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GIS-Aided Prediction of H_2S Emission Dispersion from Geothermal Power Production for the Menengai Geothermal Power Project

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ABSTRACT

In an effort to decrease reliance on carbon based energy, power production from geothermal sources is increasing in countries with the resource such as Kenya. This owes to its clean and relatively sustainable production cycle compared to fossil fuels. Its development however has some environmental impacts, with air pollution especially from hydrogen sulphide emissions being key. These impacts if foreseen early can be prevented or mitigated. This paper presents the results of a study conducted to develop prediction modeling of H_2S dispersion in the surrounding atmosphere from a planned 105 MWe geothermal power plant at the Menengai geothermal field, Kenya. A GIS-aided prediction of gas dispersion is used to envisage future concentrations of environmental emissions on a range of geographic scales. Key parameters used in control of the dispersion type for the gas and its average removal rate including meteorological conditions such as wind direction, wind speed, precipitation, atmospheric stability, relative humidity, and surface roughness and topography are used. Geographical Information System (GIS) aptitudes were run for quality visualization of the model outputs and presentation of an accurate numerical model of the study area. Results showed that the area is dominated by SSE and NNW winds and thus long term air quality impacts will be expected as most significant to the NNW and SSE of the proposed power plants. Further, the concentration trends after power production will be lower than in the pre-development phase, all indicating that the H_2S concentrations will be within acceptable OSHA limits. Nonetheless, routine air quality monitoring within the project area is emphasized.

1. INTRODUCTION.

Geothermal energy is clean compared to fossil and nuclear power sources. It uses the earth's interior heat rather than combustible fuels and therefore emits very little gas pollutants like CO_2 and H_2S.This has led to its increased utilization in the world and has largely contributed to reduction of greenhouse gas emissions (Bloomfield et al., 2003). It is for this reasons that geothermal energy is rapidly gaining momentum in many parts of the world endowed with the resource.

Kenya is the first country in Sub-Saharan Africa to tap power from the Earth's crust in a significant fashion (Karekezi and Kithyoma, 2003). Kenya has a huge geothermal resources potential located in the Rift that has not been exploited fully. Recent studies of geothermal explorations revealed that the geothermal potential in the rift exceeds 7,000 megawatts of electricity (MWe) (Simiyu, 2008). This could meet all of Kenya's electricity needs over the next 20 years (Simiyu, 2010), with a power-demand growth estimated at 8% annually. Among the existing geothermal prospects in the Kenyan Rift, Olkaria and Menengai have been explored and developed.

As much as geothermal energy is green energy studies have revealed that its development has some effects on the atmospheric environment. These are mainly due to non-condensable gases consisting of carbon dioxide ($C0_2$) and hydrogen Sulphide (H_2S).

Among all non-condensable gases emitted due to geothermal exploitation, H_2S has the greatest environmental concern not only because of its noxious smell in low concentrations but also due to its toxicity and health impacts at high concentrations, and its tendency to concentrate in hollows and low-lying areas due to its high density (Kristmannsdóttir et al., 2000).

As a way of determining environmental impacts associated with hydrogen sulphide, various modelling techniques have been employed in distinct parts of the world such as in Mexico (Gallegos-Ortega et al., 2000) and Iceland (Nyagah, 2006) among others. This study focuses on predicting H_2S dispersion from a proposed 105 MWe power plant at Menengai field. In these studies, various meteorological conditions and potential emissions were used to prepare predicted dispersion model of H_2S concentrations and defined the areas to be impacted.

AERMOD (AMS/EPA Regulatory Model) was used for H_2S dispersion modelling in the Menengai area. This model is a Gaussian diffusion model designed for two emission categories, continuous (steady-state) or instantaneous (transient). In steady state releases, source characteristics do not vary with time and the release duration is long.

AERMOD is an AERMIC Model, where AERMIC is the American Meteorological Society/EPA (Environmental Protection Agency) Regulatory Model Improvement Committee. This Model was developed in 1995. According to (Bluett, Gimson et al. 2004), the United States Environmental Protection Agency reviewed it in 1998 and endorsed it as the most suitable replacement for the Industrial Source Complex Short Term Model (ISC-ST3) in 2000.

Geothermal power plants release a variety of gaseous to the atmosphere. CO_2, H_2S, NH_3, CH_4, Rn, Hg, H_3BO_3 and As are the most important pollutants of the environment with the principal gases being H_2S and $C0_2$.The other gases are not likely to have a significant adverse effect on the surrounding environment. Contaminant non-condensable gas concentration in the exhausted gas and steam will depend on the steam chemistry, power plant technology and the ambient air quality.

