (Mutua, 2012).

Although airborne survey gives better accuracy, TIR from Landsat provides a cost-effective technique. GIS based MCDA has been used to show high geothermal potential area by classifying different datasets in Afyonkarahisar (Yalcin and Gul, 2017). Also, Sadeghi andKhalajmasoumi (2015) have demonstrated that combination of different GIS analysis techniques is useful in combining different datasets. They combined fuzzy logic and binary index overlay to reveal geothermal potential areas. There is a wealth of literature on how remote sensing imagery and GIS integration has been used to map geothermal indicators by different researches as indicated in Table 7.

Cost analysis on exploration methods; case study Olkaria field in Kenya

Both satellite data processing and ground measurements can be used as reconnaissance tools. The costs associated with these activities are dependent on many factors, the main ones being:

(1) The cost of the satellite data
(2) Size of the area
(3) The number of measurements planned
(4) Terrain
(5) Whether using in-house staff or consultancy
(6) Methodology used
(7) Cost on hire of equipment
(8) Expenses on personnel allowances including professional fee and transport.

In comparing the relative costs on using either remote sensed data or ground measurements, the following assumptions are made use of. The assumptions used in this analysis are:

Table 8. Cost analysis for ground exploration and remote sensing/ GIS methods.

Activity	Geology, geochemistry, geophysics and EIA exploration cost	Remote sensing and GIS exploration cost
	Total (Ksh)	Total (Ksh)
Phase 1: Logistical survey in Olkaria	180.000	180.000
Phase 2: Desktop Study	150.000	150.000
Phase 3: Reconnaissance		
Geochemical water analysis (6): Lab cost	24.000	-
Purchase of consumables, for example, batteries, internet	50.000	20.000
Equipment hire	4.500.000	-
Data analysis and report preparation	50.000	50.000
Salary/professional fee for personnel/casual labour	19.500.000	2.250.000
Transportation hire for Equipment and personnel	3.360.000	-
Ground truth, hiring of GPS	-	210.000
Phase 4: Technical review	340,000	340.000
Administrative costs and contingency	9,400,000	7.000.000
Total	37,554,000	10.200.000

(1) The ground work measurements will be hired out to a consultant
(2) The methodologies to be employed are geology, geochemistry, geophysics and EIA
(3) Area of coverage is about 200 Km^2
(4) Specific activities are data collection, analysis, report writing and review meetings
(5) The client will reimburse, all the cost expenses, on transport and equipment hire
(6) Satellite imagery used was Landsat 7 ETM+ and ASTER Digital Elevation Model.
(7) The exploration period is one month when all resources are available at cost.

The budget (Table 8) is based on experience and information from industry. KenGen's Olkaria geothermal field is used as an example. This is because much of KenGen's 204 Km^2 concession area is already developed and has data collected both remotely and on the ground.

In terms of development Olkaria can be divided into two parts on the basis of knowledge on the underlying resources. The best known (heavily explored) parts are the Northeast, Eastern and Domes sectors, where the existence of an exploitable resource has been confirmed by extensive drilling and long-term utilization and where comprehensive information is available on the nature and production capacity of the geothermal system.

The second part includes the less explored parts (to the west, south and south west) where drilling has been much more limited but has indirect indications of the existence of an exploitable resource and hence the field may be expanded in those directions (Table 8).

The budget is an indicative of the expected expenses. Comparing the two reconnaissance tools, that is, using remote sensed data and data collection on the ground, the large price difference is obvious. Ground data collection method is three times expensive as compared to the remote sensing methodology.

However, groundwork efforts do have an advantage over remote sensed data analysis, in that ground data is actual data as measured and not inferred from a processing technique commonly applied on remote sensed data. Further, ground surveys give opportunities for some type of data collection which satellite measurements cannot do, for example, determination of chemical parameter of geothermal fluids, physical properties of rocks and depth to reservoirs.

Nevertheless, an overriding advantage of remote sensed data use as an exploration tool lies in its coverage, availability and freely available for download. One can analyse data over a large area with minimal logistical challenges, such as seeking permission from land owners. Satellite data can show volcanic centres, heat anomalies, structures, land cover and other features of significance to geothermal energy exploration.

Satellite data processing tools allow 2D and 3D data analysis, and have the ability to integrate other mapping software which interacts with the GIS software allowing easy investigation of data quality, facilitates the understanding of complex structural geometry, and simultaneously visualizes multiple 3D models. It can also allow overlaying of many components or layers for better interpretation.

Conclusion

In this study, an in-depth review of the various methods that have been used in geothermal exploration has been given. For each of these methods, the specific indicators investigated and the respective strengths of the methods have been discussed. The benefits of using these methods have been alluded to and the intention of the paper that of putting together in one resource the various approaches that can be used in the efficient identification of suitable sites for geothermal exploitation.

Africa has a great potential of geothermal resources along the East African Rift System (EARS) which remains largely undeveloped. Although Kenya and Ethiopia are taking the lead in geothermal harvesting in Africa, other countries such as Democratic Republic of Congo, Djibouti, Eritrea, Madagascar, Malawi, Mozambique Rwanda, Tanzania, Uganda, and Zambia which are along the EARS could employ the cost effective exploitation methods (Kiplagat et al., 2011).

Many African countries have not exploited geothermal energy because of the relatively high cost and long-term commitment required so as to make returns according to Domra Kana (2015) drawing on the strengths of GIS and remote sensing in allowing the cost effective identification and siting of geothermal exploitation plants. When good exploration is done using remote sensing and GIS, then other detailed geoscientific (geophysical, geochemical and geologic) methods could follow, helping pinpoint accurately on where drilling and exploitation can take place in the prospect area. Integrating different methods is important as well as cost efficiency because certain parameters have different significance.

Therefore, a multidisciplinary approach integrating different methods is recommended. In summary remote sensing and GIS technology has contributed in deriving geothermal anomalies and providing data integration and analysis platform that leads to reveal new information. This review paper has shown through the various cases refereed, the application of these techniques, and the parameters that can be mapped giving researchers an opportunity to map and integrate with other scientific datasets, all geared towards efficient and cost effective exploitation of geothermal resources.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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