

**TRANSPORT AND DISPERSION OF HYDROGEN SULPHIDE GAS IN  
THE GREATER OLKARIA GEOTHERMAL AREA,  
KENYA**

**By:**

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## **DECLARATION**

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## **ABSTRACT**

The emission of Hydrogen sulphide ( $H_2S$ ) gas during the development of geothermal resource is a significant environmental aspect of concern that must be considered in any environmental management plan. Hydrogen sulphide gas is an extremely toxic and irritating gas. This research work sought to investigate the transport and dispersion of Hydrogen sulphide gas over the Greater Olkaria Geothermal area on a diurnal scale.

The transport and dispersion of Hydrogen sulphide gas over the Greater Olkaria Geothermal area was investigated using temporal analysis, correlation analysis, spatial analysis. Temporal analysis shows that the highest concentrations of Hydrogen sulphide were obtained when winds are calm and atmospheric temperatures are low. In Olkaria geothermal area, these weather conditions exist between 2000hrs and 0600hrs local time. The study suggests that if these weather conditions persist over prolonged period, Hydrogen sulphide gas concentrations around the power plants may rise to unsafe levels with respect to human health. There is need for a continuous monitoring of  $H_2S$  gas particularly when weather conditions point towards building up of  $H_2S$  gas concentration around the power plant.

Spatial and temporal analysis affirms that fairly high concentration of  $H_2S$  gas occurred close to the source points. In all the three averaging times (1-hourly, 8-hourly and 24-hourly) considered during the modeling of transport and dispersion of Hydrogen sulphide gas, high gas concentration were noted close to emission points and disperses away with distance. It can be concluded that the transport and dispersion of  $H_2S$  gas at Olkaria geothermal field is dependent on the prevailing weather conditions.

Early recognition and detection of the concentration of  $H_2S$  gas in the atmosphere is crucial in protecting employees and people living around geothermal power plants or any active geothermal area from deadly exposures. Employees working in areas that contain or have the potential to contain  $H_2S$  gas, should learn to recognize the signs and symptoms of  $H_2S$  gas exposure, monitor and take measures to protect themselves. Information on the concentration of  $H_2S$  gas, transport and dispersion is so critical hence it should be disseminated to the public to ensure their health and safety.

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## ACRONYMS AND CHEMICAL SYMBOLS

AERMOD	American Meteorological Society/ Environmental Protection Agency Regulatory Model
AFTOX	Air Force Toxic Chemical Dispersion Model
Ar	Argon
CBL	Convective Boundary Layer
CH <sub>4</sub>	Methane
CNS	Central Nervous System
CO <sub>2</sub>	Carbon dioxide gas
EHC	Environmental Health Criteria
EMP	Environmental Management Plan
GOGA	Greater Olkaria Geothermal Area
H <sub>2</sub>	Hydrogen
H <sub>2</sub> S	Hydrogen sulphide
ISC3View	Industrial Source Complex Model
KenGen	Kenya Electricity Generating Company
MSL	Meters above Sea Level
MMS	Minerals Management Service
MWe	Megawatt of electricity
N <sub>2</sub>	Nitrogen
NCGs	Non Condensable Gases
NIOSH	National Institute for Occupational Safety and Health
PDF	Probability density function
PPB	Parts Per Billion
PPM	Parts Per Million
SBL	Stable Boundary Layer
TSP	Total Suspended Particles
WHO	World Health Organization
WMO	World Meteorological Organization
WRPLOT	Wind Rose Plot

# CHAPTER 1

## 1. INTRODUCTION

### 1.1 Background

Geothermal energy is the natural heat from the earth's interior stored in rocks and water within the earth's crust. This energy can be extracted by drilling wells to tap concentrations of steam at high pressures and at depths shallow enough to be economically justifiable. The steam from the earth's interior is then brought to the surface through pipes so as to drive turbines and generate electricity (Mariita 2002; Nyagah 2006). Though geothermal energy is considered as a clean source of energy in comparison to other sources of energy like fossil fuel, its development still has some impacts on the environment that need to be addressed that include some emission of gases and effluent water that require proper disposal (Kristmannsdóttir and Ármannsson 2003). The exploration and exploitation of this resource should be done in a way that does not have negative impacts on the environment and human life.

Generally, during the development of any given field, pollutants are mostly emitted at a higher rate to the environment than before development and this can occur at the local, regional or even global scale. Following the development of a geothermal area, gaseous sulfuric compounds that exist in the form of Hydrogen sulphide ( $H_2S$ ) and effluents are usually emitted at a higher rate into the environment than before the development (Olafsdottir and Gardarsson 2013).

One of the key environmental concerns related to the use of geothermal fluids to generate electricity is the emission of non-condensable gases to the atmosphere. Gunnarsson *et al.*, (2013) pointed out that atmospheric disposal of geothermal gases is an unavoidable part of high temperature geothermal utilization and in some case lowering these gas emissions from geothermal power plants becomes one of the important challenges of the geothermal industry.

Research work done by Nolasco (2010) noted that carbon dioxide ( $CO_2$ ) and hydrogen sulphide ( $H_2S$ ) are proportionally the highest components in geothermal non-condensable gases. This is especially seen in the vent stacks in geothermal power plants that emit non-condensable gases thus triggering concern because of their role as greenhouse gases, despite the fact that these

emissions are relatively small compared to carbon and fossil fuel plants. Among all non-condensable gases emitted due to geothermal exploitation, H<sub>2</sub>S gas has the greatest environmental concern not only because of its noxious smell at low concentrations but also due to its toxicity and health impacts at high concentrations. This gas has a tendency to concentrate in hollows and low-lying areas owing to its high density. The gas has an unpleasant smell even at very small concentrations hence it can be sensed far away from the source (Ndetei 2010; Khoirunissa 2011; Peralta *et al.*, 2013).

Most of non-condensable gases occur naturally in low (background) concentrations hence they are largely harmless. They become pollutants only when their concentrations are relatively high compared to the background value and begin to cause adverse effects (Mulaku and Kariuki 2001). These concentrations vary widely depending on the sources of pollution and their distribution, meteorological conditions and the topographical features in the vicinity. The impacts of H<sub>2</sub>S discharged will depend on local topography, wind patterns, and land use.

Hydrogen sulphide gas has both artificial and natural sources. Some of the artificial sources include emission from geothermal power stations and generators. The major natural sources of Hydrogen sulphide gas (H<sub>2</sub>S) to the atmosphere include volcanic and geothermal regions. Baldacci *et al.*, (2002) noted that though geothermal energy is considered one of the cleanest energy resources, it may be a source of various natural contaminants released into the atmosphere. D'Alessandro *et al.*, (2009) pointed out in their study that one most important environmental impact related to the use of geothermal energy is the emission of non-condensable gases that include H<sub>2</sub>S hence its environmental effects cannot be neglected, as it is often one of the main causes of the opposition to the development of geothermal energy exploitation activities

Mathematical models have been used in all aspects of air quality planning and monitoring where prediction is a major component, from episodic forecasting to long-term monitoring. Tonnesen *et.al.*, (1998) noted that models simulate the atmosphere in varying degrees of detail by mathematically representing emissions with initial and boundary concentrations of chemical species. An understanding of the atmosphere's chemistry and meteorology is combined with estimates of source emissions of the gases so as to predict possible ground-level concentrations.

Nyagah (2006) in his work pointed out that timely and reliable information gained from air quality forecasts form a basis for developing and making management decisions about environmental damage. Forecasts are very important as they provide information on real-time emission abatement strategies, facilitating the protection of the public from the associated impacts of air pollution.

## **1.2 Problem Statement**

Hydrogen sulphide ( $H_2S$ ) is one of a number of gaseous species associated with geothermal activity in the Olkaria geothermal area. The emission of Hydrogen sulphide during geothermal development is one of the significant environmental aspects that must be considered in any environmental management/monitoring plan. This is because this gas is corrosive and is known to be acutely toxic in high concentrations.

An understanding of the transport, dispersion and associated impacts of Hydrogen sulphide gas is required in many geothermal fields in Kenya. Limited studies have been done in the geothermal fields where the resource is being harnessed. This study addresses the transport and dispersion of Hydrogen sulphide gas on a short time scale (diurnal scale). This will aid in getting a deeper understanding on the behavior of  $H_2S$  gas concentrations in relation to the prevailing atmospheric conditions and their subsequent transport from their source points. This is very crucial in putting mitigation measures in place and providing an understanding especially for the personnel and the residents exposed to this sour gas during the prevailing daytime and nighttime atmospheric conditions.

## **1.3 Objective of the Study**

The main objective of this study is to investigate the transport and dispersion of Hydrogen sulphide gas over the Greater Olkaria Geothermal area, Kenya on a diurnal scale.

The specific objectives of the study were:

1. To determine the temporal and spatial distribution of  $H_2S$  gas concentration due to its emission from Olkaria I and Olkaria II power stations.
2. To investigate the influence of meteorological parameters on transport and dispersion of  $H_2S$  gas.

3. To predict H<sub>2</sub>S gas concentrations due to its transport and dispersion as a result of emissions from Olkaria I and Olkaria II power stations on diurnal scale.

#### **1.4 Justification of the Study**

Geothermal energy has been addressed by a number of studies and has been termed as a clean and sustainable source of energy. This form of energy still emits non-condensable gases (NCGs) as a result of its exploitation. Non condensable gases are gases that are not able to condense and have impact on the systems operating conditions, energy efficiency and the life time of the system. These gases include Hydrogen sulphide gas (H<sub>2</sub>S), Nitrogen, Carbon dioxide, Methane that appears to be generally present in geothermal fields in quantities sufficient to be of environmental concern. Hydrogen sulphide gas is considered to be of great health concern in the work environment especially in a power plant than in relatively distant areas (Noorollahi 1999). This gas is considered to be toxic in high concentrations and has a very unpleasant smell in low concentrations.

Research work by Nyagah (2006), pointed out that public health scientists now recognize that Hydrogen sulphide is a potent neuro-toxin and exposure to low ambient levels causes irreversible damage to the brain and central nervous system. The sense of smell for Hydrogen sulphide gas is lost at a concentration below that at which it is harmful, so people may have little warning of the presence of the gas at dangerous concentrations hence there is need to assess the influence of meteorological parameters on transport and dispersion of this gas especially on a diurnal scale.