In this study to evaluate the impacts of H_2S on the environment, the following three specific objectives were addressed in Menengai geothermal project area.

1. Analysis of pre-development atmospheric H_2S gas levels prior to establishment of power plants
2. Estimation of atmospheric H_2S gas dispersion using a numerical model
3. Combination of the pre-development atmospheric H_2S gas levels with a predicted H_2S to define impacted areas.

2. STUDY AREA AND METHODOLOGY

The Menengai geothermal field is located to the North of Nakuru town in the Kenya Rift Valley at approximately $0^0$20'N latitude and 36^0E Longitude within the Menengai Caldera. The caldera is a 77 km^2 elliptical depression partially filled by young volcanic eruptives with geothermal manifestations like fumaroles evident on the surface. Immediately to the North West of this is the inferred Olrongai/Olbanita ring structures whose tectono-morphological impressions are still evident despite heavy cover by young Menengai eruptives (Mbia 2015).

The project area lies within the Menengai forest reserve and there are no human settlements. The closest population centres are situated approximately 5 km away from the caldera and comprise of Olrongai, Olbanita, Kwa Gitau, Wanyororo, Kiamunyi and Kabarak communities. Geothermal development activities started in 2010 at the project area and to-date over 30 geothermal production wells have been drilled with advanced plans to commission 3 x 35 MWe geothermal power plants in the immediate future. Presently a steam gathering system has been completed.

Three power plants are proposed for construction north of the project area at -0.195709°S latitude and 36.055944°E longitude covering an area of about 0.0755 sq km. In this research, we constrained our study area at 125 sq km beyond the proposed power plant area (Figure 1).

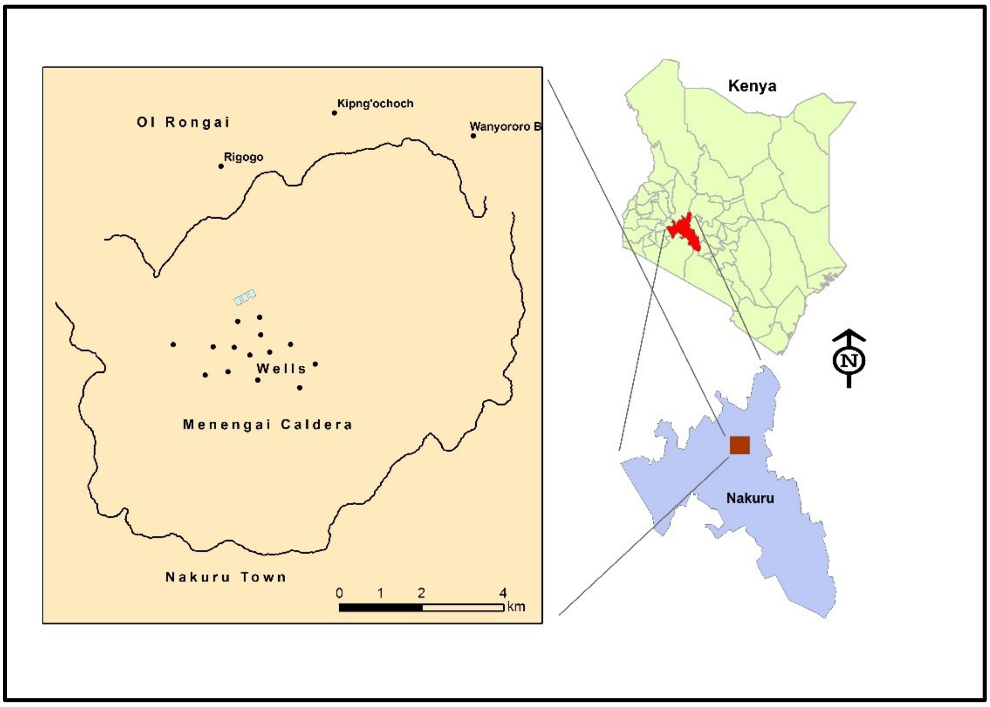

Figure 1: Location of the study area

2.1. Atmospheric Hydrogen Sulphide (H_2S) gas

H_2S is a volcanic gas that is an environmental concern universally present in geothermal fields as a pollutant. Sources of H_2S gas will include the numerous existing fumaroles and vents as well as the power plant. The power plant will emit larger quantities that might be experienced naturally, and its impact on the environment will largely depend on its dispersion which is highly influenced by local topography and meteorological parameters such as wind speed, precipitation, and wind direction amongst others. Its documented health effects include respiratory distress, eye irritation and foul smell at low concentrations (Chambers and Johnson, 2009). The rotten egg smell disappears at high concentrations of about 150 ppm. Extensive and continuous monitoring of H_2S is therefore required in any geothermal field. The data will form key input for numerical models significant in predicting the effects of the gas over a large geographical area, vital in the design of mitigation measures.

2.2. H_2S gas dispersion models

Several dispersion models have been developed over the years by different agencies like U.S. Environmental Protection Agency (EPA). The AMS/EPA Regulatory Model (AERMOD) is a steady-state Gaussian plume model that can be used to evaluate emission concentration from a point source at ground level (Lakes Environmental 2019). The pollution mapping section of AERMOD has capabilities of performing gas dispersion calculations to predict the level of concentration of the gas downwind from a point source using wind speed, wind direction, gas flow rate, terrain roughness and atmospheric stability as input parameters. The terrain is classified as flat, open field or ground with elevated barriers. The model output AERMOD is a raster map of the modelled gas plume. The color variation on the map indicates the plume length estimates from the point source.

2.3. Geographical Information System (GIS) in air quality management.

Models allow for prediction and simulation of future conditions both in space and in time. They are built to enable understanding and ultimately manage a sustainable environmental system. In the modern world GIS is an important tool necessary for sustainable development. Sustainability implies maintaining components of the natural environment over time (such as air quality), while simultaneously maintaining (or improving) human welfare. Many alternative definitions of GIS have been suggested, but a simple definition is that a GIS is a computer-based system for the capture, storage, retrieval, analysis and display of spatial data (USGS 1997). GIS are differentiated from other spatially related systems by their analytical capacity, thus making it possible to perform modelling operations on the spatial data. In air quality modeling GIS is utilized in the development of geospatial air quality models, locating of gas monitoring stations and effective visualization of model outputs. This study utilizes ESRI's ArcMap 10.6 GIS application for the quality mapping and analyzing of H_2S dispersion because of its analytical capabilities.

2.4. Gaussian diffusion equation.

The steady-State Gaussian plume for continuous elevated source equation was used in this study. The AERMOD software was used to key in the parameters for each source and each hour. The origin of the source's coordinate system was placed at ground surface at the base of the stack. The X-axis is positive in the downwind direction; the axis is crosswind (normal) to the Y-axis and the Z-axis extends vertically. The fixed receptor locations are converted to each source's co-ordinate System for each hourly concentration calculation. The hourly concentration that was calculated for each source at each receptor is summed up to obtain the total concentration produced at each receptor by the combined source emissions. For the steady-state Gaussian plume, the hourly concentration at downwind distance X (m) and crosswind distance Y (m) was given by;

$$C = \frac{QKVD}{2\pi U_S \sigma_y \sigma_Z} \times \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \quad (1)$$

where;

Q=Pollutant emission rate,
K= Scaling coefficient, (default value for Q of 1×106 g/s and Concentration in µg/m^3),
V= Vertical term,
D= Decay term,
σ_x, σ_y= Standard deviation of lateral and Vertical concentration distribution (m), and
Us= wind speed at release height (m/s).
(Yousefi, 2008)

Cox and Sheppard (1980) and Cox and Sandalls (1974) have estimated average removal rates of hydrogen sulphide. Using an average reaction rate 5×10-12 cm^3/s and an average hydroxyl concentration of 3×10^6 molecules/m^3, an average removal rate of hydrogen sulphide was estimated to be approximately 5 % per hour. This will give an exponential decay rate of 1.425×10^{-5} s^{-1} when used in the AERMOD model. (Yousefi 2008)

2.5. Meteorological parameters

Meteorological data used in this study was collected from one automatic weather station with hourly logs installed within the project area for the period 2011 to 2015. The data was used for analysis and modeling to predict and compare the condition of ambient air before and after utilization of the proposed Menengai geothermal power plants. Statistical analysis was done to ensure that the data was of quality. The model requires two meteorological data files which must be pre-processed by the AERMET model – a component of the AEROMOD model: Surface met data file (*.SFC) and Profile met data file (*.PFL). Surface Met Data File includes hourly Wind speed, Wind direction, ambient temperature, Cloud cover (tenths). Other data set required include Surface roughness, Bowen ratio and Albedo. The upper air data (Profile met data) is the mixing layer height. AERMOD can estimate the mixing layer height from the surface data.