The atmospheric concentration of H<sub>2</sub>S gas, its transport and dispersion are affected by a number of meteorological parameters that include air temperature, relative humidity, temperature, atmospheric pressure, radiation, rainfall, wind direction and wind speed among others. This work seeks to provide an understanding of the influence of meteorological parameters on the dispersion and transport of Hydrogen sulphide away from the source points. This will give an advisory that can be used by workers and residents in the project site and its environs thus avoiding its related impacts

## **1.5 Area of Study**

Kenya is the first country in the sub-Saharan Africa to tap energy from the crust of the earth for national development in a larger quantity (Karekezi and Kithyoma 2003). The country has abundant geothermal resources that have not been tapped to their full potential. The geothermal resources are located in the Kenyan Rift Valley that transects the country from North to South (Figure 1). Recent studies of geothermal explorations reveals that the geothermal potential in the Rift Valley exceeds 7,000 megawatts (MW) of electricity and is capable of meeting all of Kenya's electricity needs over the next 20 years (Simiyu 2010). Geothermal energy in Kenya lies beneath the vast, but environmentally and culturally sensitive East African Rift Valley.

Olkaria geothermal field also called Greater Olkaria Geothermal Area (GOGA) is located on the floor of the Great Kenyan Rift Valley, about 120 km North West of Nairobi, 27 km South of Naivasha town. The map (Figure 1) shows Olkaria geothermal field (highlighted box) and other geothermal fields in Kenya that transects the country from North to the South of the Kenyan Rift valley.

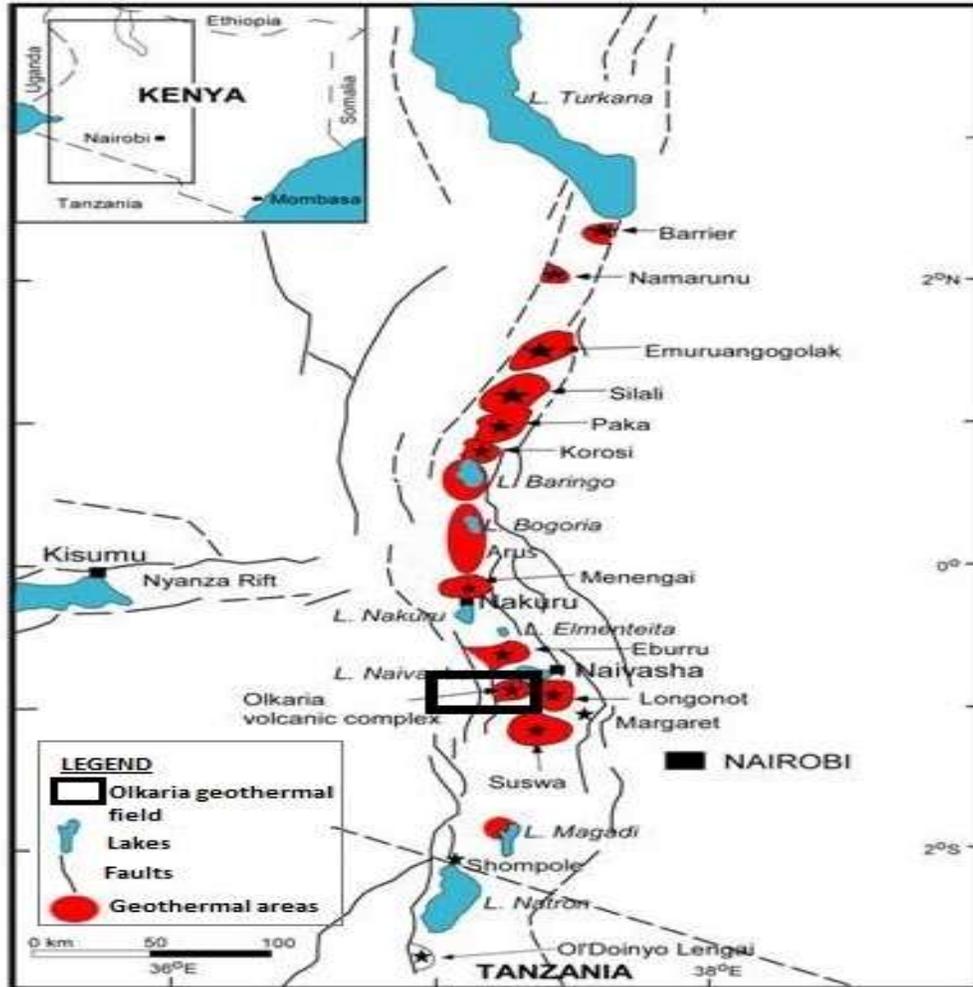


Figure 1: Map of Kenya showing the study area and other geothermal fields (Omenda 2009)

The total area of Olkaria geothermal field is approximately 80 km<sup>2</sup> (Simiyu 2008). Due to its large size, it was found sensible to segment the field into seven sub-fields, namely Olkaria East, Olkaria West, Olkaria Northwest, Olkaria Northeast, Olkaria Central, Olkaria Domes and Olkaria Southwest for ease of development as shown in Figure 2. The proven geothermal resource at the Greater Olkaria Geothermal Area is more than 450 MWe (Simiyu 2010). Of particular interest in this study is the existing Olkaria I and Olkaria II power stations. Olkaria I power plant is located in Olkaria East field and it has three units each generating 15 MWe, whereas Olkaria II power plant is located in the Northeast field and it has three units, each

generating 35 MWe. Both Olkaria I and II power plants are operated by the Kenya Electricity Generating Company (KenGen).

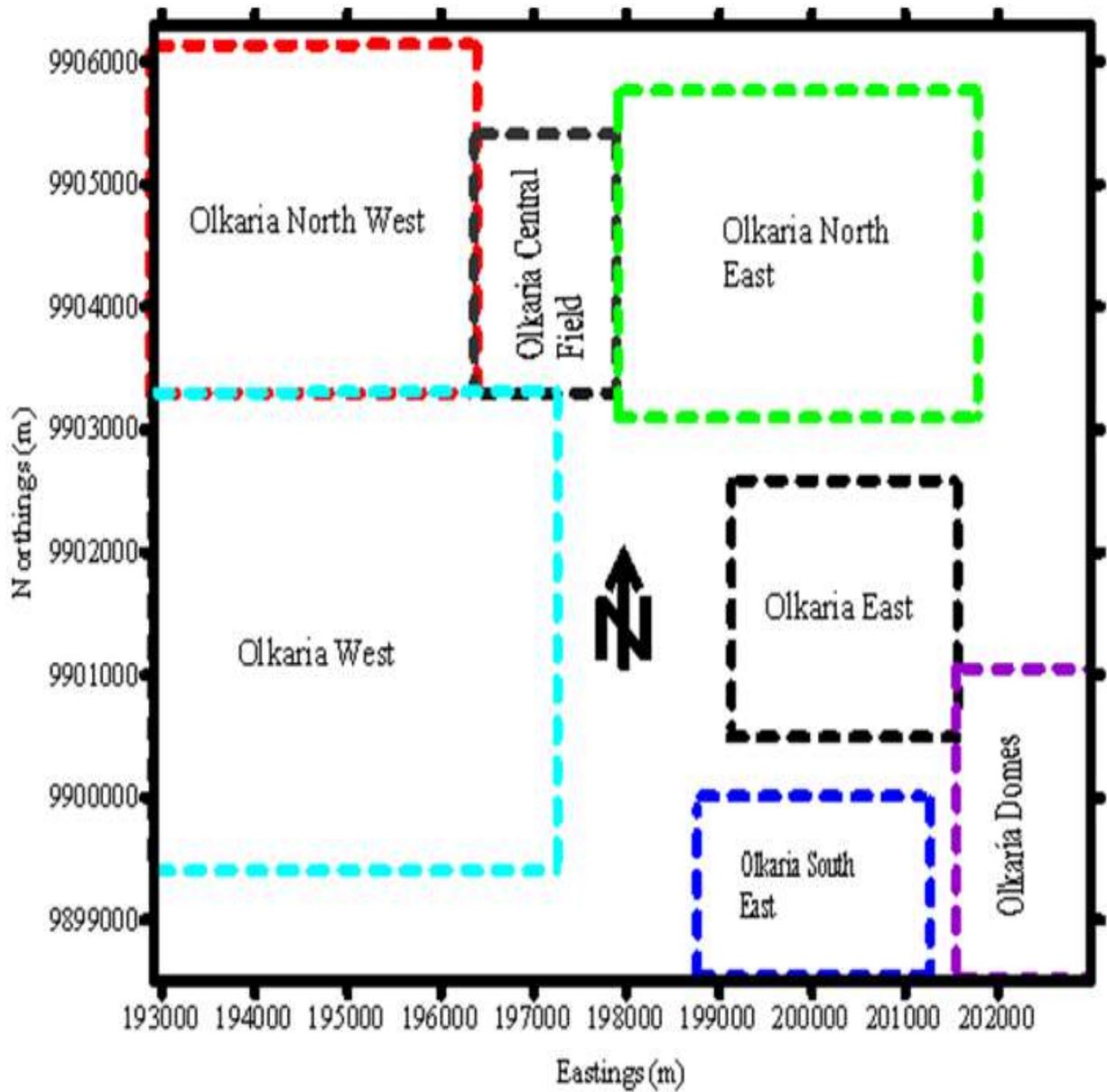


Figure 2: Map of the Greater Olkaria geothermal area showing the locations of the sub-fields.

The topography (Figure 3) at Olkaria is rugged and undulating with altitude ranging from about 1880 m above mean sea level at Lake Naivasha to more than 2400 m.a.s.l at the top of Olkaria hill. Around the power station elevation varies from 1800 m.a.s.l to about 2300 m.a.s.l. There is therefore a danger of H<sub>2</sub>S gas accumulating in valleys and depressions in the area since the gas is denser than air. The area is in eco-climatic zone V with loose soils and little rainfall. The average annual rainfall is about 600 mm being concentrated in the two rainy seasons of April to May and October to November. In this area the wind system is characterized by light breezes in the morning and stronger breezes in the afternoon throughout the year. The study area is a sensitive field located in Hells Gate national park and in close proximity to Lake Naivasha, flower farms and residential areas (Lake View estate) as shown in Figure 3.