2.5.1 Atmospheric stability.

Dispersion of H_2S gas is dependent on a number of variables including but not limited to atmospheric stability and distance from the source. Atmospheric stability classification is required to quantify the dispersion capabilities of the ambient atmosphere (i.e. the dispersion coefficients or the standard deviation of concentration distribution in lateral and vertical directions, σ_y and σ_z, respectively) in the air quality models for concentration predictions. Several different types of stability classification schemes are given depending on the availability of meteorological parameters and the related atmospheric processes in the lower part of the boundary layer. In the present study, atmospheric stabilities are estimated based on Monin–Obukhov length, bulk and gradient Richardson numbers, temperature gradient, wind speed ratio, etc.

The Monin-Obukhov length (LMo) provides a measure of the importance of buoyancy generated by the heating of the ground and mechanical mixing generated by the frictional effect of the earth's surface. The atmospheric boundary layer constitutes the first few hundred meters of the atmosphere. During the daytime, the atmospheric boundary layer is characterized by thermal turbulence due to the heating of the earth's surface. Night times are characterized by weak vertical mixing and the prevalence of a stable layer and are normally linked with low wind speeds and less mixing. During windy and/or cloudy conditions, the atmosphere is normally neutral. The highest ground level concentrations would occur during weak wind speeds and stable (night-time/early morning) atmospheric conditions.

2.5.2 Wind patterns

Wind data collected was analyzed for the period of study, years 2011 - 2015. The dominant wind directions were SSE and NNW which means H_2S gas will be mainly dispersed towards SSE, NNW in the project area. Annual wind rose diagrams of the field are shown in Figure 2.

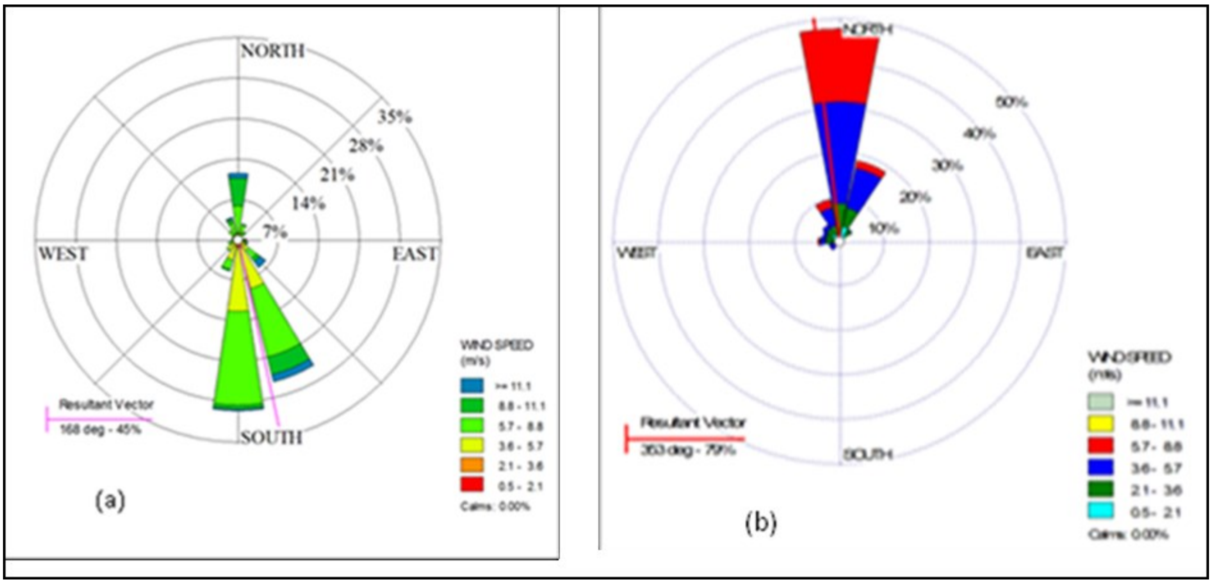

Figure 2. Wind rose diagram of prevailing winds in Menengai

2.5.3 Ambient air temperature.

Analysis of ambient air temperature variations in the study area was done for the year 2015. The graphical analysis (Figure 3) shows that temperatures are typically low in July and high between January and March.