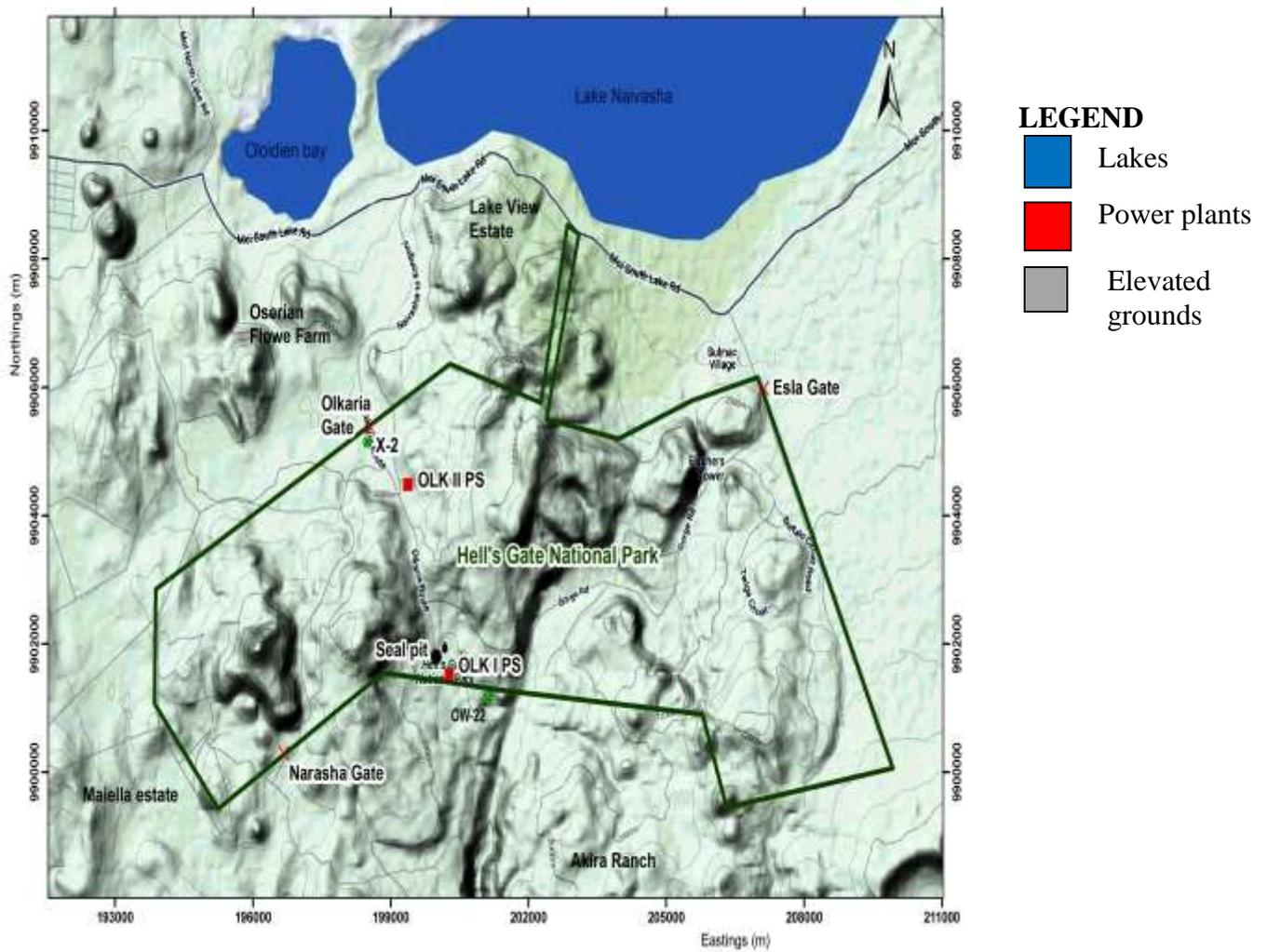


Figure 3: Map showing the undulating topography of the study area

The existing Olkaria I and Olkaria II power plants are located inside Hell's Gate National Park, which is a protected area for wildlife conservation (Figure 4). The approximate distance between Olkaria I and Olkaria II power stations is 3.3 km. About 3 km northwest of the Olkaria II power station is the Oserian Development Company which is a flower company. This flower company is a commercially vibrant floricultural farm that grows high quality cut flowers for export to Europe and other parts of the world. In the surrounding of the Greater Olkaria Geothermal field are some residential areas and community settlements.

Near ground Hydrogen sulphide gas concentrations are being monitored in and around Olkaria I and Olkaria II power stations using manually operated samplers (RAE pump systems and Hydrogen sulphide analyzers). At Olkaria I power plant, the gas ejector and the plant are essentially co-located whereas at Olkaria II power plant, gas ejection occurs in the cooling towers hence the actual H<sub>2</sub>S sources are different for the two power stations. The sites for monitoring H<sub>2</sub>S gas concentration at Olkaria I power plant include the MV rig workshop, power station, Olkaria I administration offices, seal pit 1, seal pit 2, well OW-10, well OW-22, scientific laboratories and a general store. At Olkaria II power plant, the identified sites include compressor room, hot well pit unit 1, hot well pit unit 2, cooling towers, power house, Olkaria II administration offices and Kenya Wildlife Service (KWS) Olkaria gate. Monitoring is also carried out in residential areas such as Lake View and Lake Side housing estates. Figure 4 shows the identified monitoring sites for H<sub>2</sub>S gas concentrations.

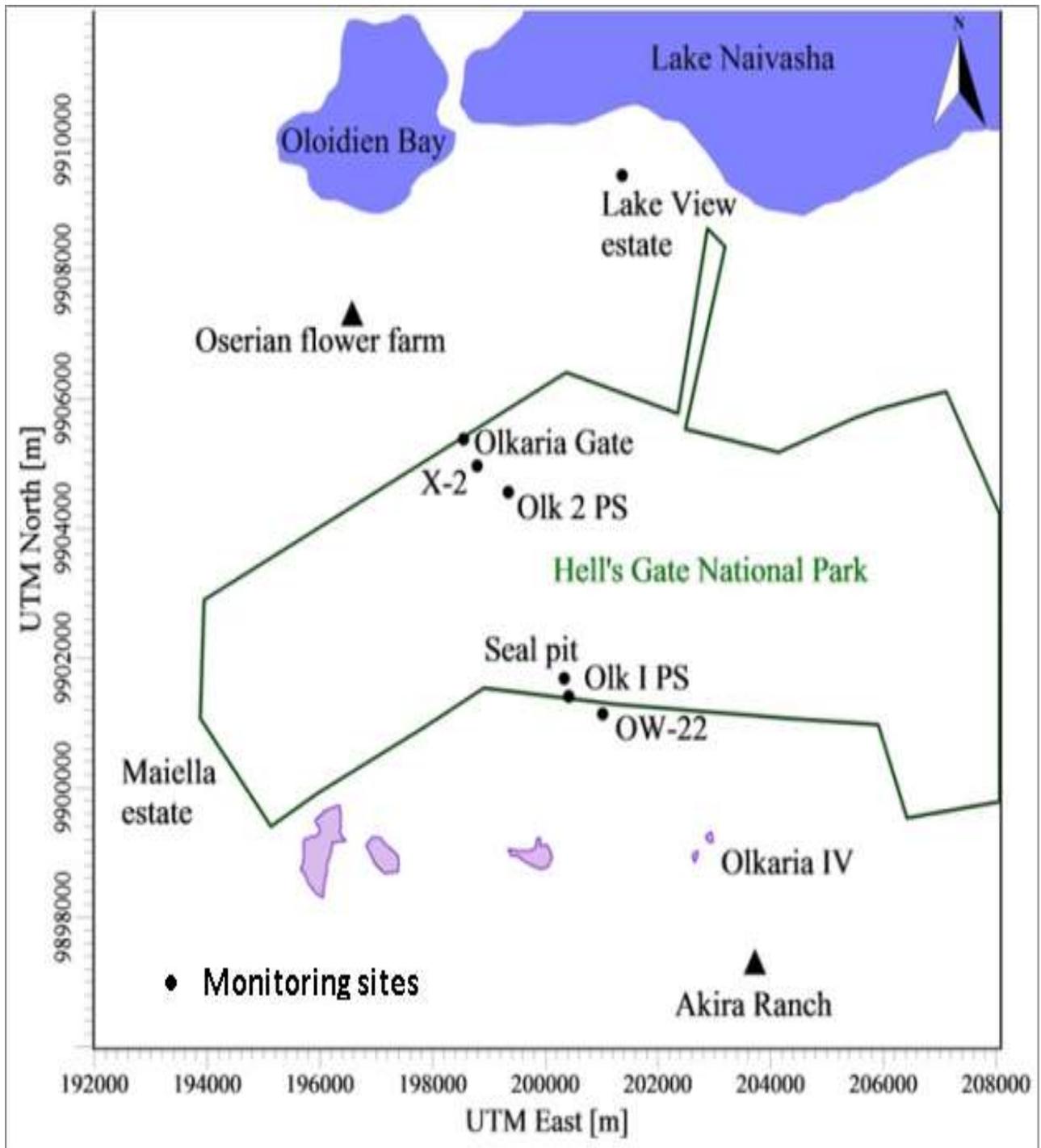


Figure 4: Location of monitoring sites for Hydrogen sulphide gas at Olkaria I and Olkaria II power plants.

## CHAPTER 2

### 2. LITERATURE REVIEW

#### 2.1 Introduction to Hydrogen Sulphide Gas

Hydrogen sulphide (H<sub>2</sub>S) gas is a corrosive gas known to be acutely toxic in high concentrations. It is one of a number of gaseous species (including HCl, SO<sub>2</sub>, CO<sub>2</sub> and H<sub>2</sub>O) associated with geothermal resource development activity.

##### 2.1.1 Chemical and Physical Properties of Hydrogen Sulphide Gas

Hydrogen sulphide has been discussed by (WHO 2003) as a colourless, flammable gas, with a distinctive smell of rotten eggs at low concentrations, and it is toxic in higher concentrations when it becomes non-detectable by humans. This toxic gas is naturally present in geothermal fields and when released to the atmosphere it can be a nuisance. Hunt, (2001) noted that because H<sub>2</sub>S gas is heavier than air, it can accumulate in topographic depressions where there is still air, such as well cellars and the basements of buildings near the gas exhausters.

Hydrogen sulphide gas whose chemical formula is H<sub>2</sub>S is also known as hydrosulfuric acid, sulfureted hydrogen, hepatic gas, stink damp, sulfur hydride, di-hydrogen mono-sulphide, di-Hydrogen sulphide and sewer gas (HSDB, 2010). The H<sub>2</sub>S gas is detectable at very low concentrations in the air at below 8 µg m<sup>-3</sup>. Hydrogen sulphide's relative molecular mass is 34.08 and its structural formula is illustrated as H-S-H. Its relative density at atmospheric pressure of 101.325 kPa at 25°C is 1.188 (which is heavier than air) and its vapour pressure at 20°C is 1814 kPa. Hydrogen sulphide is soluble in alcohol, ether, glycerol, gasoline, kerosene, crude oil, water, and carbon disulfide; the water solubility at 20°C is 1g in 242 ml (WHO, 2003).

##### 2.1.2 Occurrence of Hydrogen Sulphide Gas

WHO, (2003) noted that Hydrogen sulphide gas is produced naturally and as a result of human activity. Natural sources account for about 90% of the total Hydrogen sulphide gas in the atmosphere through non-specific and anaerobic bacteria reduction of sulphates and sulphur-

containing organic compounds. H<sub>2</sub>S gas is released primarily as a gas and is found naturally in crude petroleum, natural gas, volcanic gases, hot springs and groundwater.

ATSDR, (2006) further noted that Hydrogen sulphide gas is one of the principal compounds involved in the natural cycle of sulphur in the environment. Most of the atmospheric Hydrogen sulphide gas has natural origin especially from geothermal fields (natural emission like steaming ground, fumaroles, and mud pools). Artificial activities that release H<sub>2</sub>S gas include landfill sites, sewer systems, wastewater-treatment plants, reverse-osmosis drinking water plants, septic tank systems and geothermal power plants. It can also be formed under conditions of deficient oxygen in the presence of organic material and sulfate. It is a by-product of many industrial processes including petroleum refining, mining and wood pulp processing hence making it one of the pollutants which is of environmental concern.

### **2.1.3 Behavior and Life-Time of Hydrogen Sulphide in the Atmosphere**

Hydrogen sulphide exists as a gas at atmospheric pressure, dispersion in the air is likely to occur after its release. As it is soluble in oil and water, it may dissolve in surface water, groundwater, or moist soil and subsequently travel great distances. It has long been known by observations on the surface in geothermal fields, and around fumaroles, that some of the H<sub>2</sub>S is oxidized to Sulphur compound, which accumulates near or within the geothermal field. Volcanoes emit sulfur dioxide which can be oxidized to sulfur trioxide which then reacts with water forming sulfuric acid. In addition, absorption of Hydrogen sulphide from air into soils and plant foliage may occur (WHO 2003)

According to ATSDR (2006) Hydrogen sulphide gas in the atmosphere, may be oxidized by oxygen (O<sub>2</sub>) and ozone (O<sub>3</sub>) to give sulphur dioxide (SO<sub>2</sub>) and ultimately sulphate compounds. Sulphur dioxide and sulphate are eventually removed from the atmosphere through absorption by plants, deposition on and absorption by soils or through precipitation. Hydrogen sulphide gas in the air can also react with photo-chemically generated hydroxyl radicals (OH). WHO, (1981) noted that the atmospheric chemistry of Hydrogen sulphide and other sulfur compounds involves

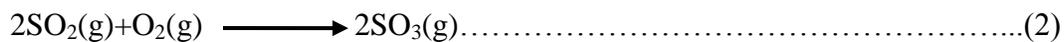
chemical and photochemical oxidation reactions of emissions from both natural and man-made sources. The eventual oxidation products are sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and/or sulfate ion (SO<sub>4</sub><sup>2-</sup>).

There have been relatively few studies of the persistence and conversion of Hydrogen sulphide gas under atmospheric conditions. WHO (1981) studied the relationship between concentrations of Hydrogen sulphide, sulfur dioxide, carbon monoxide, hydrocarbons and the distance from their industrial sources. Hydrogen sulphide gas concentrations dropped by a factor of 2 between the immediate neighborhood of the source and a 2.5 km radius. A further decrease in concentration by a factor of 8 occurred between 2.5 km and 20 km radii. These decreases were generally greater than those observed for any of the other pollutants measured.

Moreover, WHO (2003) pointed out that natural decay of organic matter releases Hydrogen sulphide gas (H<sub>2</sub>S) which can be oxidized to sulfur dioxide (SO<sub>2</sub>):



Sulfur dioxide formed in Equation (2) can be oxidized to sulfur trioxide (SO<sub>3</sub>):



Sulfur trioxide (Equation 3) then reacts with water to form sulfuric acid:



Studies carried out by Sequeira (1999) noted that H<sub>2</sub>S gas can contribute to the formation of acid rain. Studies have shown that part of the H<sub>2</sub>S emissions from geothermal plants are oxidized in the air to SO<sub>2</sub>. The H<sub>2</sub>S gas will oxidize to form elemental sulphur or ultimately, sulphate (SO<sub>4</sub><sup>2-</sup>), depending on pH. Oxidation to SO<sub>4</sub><sup>2-</sup> changes the oxidation state of sulphur ion from -2 to +6. Corrosion is another important aspect to keep in mind when there is H<sub>2</sub>S in the atmosphere. Aluminium conductors in substations and on transmission lines will usually take on a protective coating of black sulphide which inhibits further attack. However, instruments and relay contacts will almost certainly suffer if they feature exposed copper, as sealing is seldom perfect. Contacts and bare connectors of silver are advisable. Exciter commutators of copper can be very troublesome, not only because the copper itself is attacked by H<sub>2</sub>S but also because the sulphide film causes sparking at the brushes which wear away at a startling rate.

WHO (1981) and ATSDR (2006) reported that the residence time of Hydrogen sulphide was approximately 1.7 days in the presence of an ozone level of  $0.05 \text{ mg/m}^3$ . A similar residence time was estimated using data from the global budget of the sulfur cycle. A residence time in relatively clean air of about 2 days, compared with only about 2 hour in a polluted urban atmosphere. The atmospheric residence time of Hydrogen sulphide is typically less than 1 day in summer, but may be as high as 42 days in winter.

## **2.2 Regulations For Hydrogen Sulphide ( $\text{H}_2\text{S}$ ) Gas**

Regulations on air pollution are organized on the basis of two important concepts: the emission and the air concentration of pollutants. Emission refers to the release of pollutants into the atmosphere from mobile or stationary sources, while air concentration represents the presence of pollutants in the atmosphere as the receiving body. In Kenya, the National Environmental Management Authority (NEMA) which is the regulatory body has not issued any regulation for  $\text{H}_2\text{S}$  emissions nor for air concentrations that can be attributed to geothermal development or geothermal power plants. Air quality regulations are still in a draft form therefore, it is important to refer to international guidelines for environmental assessment or occupational safety.

### **2.2.1 Health Effects Of $\text{H}_2\text{S}$ Gas Exposure On Humans**

Hydrogen sulphide is released from geothermal field development mainly as a gas that disperses in the air. Hydrogen sulphide is both an irritant and a chemical asphyxiant with effects on both oxygen utilization and the central nervous system. Its health effects can vary depending on the level and duration of exposure. As a result of this fact, inhalation in the ambient air is the major route of exposure to Hydrogen sulphide gas (WHO 2003). Research work by WHO (2000) and ATSDR 2006 further noted that the common impact from the existence of  $\text{H}_2\text{S}$  gas in the atmosphere is the annoyance it causes to humans. The detection and perception of odours of  $\text{H}_2\text{S}$  gas by humans is an extremely complex process. On the basis of the scientific literature, it is not possible to state a specific concentration of Hydrogen sulphide gas at which odour nuisance starts to appear. Health effects from exposure to Hydrogen sulphide gas vary greatly, based upon differences in the concentrations present in the air. Effects can range from no long-term health

effects at concentrations below 100 ppm to potentially fatal effects from inhaling a single breath of gas containing 1,000 ppm H<sub>2</sub>S gas.

Latos *et.al.*, (2010) found that the main factors determining whether an odour causes annoyance are the concentration of the odorous compound in the air, the frequency of appearance of the odour and the duration of odour. The threshold concentration is associated with an averaging time of a few seconds or minutes, which means that it is necessary to estimate the frequency distribution of concentrations at short timescales to quantify the impact of odour. The presence of H<sub>2</sub>S gas in the atmosphere increases health risks in a given population. Health effects from exposure to sour gas vary greatly, based upon differences in the concentrations of H<sub>2</sub>S gas present in the air.

Most human data on the impacts of H<sub>2</sub>S are derived from acute poisoning case reports, occupational exposures and limited community studies. The available studies using human data suggest that the respiratory tract and nervous system are the most sensitive targets of Hydrogen sulphide toxicity. In confined spaces, human acute poisoning continues to occur. Single inhalation exposures to high concentrations of Hydrogen sulphide gas cause health effects in many systems. Health effects that have been observed in humans following exposure to Hydrogen sulphide gas include death and respiratory, ocular, neurological, cardiovascular, metabolic, and reproductive effects. Respiratory, neurological, and ocular effects are the most sensitive end-points in humans following inhalation exposures (WHO 2003).

Studies by Chambers and Johnson (2009) noted that H<sub>2</sub>S gas is considered a broad-spectrum toxin, meaning that it can affect several different body systems at the same time with the nervous system being the most susceptible. Exposure to lower concentrations of H<sub>2</sub>S gas can result in less severe neurological and respiratory effects. It can cause eye irritation, sore throat, coughing, nausea and shortness of breath. Impaired lung function has also been observed in asthmatics acutely exposed to 2 ppm Hydrogen sulphide while no alterations in lung function were observed in studies of non-asthmatic workers. The effects can be delayed for several hours, or sometimes several days, when working in low-level concentrations. Long-term, low-level exposure may result in fatigue, loss of appetite, headaches, irritability, poor memory and dizziness.

Prolonged exposures may cause eye inflammation, headache, fatigue, irritability, insomnia, digestive disturbances and weight loss. Moderate concentrations can cause more severe eye and respiratory irritation (including coughing, difficulty breathing, and accumulation of fluid in the lungs), headache, dizziness, nausea, vomiting, staggering and excitability. High concentrations can cause shock, convulsions, inability to breathe, extremely rapid unconsciousness, coma and death. Effects can occur within a few breaths, and possibly a single breath (WHO 2000; WHO 2003; ATSDR 2006). In addition, Noorollahi (1999) found that repeated exposure can result in health effects occurring at levels that were previously tolerated without any effect. Detection by smell is possible at a concentration of about 0.03 ppm. As the concentration increases, the odour becomes sweeter and finally the odour disappears at around 150 ppm, thus smell is not a reliable indicator of concentration

WHO, (2000) noted that in its acute form, Hydrogen sulphide gas intoxication is mainly the result of action on the nervous system. At concentrations of  $15 \mu\text{g m}^{-3}$  and above, Hydrogen sulphide causes conjunctival irritation, because sulfide and Hydrogen sulphide anions are strong bases. Hydrogen sulphide affects the sensory nerves in the conjunctivae, so that pain is diminished rapidly and the tissue damage is greater. Serious eye damage is caused by a concentration of  $70 \mu\text{g m}^{-3}$ . At higher concentrations (above  $225 \mu\text{g m}^{-3}$ ), Hydrogen sulphide has a paralyzing effect on the olfactory perception, so that the odour can no longer be recognized as a warning signal. At higher concentrations, respiratory irritation is the predominant symptom, and at a concentration of around  $400 \mu\text{g m}^{-3}$  there is a risk of pulmonary oedema. At even higher concentrations there is strong stimulation of the central nervous system (CNS), with hyperpnoea leading to apnoea, convulsions unconsciousness, and death. At concentrations of over  $1400 \mu\text{g m}^{-3}$  it leads to immediate collapse. In fatal human intoxication cases, brain oedema, degeneration and necrosis of the cerebral cortex and the basal ganglia have been observed.

A summary of the human effects at which various concentrations of Hydrogen sulphide gas occur are presented in Table 1.