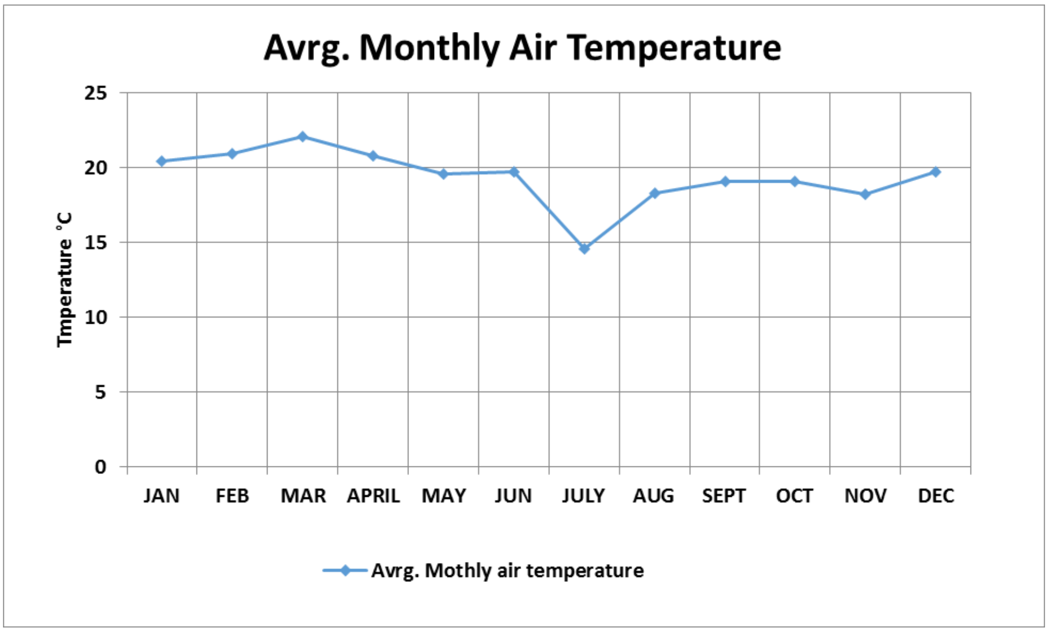

Figure 3: Annual variation of ambient air temperature at Menengai geothermal field.

2.5.4 Relative Humidity

The Relative Humidity (RH) in the study area is fairly distributed though depressed between January and March for the years 2011 - 2015. The annual average Relative Humidity is 66.5 %. Generally RH was fairly distributed in the project site. The maximum RH is in May with 79.6 % and the minimum is in January, 39.6%.

2.5.5 Rainfall

Average rainfall in the study area depicted a bimodal kind of a trend (long rainy season from March to May and short rainy season from September to December 2011 - 2015) which is typical for the East Africa region. The measurements from January 2011 to

December 2015 show that the area recorded an annual average of 635.28 mm/year. Dry season prevailed between January and March.

2.6 Pre-development atmospheric H_2S gas levels

A network of 18 sampling points was considered for H_2S gas measurements for the period 2011 to 2015. The sampling points comprised of the following: staff camp site area, materials laydown area, water tank site area (within a fumarolic area), well sites, discharging wells and the automatic weather station site located at the top of Mlima Punda hill.

H_2S air pollutant values were measured from the eighteen sampling points from January 2011 to December 2015. A hand-held Jerome® J605 gas detector with a detection range of 0.003-50 ppm was used for measurements in the stations. The sampling stations are shown in Figure 4.