**Table 1: Hydrogen Sulphide Gas Concentrations At Which Adverse Human Health Effects Occur (WHO 2003)**

Exposure(mg m <sup>-3</sup> )	Heath Effects/Observations
0.011	Odour threshold
2.8	Bronchial constriction in asthmatic individuals
5	Increased eye complaints
7 or 14	Increased blood lactate concentration, decreased skeletal muscle citrate synthase activity, decreased oxygen uptake
5-29	Eye irritation
28	Fatigue, loss of appetite, headache, irritability, poor memory, dizziness
>140	Olfactory paralysis
>560	Respiratory distress
≥ 700	Death

### 2.2.2 Occupational Safety Guidelines

Currently there are no occupational safety guidelines for H<sub>2</sub>S gas in force in Kenya. Thus (WHO 2000) guidelines and standards have been adopted in many studies in the country where, 24-hour average concentrations of H<sub>2</sub>S gas should not exceed 0.108 parts per million (150 µg m<sup>-3</sup>) beyond the immediate power plant boundary. This guideline is based on the avoidance of eye irritation. In order to avoid substantial complaints about odour annoyance among the exposed population, WHO recommends that Hydrogen sulphide gas concentrations should not be allowed to exceed 7 µg m<sup>-3</sup>, with a 30-minute averaging period.

For protection of occupational health National Institute for Occupational Safety and Health (NIOSH) gives limits of 10 ppm of H<sub>2</sub>S gas for workers working 40 hours a week. Hydrogen sulphide gas is reported to be detectable by the majority of people at concentrations of between 0.005 – 0.025 parts per million. This detectable interval is often referred to as the odour threshold. Loss of smell occurs at levels around 100 – 150 ppm due to the Hydrogen sulphide gas overwhelming the sense of smell. Some eye irritations can occur at levels between 50 to 100

ppm, which is the level where the loss of smell begins. Usually these irritations occur with prolonged exposures. A summary of international guidelines for Hydrogen sulphide limits are given in Table 2.

**Table 2: International Guidelines For H<sub>2</sub>S Gas Exposure Limits (symbols are defined below)**

Agency	Level	Averaging period	Reference
ACGIH	10 ppm	TLV-TWA(8hour)	ACGIH, 2009
	15 ppm	TLV-STEL (15min)	
OSHA	20 ppm	PEL-C	OSHA, 2006
NIOSH	10 ppm	REL-C (10 min)	NIOSH ,2005
The European Commission	5 ppm	TLV-TWA (8-hour)	ECD, 2009
	10 ppm	TLV-STEL (15min)	

**TLV:** Threshold Limit Values are defined as an exposure limit "to which it is believed nearly all workers can be exposed day after day for a working lifetime without ill effect".

**PEL:** Permissible Exposure Limits: are regulatory limits on the amount or concentration of a substance in the air, and they are enforceable.

**TWA:** Time-Weighted Average: the time-weighted average concentration for a conventional 8-hour workday and a 40-hour workweek, to which it is believed that nearly all workers, may be repeatedly exposed, day after day, without adverse effect (ACGIH, 2009).

**STEL:** Short Term Exposure Limit: the concentration to which it is believed that workers can be exposed continuously for a short period of time without suffering from Irritation, chronic or irreversible tissue damage, or narcosis (ACGIH,2009).

**REL-C:** Recommended Exposure Levels - Ceiling: the concentration that should not be exceeded during any part of the working exposure

**Threshold Limit Value – Ceiling (TLV-C):** the concentration that should not be exceeded during any part of working exposure. If instantaneous measurement is not available, sampling should be conducted for the minimum period of time sufficient to detect exposures at or above

the ceiling value. There is increasing evidence that physical irritation may initiate, promote or accelerate adverse health affect and interaction with other chemical biological or through other mechanisms (ACGIH, 2009).

### 2.2.3 Environmental Guidelines

Concentrations of Hydrogen sulphide in ambient air as a result of natural sources have been estimated to be between 0.14 and 0.4  $\mu\text{g m}^{-3}$  (WHO 2003). The environmental regulations that can serve as reference are the air concentration guidelines by the World Health Organization (WHO) and regulations of countries where geothermal energy is more developed. Table 3 gives a summary of some various international environmental guidelines for Hydrogen sulphide air concentrations and emissions.

**Table 3: Various Environmental Guidelines For H2S Air Concentration And Emissions**

Country / Agency	Level $\mu\text{g m}^{-3}$	Averaging period	Notes	Ref.
WHO	7	30 min	To avoid odour annoyance.	WHO, 2000
	150	24 hours		
Iceland	50	24 hours	The limit may be exceeded 5 times per year. From 1st July 2014, the limit may not be exceeded.	Nolasco, 2010
New Zealand	7	1 hour	The Hydrogen sulphide value is based on odour nuisance and may be unsuitable for use in geothermal areas.	MfE,2002
USEPA California	43	1 hour	In 1969, the Air Resources Board adopted this standard and in 1984, the ARB retained this standard. From any geothermal power plant.	James and David, 2000

Previous studies have presented geothermal power generation to be a clean alternative source of energy to fossil fuel or nuclear power plants, which is increasingly being developed as part of an effort to decrease reliance on carbon based energy in countries that have geothermal resources. Though geothermal power plants are very clean, it is necessary to monitor the effect of geothermal contamination on the environment (Noorollahi 1999). Research work done by Gunnarsson *et al.*, (2013) noted that geothermal fluids contain dissolved CO<sub>2</sub>, H<sub>2</sub>S, H<sub>2</sub>, N<sub>2</sub>, CH<sub>4</sub> and Ar. Concentration of individual gases can range from ppb levels to several thousand ppm depending on geological settings, temperature and composition of the geothermal reservoir. During utilization and depressurization of the geothermal fluid, gases are concentrated in the steam phase and are finally vented out of the condensers of the turbines to atmosphere. The gas emission therefore inevitably affects the air quality around the power plants as the concentration of the geothermal gases increases. Under certain weather conditions and if good distribution of the gases at the disposal site is not secured the gases can affect air quality tens of kilometers from the power plant site.

Mariita (2002) pointed out in his work that the present geothermal power stations in Olkaria contain about 9.5% of H<sub>2</sub>S gas and 80% of carbon dioxide gas. When these gases are emitted into the atmosphere, they are at a higher temperature than ambient air. Hot non-condensable fumes are lighter than normal air and this helps the gases to mix rapidly with ambient air. Therefore H<sub>2</sub>S emitted from the gas ejectors does not preferentially settle out from the plume any more than other gases in air. He further noted that the only time that H<sub>2</sub>S gas settles down more preferentially than other gases in the air is in an enclosed area; where there is no wind (calm conditions prevail).

When geothermal areas are developed, Hydrogen sulphide gas is usually emitted at a higher rate to the environment than before development (Olafsdottir *et.al.*, 2010). Research work by Horwell *et.al.*, ( 2005) in their analysis of geothermal gases, including Hydrogen sulphide gas, were found to be entering buildings in Rotorua, New Zealand directly from the ground through floors, walls and subsurface pipes; indoor vents emitting up to approximately 200 ppm were reported. The general population may also be exposed to Hydrogen sulphide gas by accidental release (blowout) from natural gas wells during drilling operations especially near residential areas. Due

to increased geothermal exploitations in the field of study there is need to assess and clearly bring out the influence of meteorological conditions affecting its transport and dispersion in the atmosphere.

Studies carried out by Kristmannsdóttir *et al.*, 2000 and Thorsteinsson *et al.*, 2013 noted that monitoring of sulfuric gas emissions at and around geothermal power plants is important to avoid negative local effects. In addition, it is of concern with regard to global damages on the environment due to SO<sub>2</sub> (if H<sub>2</sub>S is oxidized to SO<sub>2</sub>) in the atmosphere causing acid rain which degrades soil, water and vegetation. Protection of geothermal areas is necessary due to their natural beauty, historical interest and/or their potential as touristic attraction. Complaints about odor nuisance by H<sub>2</sub>S emitted by power plants vary strongly between locations, mainly depending on the level of geothermal activity in the area before its exploitation and during exploitation process.

Studies have shown that transport and dispersion of Hydrogen sulphide gas from the source (power plant or natural emissions) is highly dependent on the prevailing weather conditions in that given locality. Bluet *et. al.*, (2004) noted that the ground-level concentrations resulting from a constant discharge of contaminants change according to the weather (particularly the wind) conditions at the time. With regard to the present increased emphasis on the environmental viability of energy projects, the associated effects of its development need to be identified, quantified and if necessary eliminated or abated. To reduce environmental impacts, monitoring and control measures must be put in place in all areas of operation. To achieve this, the extent of contamination must be ascertained quickly and in near-real-time. One approach to undertake this is to make use of models which can predict the spatial distribution and temporal concentration of the pollutant in a given locality.

Air dispersion models have been used routinely in environmental impact assessments, ecological risk analysis and emergency planning. The models are also useful in properly designing and configuring sources of pollution to minimize ambient impacts and effectively predict the impacts of Hydrogen sulphide on both the workers inside the plants and the nearby population. Dispersion models are typically used in the permitting process to estimate the concentration of

pollutants at specified ground-level receptors surrounding an emissions source (ADEQ 2013). These models are currently used by many regulatory agencies as a means of assessing the impact of a facility on the air quality of the surrounding area and to determine the compliance status. Such models are a reliable basis for developing and making decisions about environmental management and sustainability and to provide information on real-time emission abatement strategies.

There are a number of models that have been used by scientists to perform dispersion modeling. These models include ISC3View, AFTOX and AERMOD among others. ISC3 View prescribes the puff dispersion in time. AFTOX was designed to model neutrally buoyant gas releases. It is a Gaussian puff-plume dispersion model designed for three emission categories, continuous, instantaneous and finite duration releases. In the finite duration, the source emission characteristics are constant for several minutes, but in the instantaneous release the emission duration is for only few seconds. AFTOX uses a Gaussian equation to describe the gas puff dispersion in time. The model assumes that there is no decay or material deposition Both the AFTOX and ISC3View models are Gaussian puff/plume dispersion models designed for two emission categories; continuous (steady-state) or instantaneous (transient). In steady-state releases, source characteristics do not vary with time (i.e., emission rate is constant), and the release duration is long compared to advection (travel) time, For transient release, the source characteristics do not vary with time but the duration of the release from the source is limited. (Kholliko, 1998, Trinity, 1999).

Gaussian and numerical models are widely used for the simulation of air quality. The models simulate the atmosphere in varying degrees of detail by mathematically representing emissions, with initial and boundary concentrations of chemical species (Tonnesen *et al.*, 1998). This way, an understanding of the atmosphere's chemistry and meteorology is combined with estimates of source emissions to predict possible ground-level concentrations. This timely and reliable information gained from air quality forecasts forms a basis for developing and making decisions about environmental conservation. Additionally, forecasts provide information on real-time emission abatement strategies, facilitating the protection of the public from its impacts.

Gaussian and numerical models are widely used for the simulation of air quality. A study by Nyagah, (2006) on modeling the dispersion of Hydrogen sulphide emitted from the Nesjavellir geothermal power station using numerical and Gaussian models (AERMOD) showed that simulated results for dispersion of Hydrogen sulphide from the plant is highly dependent on weather. The near-ground concentrations are very responsive to variations in wind direction. The study further highlighted that the dispersion and spatial distribution of Hydrogen sulphide gas mainly depends on the wind speed and wind direction. Increased wind speeds reduce ambient concentration levels of Hydrogen sulphide gas.

Studies by Zhang and Chen (2009) have further indicated that dispersion of gases depends on the prevailing wind speeds. It shows that in a relatively higher wind speed situation, gas disperses quickly in the leakage jet flow direction, and there is less threat in the direction perpendicular to the leakage jet flow. In a relatively smaller wind speed scenario, gas disperses slowly in the leakage jet flow direction and there is more threat in the direction perpendicular to the leakage jet flow. In places adjacent to the leakage sources, the concentration of H<sub>2</sub>S is high and goes up quickly hence leaving exposed individuals little available emergency response time Olafsdottir and Gardarsson (2013) reported a correlation between H<sub>2</sub>S concentration and wind speed, air temperature and increasing air stability. Kristmannsdóttir *et. al.*, (2000) reported a negative correlation with precipitation. Thorsteinsson *et. al.*, (2013) noted the occurrence of high Hydrogen sulphide gas concentration with low atmospheric exchange and autochthonous weather.

A study carried out by (Kholliko 1998) on the dispersion of Hydrogen sulphide for Svartsengi geothermal power plant South West Iceland using Industrial Source Complex model (ISC3 view) and Air Force Toxic Chemical Dispersion Model (AFTOX). The study showed that the concentrations decreased with increasing distance and the H<sub>2</sub>S patterns in Svartsengi follow the annual wind pattern with high concentrations in the regions characterized by high frequency of wind towards that direction.

Sarleno and Clerici (1995) noted that modeling has been used widely in studying the transport of plumes from cooling towers. In all the cases modeled, it clearly showed the importance of

meteorological conditions and topography being emphasized. The analyses of the concentrations have shown that there is an increase of dispersion along wind direction (a typical feature of the complex topography region) and the possibility of impingement of the plume on a slope during stable conditions, with the accumulation of the pollutant at the ground.

## CHAPTER 3

### 3. DATA AND METHODOLOGY

#### INTRODUCTION

This chapter is devoted to the discussion of the data and model used in this study and the various methods used to achieve the objective of the study.

#### 3.1 DATA USED IN THE STUDY

The data used in this study included observed surface data on meteorology and hydrogen sulphide gas data. Details of these are discussed in the following sub-sections.

##### 3.1.1 Surface Data On Meteorology

Meteorology is a fundamental component for the dispersion of pollutants because it is the primary factor determining the diluting effect of the atmosphere. Therefore, good-quality data are needed, ideally from a monitoring station within the area of interest. In regard to this fact, it is important that meteorology is carefully considered when undertaking modeling. Air temperature, wind speed and direction, relative humidity data that was used in the study were obtained from the Environment unit of KenGen, Olkaria. The data was obtained from an automatic weather station located at X-2, about 500 m northwest of the Olkaria II power plant, for the period November 2003 to November 2011. For purposes of modeling hourly meteorological data for 1<sup>st</sup> to 31<sup>st</sup> of November 2011 was used since it was a complete data set.

##### 3.1.2 Hydrogen Sulphide Concentrations Data

Hydrogen sulphide concentration data that was used was obtained from monitoring locations in the study area that included power station, administration block, KWS gate, lake view, lake side, Olkaria stores and scientific laboratory. For the purpose of analyzing diurnal variation, data was collected for 20 days 24 hour cycle for the month of November 2011 at Olkaria I and Olkaria II power stations. The main sources of Hydrogen sulphide are the cooling towers and the gas ejectors at the power house. There are other sources of H<sub>2</sub>S gas such as from drilling operations and well testing though these are only temporary and typically last for a few days. Thus, the main emphasis is on the assessment of H<sub>2</sub>S gas from permanent sources such as cooling towers and the gas ejectors.

### **3.1.3 Data Quality Control**

There was need to examine the quality of the data before performing any analysis. This exercise was necessary if correct statistical inferences were to be made from the data. The quality of data may be compromised by inconsistencies in records and data gaps. Inconsistent data can occur due to several reasons, for example change of location of observing stations and/or in instruments, and also due to human error. World Meteorological Organization (WMO) standard recommends that a climate dataset for which more than 10% is missing is not good and therefore should not be used.

## **3.2 Methodology**

This section presents the various methods that were employed in this study. Various methods were used to investigate the specific objectives of the study. These included temporal analysis, Pearson correlation analysis, spatial analysis and the ability of the AERMOD model to correctly predict the concentrations of Hydrogen sulphide gas over the GOGA. Details of the methods and the model are presented in the following sections.

### **3.2.1 Assessing Temporal Distribution Of Hydrogen Sulphide Gas And Observed Weather Parameters**

Assessment of temporal pattern of observed meteorological parameters and H<sub>2</sub>S gas data was examined by use of time series plots. This was done so as to give a display of their temporal variability over the study area.

### **3.2.2 Pearson Correlation Analysis**

Correlation analysis provides the degree of relationship between variables. Simple correlation coefficient can range between 1.0 (plus or minus one). A coefficient of +1.0 denotes perfect positive correlation, means that changes in the independent parameter will result in similar change in the dependent parameter. A coefficient of -1.0 denotes a perfect negative correlation, means that changes in the independent parameter will result in a similar change in the dependent parameter, but the change will be in the opposite direction. A coefficient of 0.0 means there is no relationship between the two parameters and that a change in the independent parameter will have no effect in the dependent parameter.

In this method simple correlation coefficient (r) was calculated between measured Hydrogen sulphide gas (X) and observed weather parameters (Y) over the study area. The value of r was computed using Equation 4.

$$r = \frac{n \sum XY - \sum(X) \sum(Y)}{\sqrt{n \sum X^2 - (\sum X)^2} \sqrt{n \sum Y^2 - (\sum Y)^2}} \text{----- (4)}$$

In Equation 4, X and Y refer to measured Hydrogen sulphide gas and observed weather parameters respectively, n is the number of values.

### 3.2.3 Spatial Analysis Of Hydrogen Sulphide Gas

Spatial analysis was done so as to determine the spatial distribution of Hydrogen sulphide gas in the study area in terms of its concentration and transportation away from the source. This was achieved using the ninth version of surfer software. The spatial maps obtained in the analysis are discussed in chapter 4.

### 3.2.4 Wind Field Analysis

Wind field is a meteorological parameter that appreciably influences the direction of transport and dispersion of the pollutant and depicts the concentration of a given air pollutant based on its strength. The prediction of the direction of the movement of the pollutants when they are released into the atmosphere depends on the airflow over the area. Pollution concentration levels will fluctuate in response to the changing state of the atmospheric stability and wind flow. Wind direction determines the path followed by pollutants while wind strength determines the concentration and dispersion rate. Air pollutants tend to move with the prevailing winds and the areas most affected in a given locality are predicted by examining a site-specific wind rose.

This analysis was done on seasonal basis to be able to ascertain if the wind is blowing in the same direction throughout the season in a given year hence giving a clear indication of the dispersion of Hydrogen sulphide in the study area. This was achieved by plotting wind rose diagrams using WRPLOT software version 7.0.0. This WRPLOT is fully operational software that provides visual wind rose plots, frequency analysis, and plots for several meteorological data

formats. A wind rose depicts the frequency of occurrence of winds in each of the specified wind direction sectors and wind speed classes for a given location and time period.

The months of the year were divided into four seasons namely; warm and dry season, long rainy season, cool and dry season and short rainy season with the months shown in Table 4;

**Table 4: Summary of Seasons used in Plotting Seasonal Wind Roses**

Season	Months
Warm and Dry season	Dec – Feb (DJF)
Long rains	March - May (MAM)
Cool and Dry season	June – Aug (JJA)
Short rains	Oct – December (OND)

A combination of the results obtained from spatial analysis and wind field analysis is meant to aid in giving a better advisory to the workers and people living around the study area.

### 3.2.5 Air Dispersion Modeling

#### 3.2.5.1 Theoretical Approach To Air Dispersion

Air pollutant plume dispersion equations have been undertaken by numerous researchers. By performing a mass balance on a small control volume, a simplified diffusion equation, which describes a continuous cloud of material dispersing in a turbulent flow, can be written, Equation 5 (Macdonald 2003):

$$\frac{dC}{dt} + U \frac{dC}{dx} = \frac{d}{dy} \left( Ky \frac{dC}{dy} \right) + \frac{d}{dz} \left( Kz \frac{dC}{dz} \right) + S \quad \text{----- (5)}$$

- x      along-wind coordinate measured in wind direction from the source
- y      cross-wind coordinate direction
- z      vertical coordinate measured from the ground
- C(x, y, z)      mean concentration of diffusing substance at a point (x,y,z) [kg/m<sup>3</sup>]
- Ky, Kz      eddy diffusivities in the direction of the y- and z- axes [m<sup>2</sup>/s]

- U mean wind velocity along the x-axis [m/s]
- S source/sink term [ $\text{kg/m}^3\text{-s}$ ]

A term-by-term interpretation of Equation (5) is:

$\frac{dC}{dt} + U \frac{dC}{dx}$  ----- Time rate of change and advection of the cloud by the mean wind.

$\frac{d}{dy} \left( K_y \frac{dC}{dy} \right)$  -----Turbulent diffusion of material relative to the center of the pollutant cloud.

S -----Source term which represents the net production (or destruction) of pollutant due to sources (or removal mechanisms).

In deriving Equation 5, it is assumed that the pollutant concentrations do not affect the flow field (passive dispersion) and molecular diffusion and longitudinal (along-wind) diffusion are negligible, the flow is incompressible, wind velocities and concentrations can be decomposed into a mean and fluctuating component with the average value of the fluctuating (stochastic) component equal to zero, turbulent fluxes are linearly related to the gradients of the mean concentrations and the mean lateral (V) and vertical (W) wind velocities are zero.

An analytical solution to Equation 5, gives the Gaussian plume model. For a continuous point-source released at the origin in a uniform (homogenous) turbulent flow, the solution to Equation 5, as given by Macdonald (2003),

$$C(x, y, z) = \frac{Q}{4\pi x \sqrt{K_y K_z}} \exp\left(\frac{-y^2}{4K_y(x|U)}\right) \exp\left(\frac{-z^2}{4K_z(x|U)}\right) \quad \text{----- (5)}$$

Q ----- The source pollutant emission rate.