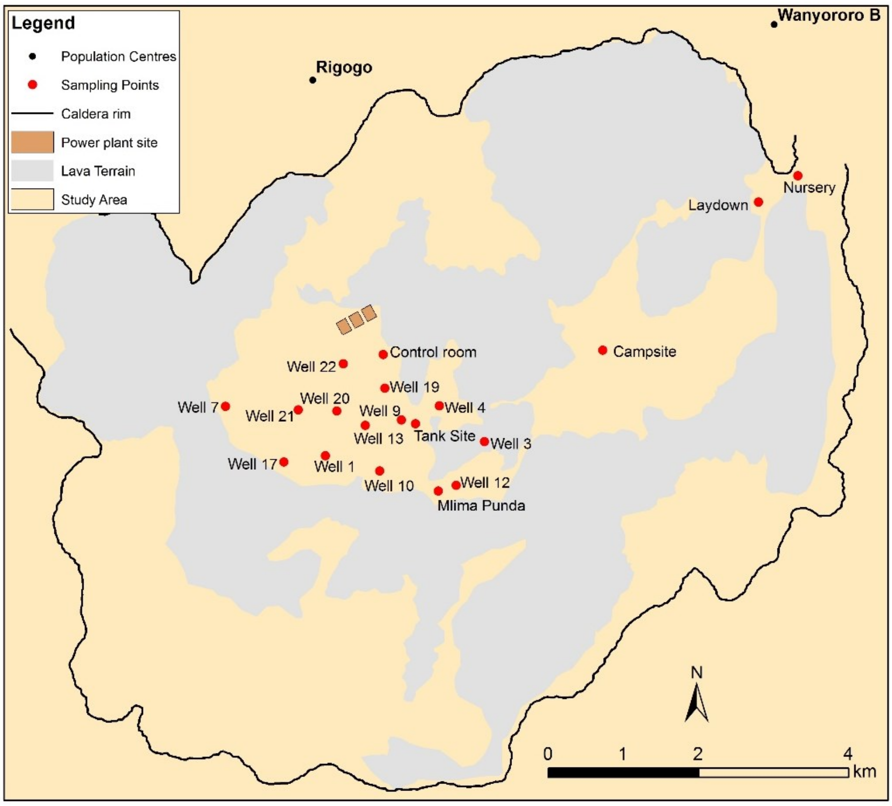

Figure 4: H_2S sampling stations

2.7 Menengai 105 mw geothermal power plant

Three independent power producers (IPPs) are scheduled to put up 3x35 MWe power plants in Menengai geothermal field. A conventional flash geothermal power plant in high-temperature liquid-dominated field would require the following key components in its system: Steam turbine, cooling towers, condensers, silencers, separators and the steam piping. H_2S and other gases will be released to the atmosphere from separators and condenser stacks. In this study the specifications of these conventional systems were applied in the H_2S prediction dispersion model as a possible pollutant point source. In the AERMOD model which is based on the Gaussian diffusion system the required emission parameters and power generation specifications were calculated assuming dispersal from a single stack. These parameters are shown in Table 1.

Table 1: Emission parameters used for modeling.

Stack parameter	Single stack
Height	30 m
Exit diameter	0.4 m
Gas exit temperature	33 °C
Gas exit velocity	13 m/s
H_2S flow	76 - 92 g/s

The steam geochemistry analysis evaluations indicate a cumulative weighted average of NCG at about 4 % of the steam which will be used for power generation (840 tons/h). Between these gases 98 % is CO_2, 1 % H_2S and 1 % others which are non-condensable at the power plants operating temperatures and pressures.

3.0 RESULTS AND DISCUSSION.

3.1 Pre-development atmospheric H_2S gas levels prior to establishment of power plants

Menengai Caldera is broadly a natural area with no industrial or any other air polluting activities in the proximity. Gases from geothermal manifestations, drilled wells and burnt fuel emissions from transportation vehicles and rig generators are the only significant air pollutants. These pollutants have been continuously monitored in the Menengai geothermal field.

The pre-development H_2S measurements were collected from 18 sampling points over the 5 years monitoring period. The collected data was used in a GIS environment to generate the pre-development dispersion model by a Gaussian interpolator (Figure 5). H_2S concentrations below detection limits (0.003 ppm) are in most areas in the study area, This was as a result of the below detection levels recorded in stations (Mlima punda, materials lay down area and staff campsite areas) that were away from drilled/discharging wells and the fumarolic areas. High values of H_2S up to 0.3 ppm are seen in the high activity area in the prospect. This was as a result of the measurements recorded around drilled and discharging wells (Wells 7, 17, 4, 3 and 21) during the well tests periods and were within the radius of 50 m around the well pad area. The concentrations were constrained around the working area where crew working are always equipped with relevant personal protective equipment and H_2S gas detectors. Dispersion from the pre-development model is constrained at the well site area at around 1.5 square kilometers and this will have no effect when the wells will be connected to the power plant for production or when shut.

Considering the threshold values of WHO (1981) and Kenya Air Quality (2014) standards, result of the measured gases show that the concentrations value of data are below the standards and therefore show that there is no air pollution related to H_2S in the study area.