The turbulent diffusivities  $K_y$  and  $K_z$  are unknown in most flows, and in the atmospheric boundary layer  $K_z$  is not constant, but increases with height above the ground. In addition,  $K_y$  and

$K_z$  increase with distance from the source, because the diffusion is affected by different scales of turbulence in the atmosphere as the plume grows. If we define the following Gaussian parameters:

$$\sigma_y = \sqrt{2K_y \frac{x}{U}} \quad , \quad \sigma_z = \sqrt{2K_z \frac{x}{U}} \quad \text{----- (6)}$$

Then the final form of the Gaussian plume equation, for an elevated plume released at  $z = H_p$  is:

$$C(x, y, z) = \frac{Q}{2\pi U_p \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left[ \exp\left(-\frac{(z-H_p)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H_p)^2}{2\sigma_z^2}\right) \right] \quad \text{---- (7)}$$

In this expression, a second z-exponential term has been added to account for the fact that a pollutant cannot diffuse downward through the ground at  $z = 0$ , but is assumed to be reflected. This “image” term can be visualized as an equivalent source located at  $z = -H_p$  below the ground.

Equation 7 is the Gaussian plume formula for a continuous point source. The plume height  $H_p$  is the sum of the actual stack height  $H_s$  plus any plume rise  $H$  due to initial buoyancy and momentum of the release. The wind speed  $U_p$  is taken to be the mean wind speed at the height of the stack. Considering concentrations at ground level (where receptors such as people are),  $z$  is assumed to be zero (Macdonald, 2003),

$$C(x, y, z) = \frac{Q}{\sqrt{2\pi} U_p \sigma_y} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{H_p^2}{2\sigma_z^2}\right) \quad \text{----- (8)}$$

A more general, non-Gaussian model, which allows for the vertical variation of  $K_z$  can be written as:

$$C(x, y, z) = \frac{Q}{\sqrt{2\pi} U_p \sigma_y} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) f(z) \quad \text{----- (9)}$$

In equation (9)  $f(z)$  is a normalized function which describes the vertical distribution of material in the plume.

The rate of transfer of a pollutant through any vertical plane downwind from the source is a constant steady state, and this constant should equal the emission rate of the source,  $Q$ . Thus:

$$\iint_{y,z} CUdydz = Q \quad \text{----- (10)}$$

The integration is performed over the  $y$ - $z$  plane, perpendicular to the plume axis.

### 3.2.5.2 Software AERMOD View

The selection of an air dispersion model depends on many factors, such as, the nature of the pollutant (e.g., gaseous, particulate, reactive, inert), the characteristics of emission sources (point, area, volume, or line) and receptor relationship, the meteorological and topographic complexities of the area, the complexity of the source distribution, the spatial scale and resolution required for the analysis, the level of detail and accuracy required for the analysis, and averaging times to be modeled. Some of these models include: ISCST3, AERMOD, ASPEN, CALPUFF, UTM-TOX and CAMx.

AERMOD stands for AERMIC Model, where AERMIC is the American Meteorological Society/EPA Regulatory Model Improvement Committee. AERMOD was developed in 1995, reviewed in 1998 and formally proposed by the United States Environmental Protection Agency (US EPA) as a replacement for the Industrial Source Complex Short Term model (ISC-ST3) in 2000 (Bluett *et al.*, 2004).

A detailed description of AERMOD was given by (Alan *et al.*, 2004). AERMOD is a steady-state plume model designed to run with a minimum of observed meteorological parameters. In the stable boundary layer (SBL), it assumes the concentration distribution to be Gaussian both vertically and horizontally. In the convective boundary layer (CBL), the horizontal distribution is also assumed to be Gaussian, but the vertical distribution is described with a bi- Gaussian probability density function (pdf). Additionally, in the CBL, AERMOD monitors “plume lofting”, whereby a portion of plume mass, released from a buoyant source, rises to and remains

near the top of the boundary layer before becoming mixed into the CBL. AERMOD also tracks any plume mass that penetrates into the elevated stable layer, and then allows it to re-enter the boundary layer when and if appropriate. For sources in both the CBL and the SBL, AERMOD treats the enhancement of lateral dispersion resulting from plume meander.

AERMOD handles the computation of pollutant impacts in both flat and complex terrain within the same modeling framework. Using a relatively simple approach, AERMOD incorporates current concepts about flow and dispersion in complex terrains. Where appropriate, the plume is modeled as either impacting and/or following the terrain. The model also has the ability to characterize the Planetary Boundary Layer (PBL) through both surface and mixed layer scaling (Alan *et al.*, 2004).

In this study AERMOD model was used to model Hydrogen sulphide gas dispersion. The software consists of one main program (AERMOD) and two pre-processors (AERMET and AERMAP). Figure 5 shows the flow and processing of information in AERMOD software.

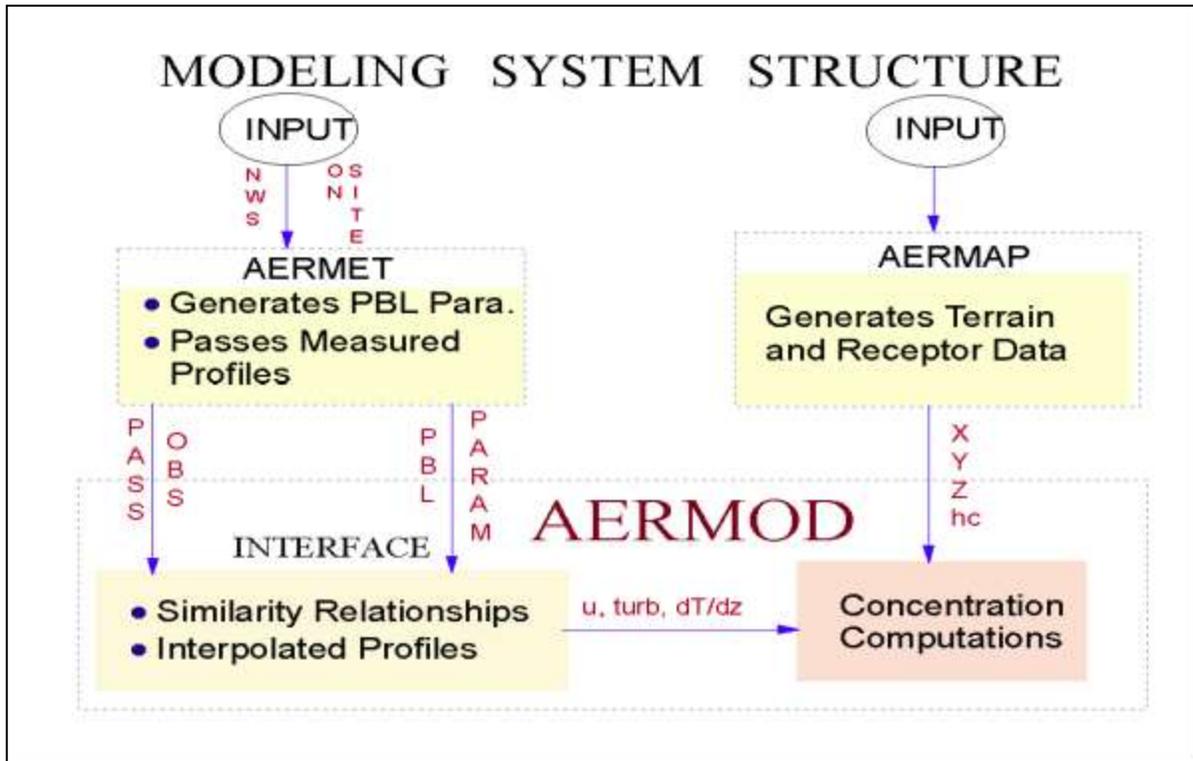


Figure 5: Data flow in the AERMOD modeling system (Alan *et al.*, 2004)

### 3.2.5.3 AERMET (Meteorological pre-processor)

The purpose of AERMET is to use meteorological measurements, representative of the modeling domain, to compute certain boundary layer parameters used to estimate the profiles of wind, turbulence and temperature. The input data to AERMET, as described by Alan *et al.*, (2004) consists of surface characteristics in form of surface roughness, albedo and Bowen ratio, plus standard meteorological observations including wind speed, wind direction, temperature and cloud cover. AERMET then computes the PBL parameters which include friction velocity ( $u_*$ ), Monin- Obukhov length ( $L$ ), convective velocity scale ( $w_*$ ), temperature scale ( $\theta_*$ ), mixing height ( $z_i$ ), and surface heat flux ( $H$ ). These scaling parameters are used to construct vertical profiles of wind speed ( $u$ ), lateral and vertical turbulent fluctuations ( $\sigma_x$ ,  $\sigma_y$ ), potential temperature gradient ( $d\theta/dz$ ), and potential temperature ( $\theta$ ). Figure 6 shows the AERMET system.

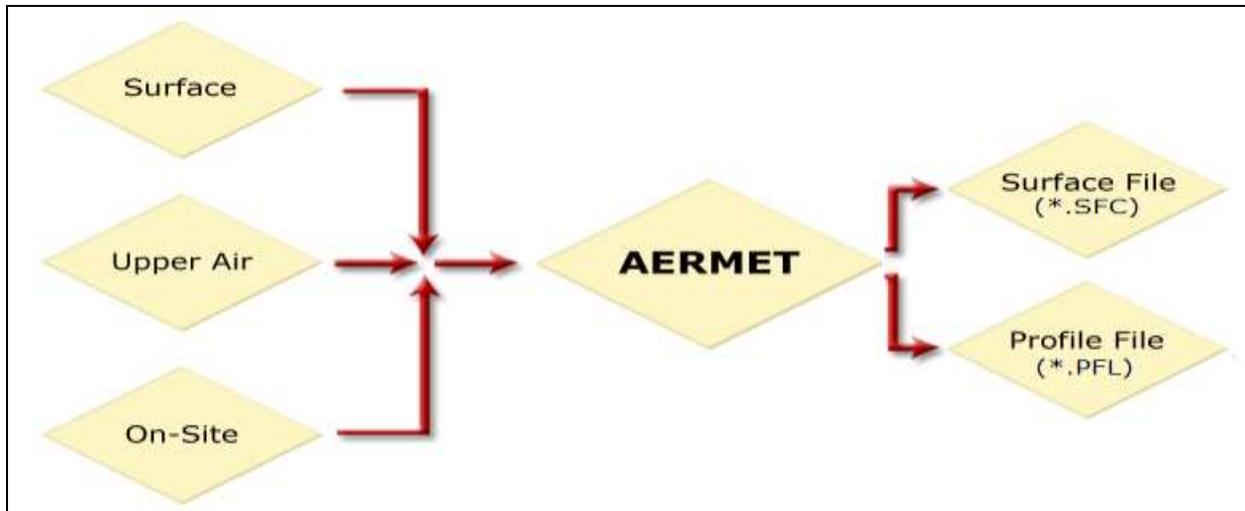


Figure 6: AERMET System

#### 3.2.5.4 AERMAP (Terrain pre-processor)

AERMAP is the terrain pre-processor of AERMOD (Alan *et al.*, 2004). It uses gridded terrain data to calculate a representative terrain-influence height ( $h_c$ ) for each receptor with which AERMOD computes receptor specific  $H_c$  values. AERMOD handles the computation of pollutant impacts in both flat and complex terrain within the same modeling framework thereby removing the need to differentiate between the formulations for simple and complex terrain.