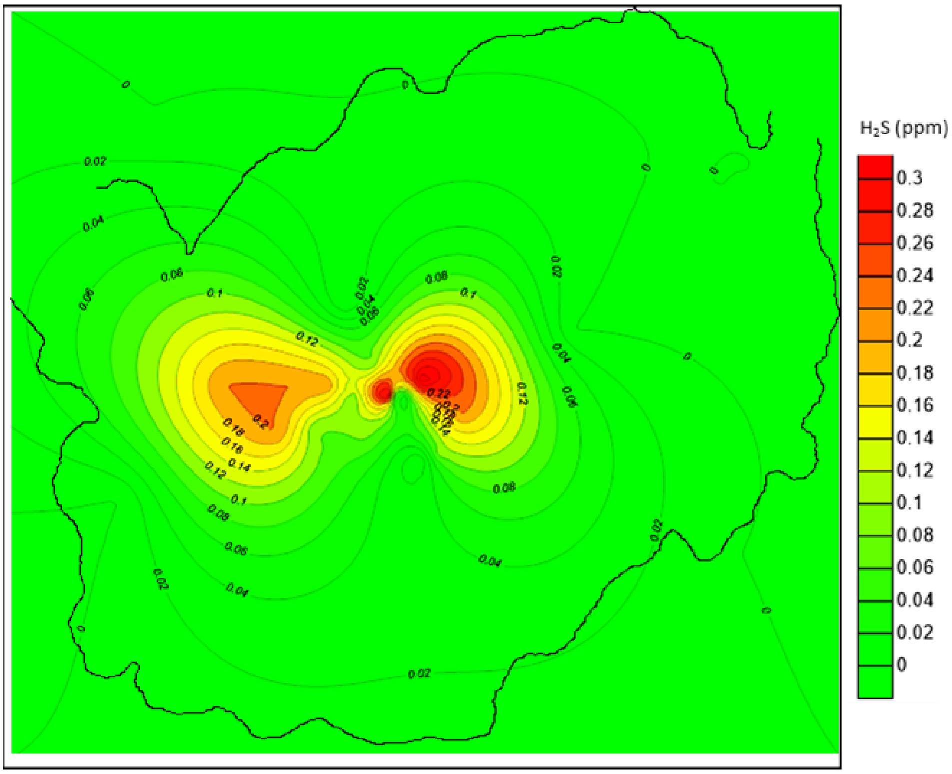

Figure 5: Pre-development dispersion model of H_2S in the ambient air of the study area

3.2 Atmospheric H_2S gas dispersion prediction model

The proposed power plant area was selected as the point pollutant source for dispersion and is located at -172245.079 m E and 9978623.72 m N in the zone 37S of the UTM coordinate system. After running the AERMOD model the results of surfer grid digital data and dispersion map for a 24 hour average (Figure 6) were transferred to a GIS environment. The data was edited and improved to achieve better visualized maps.

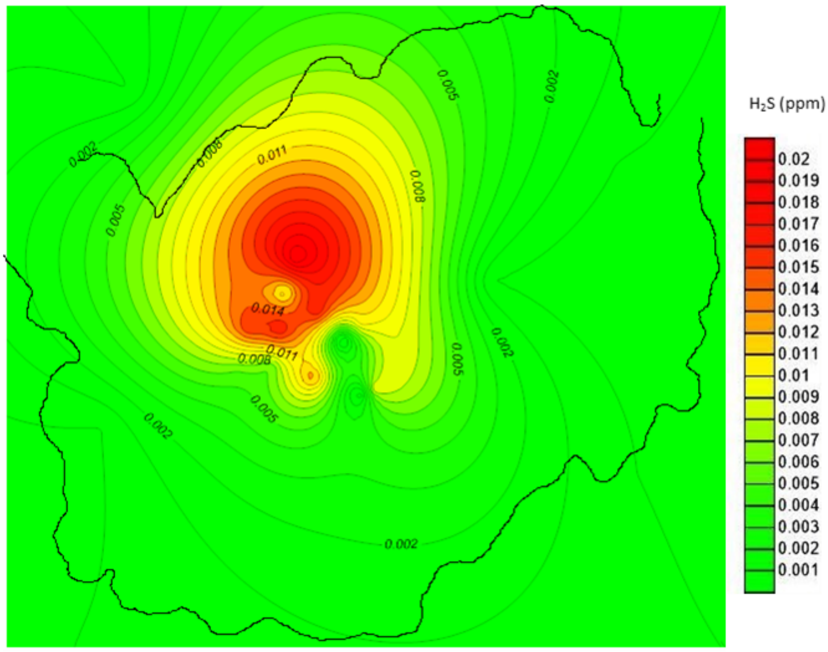

Figure 6: Twenty four hour average prediction dispersion model of H_2S from a 105 MWe power plant

The results from the model showed that dispersion from the power plant extended to a maximum distance of around 1 km from the source. Gas concentrations of 0.02 ppm occur at the source and as dispersion occurs over 24 hours a peak concentration of 0.006 ppm is achieved away from the source in the NNW direction of the study area. This was consistent to the dominant wind direction in the prospect. The 0.006 to 0.02 ppm H_2S gas concentrations are within the acceptable limits of exposure as stated by the World Health Organization WHO and the Kenya OSHA Act 2007.

WHO guidelines and standards have been adopted in many studies in Kenya. According to WHO (2000) guidelines, 24-hour average concentrations should not be permitted to exceed 0.1 ppm beyond the immediate power station boundary. The National Institute for Occupational Safety and Health (NIOSH), and the American Conference of Governmental and Industrial Hygienists (ACGIH) air quality standards for the protection of occupational health give limits of 10 ppm for H_2S in atmospheric air (Webster, 1995). Thus, in workplaces, H_2S concentrations should not exceed 10 ppm over an 8 hour period for staff working five days a week. OSHA records that the permissible exposure limit for hydrogen sulfide is 10 ppm. It also confirms that an individual should not experience a peak exposure of 50 ppm for a duration exceeding 10 minutes.

3.3 Combined pre-development atmospheric H_2S gas levels and the predicted H_2S model plus impacted areas

To predict the H_2S gas impacts from the proposed 105 MWe geothermal power plant and to delineate the area that will be impacted, the pre-development concentration dispersion model and the predicted calculated dispersion model of the study area were combined in the raster format by using the raster calculator operator in GIS. The result of this combination is shown in Figure 7. Results for the H_2S distribution prediction model show that the gases from the power plant will be transferred to the North West. The maximum concentration of H_2S will be about 0.07 ppm at the areas close to the power plant. The concentration of H_2S will be will be within the allowable exposure concentrations by the WHO standard level for ambient air quality. The impact within the study area will be very small limited to the production well sites and the power plant sites. The concentrations of H_2S in these areas will be 0.076 - 0.1 ppm which can be defined as impacted areas or areas under risk. Therefore continuous monitoring of H_2S is recommended after power plant development. The impacted area is approximately 7.1 square km which is around 5.6 % of the study area.

4.0 CONCLUSION AND RECOMMENDATION

4.1 Conclusion.

H_2S is one of the principal gases of concern in a geothermal environment. The potential flow rate of H_2S depends on the steam chemistry and the design of the geothermal power plant. The dispersion of the gas depends on the meteorological conditions such as wind directions, wind speed, precipitations, atmospheric stability and surface roughness and topography. Prediction of dispersion of the gas and areas to be affected or under risk depend on the pre-development background concentrations of the gas being modelled.

The H_2S distribution prediction model was successfully generated for the study area to predict the impacts on local air quality from the planned 105 MWe power plant in Menengai geothermal field. It was established that the emissions from the power plant do not have any significant effects on the surrounding environment, with only 5.6% of the area likely to be impacted. The flagged areas are close to the power plant and well site area. The concentrations of H_2S in the flagged areas is predicted to be 0.076 - 0.1 ppm.

4.2 Recommendation.

An elaborate and regular monitoring plan of H_2S and other gases needs to be developed and implemented

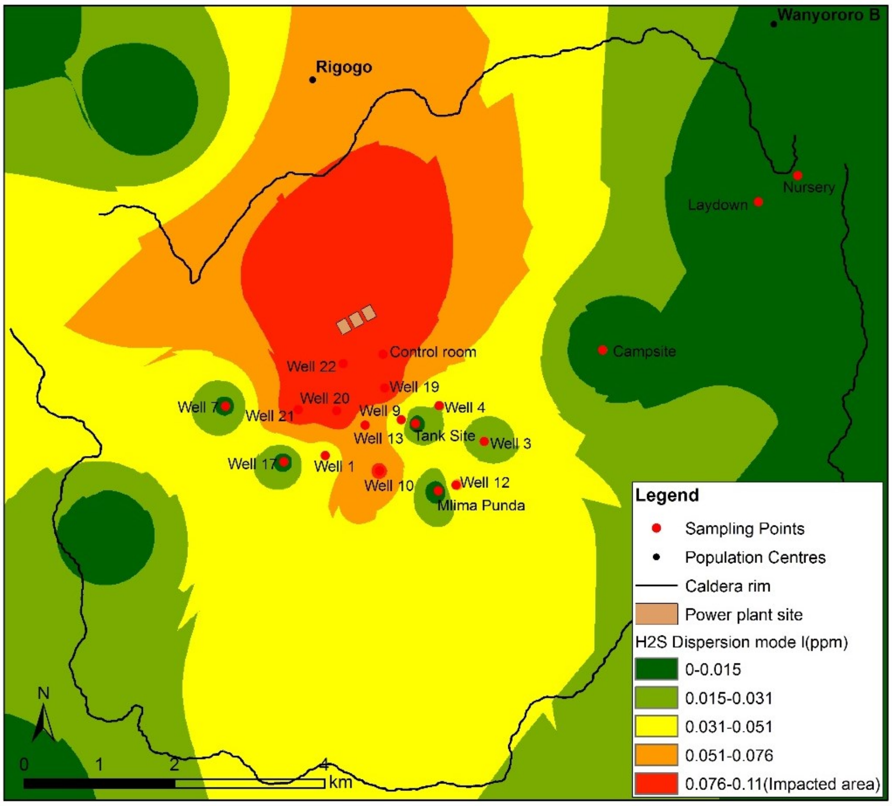

Figure 7: Final prediction dispersion model of H_2S and areas likely to be impacted.

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