In complex terrain, AERMOD incorporates the concept of the dividing streamline for stability-stratified conditions. Where appropriate, the plume is modelled as a combination of two limiting cases: a horizontal plume (terrain impacting) and a terrain-following (terrain responding) plume. In stable flow, a two-layer structure develops in which the lower layer remains horizontal while the upper layer tends to rise over the terrain. In neutral and unstable conditions  $h_c = 0$ . AERMOD captures the effect of flow above and below the dividing streamline by weighting the plume concentration associated with two possible extreme states of the boundary layer: horizontal plume and terrain-following. The relative weighting of a horizontal plume and terrain-following depends on the degree of atmospheric stability, the wind speed and the plume height relative to the terrain. The weighting of the two plume states depends on the amount of mass residing in each state. This mass partitioning is based on the relationship between the critical dividing streamline height ( $H_c$ ) and the vertical concentration distribution at a receptor. An illustration of

the relationship between the actual plume and AERMOD's characterization of it is as shown in Figure 7 below.

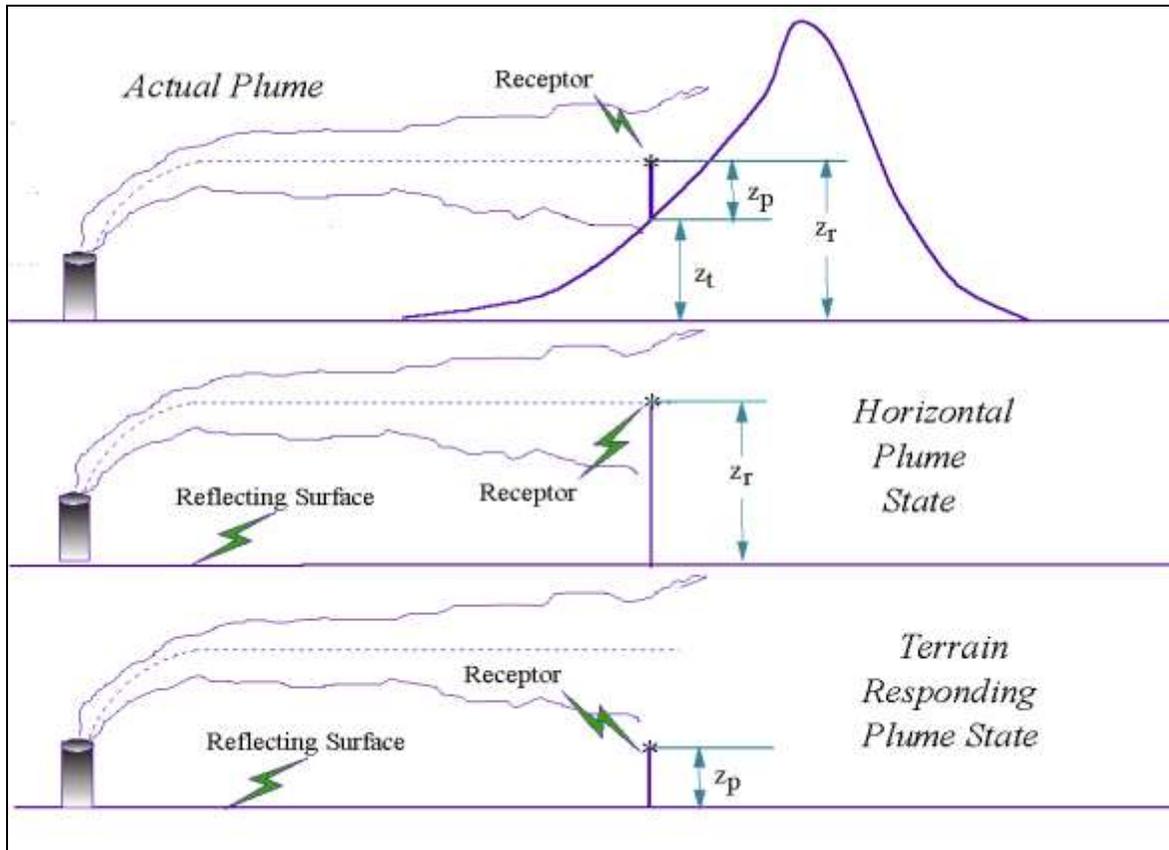


Figure 7: The relationship between the actual plume and AERMOD's characterization (Alan *et al.*, 2004)

During convective conditions the concentration at an elevated receptor is the average of the contributions from the two states. As plumes above  $H_c$  encounter terrain and are deflected vertically, there is also a tendency for plume material to approach the terrain surface and to spread out around the sides of the terrain. To simulate this, concentration estimates always contain a component from the horizontal state and, hence, under no condition is the plume allowed to completely approach the terrain-following state. For flat terrain, the contributions from the two states are equal in value and are equally weighted. Figure 8 illustrates how the weighting factor is constructed and its relationship to the estimate of concentrations as a weighted sum of two limiting plume states.

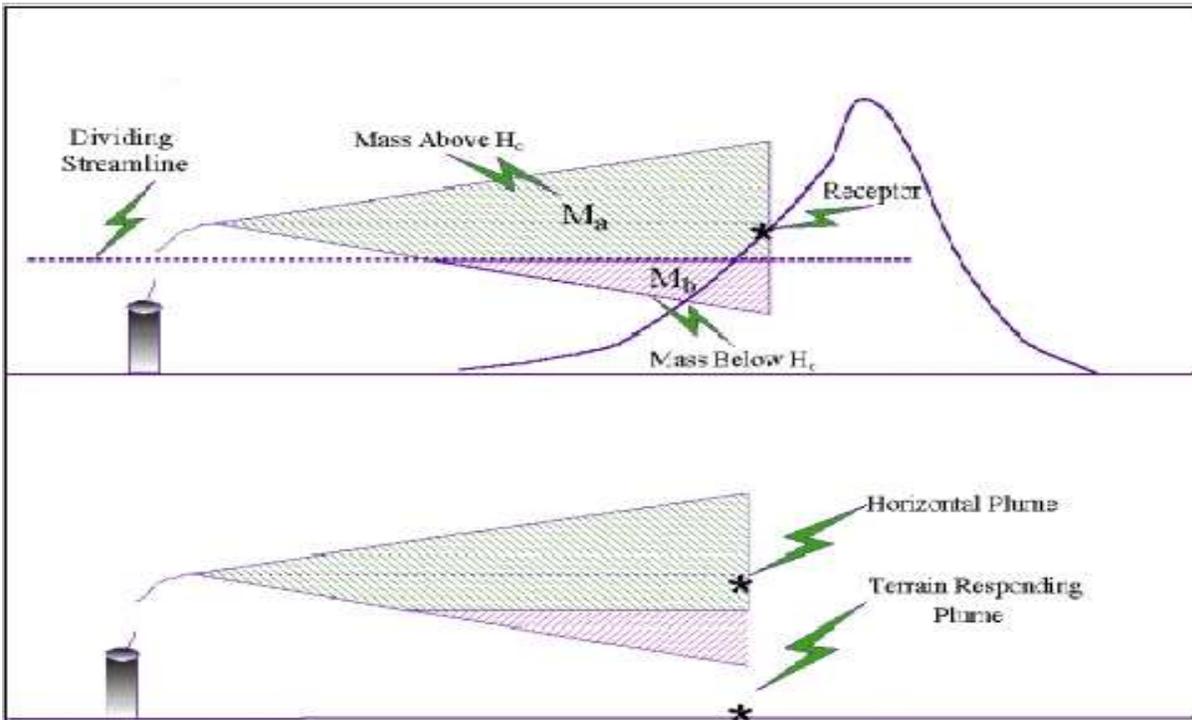


Figure 8: Treatment of Terrain in AERMOD. Construction of the weighting factor used in calculating total concentration (Alan *et al.*, 2004)

The Bowen ratio of 3, albedo of 0.25 and surface roughness of 0.25 were used during modeling. Emission parameters that were used in modeling the dispersion of hydrogen sulphide gas from Olkaria I and Olkaria II power plants are as shown in Table 5

**Table 5: Emission Parameters Used To Model Dispersion Of Hydrogen Sulphide Gas From Existing Olkaria I And Olkaria II Power Stations (Ndeti 2010)**

Parameter	Olkaria I	Olkaria II(unit 1 and 2)	Olkaria II (unit 3)
Height of emission point (m)	19	16	19
Exit velocity (m/s)	20	9.2	8.6
Exit temperature (K)	375	304	303
Diameter of discharge point at tip (m)	0.2	9.14	9.64
Mass emission rate (g/s)	4.46	3.55	3.55

## CHAPTER 4

### 4. RESULTS AND DISCUSSIONS

In this chapter, the results of the analyses are presented and discussed. These include results from temporal and spatial distribution of H<sub>2</sub>S gas due to emission from Olkaria I and Olkaria II power stations, influence of meteorological parameters on the transport and dispersion of H<sub>2</sub>S gas and develop a tool for advising workers and people living around the area of study.

#### **4.1 Temporal Distribution of Hydrogen Sulphide due to Gaseous Emissions from Olkaria I and Olkaria II Power Stations**

The temporal distribution of observed Hydrogen sulphide gas was examined on diurnal scale using simple graphical time series plots. The results of the observed diurnal variation are presented in the following sub-sections.

##### **4.1.1 Temporal Distribution of the Observed Hydrogen Sulphide gas due to Gaseous Emissions from Olkaria I and Olkaria II Power Plants**

The mean temporal distribution of H<sub>2</sub>S gas concentration on diurnal scale is presented in Figure 9. The analysis indicates that, the concentration of ambient Hydrogen sulphide gas distribution at Olkaria I power plant was high during the period 1900hrs to 0700hrs local time. It ranges from a low of 0.14ppm that was recorded at 1900hrs on day 4 during the monitoring period, to a high value of 4.59 ppm that was recorded at 0200hrs on day 3 during the monitoring period. The diurnal variations of Hydrogen sulphide gas at Olkaria II power plant have minimum concentrations between 1400hrs and 1600hrs and a maximum between 0000hrs and 0200hrs. This is an indication that the concentrations of Hydrogen sulphide gas are higher between 2100hrs and 0600hrs where stable atmospheric conditions prevail when no convective activities are taking place, wind speeds are low and calm conditions prevail.

Hydrogen sulphide gas concentrations are fairly high at Olkaria I power station site in comparison to Olkaria II power station. This can be attributed to the chemistry of the steam field and the mode of which the gas is being released into the atmosphere. At Olkaria II power plant the gas is released through the cooling towers thus achieving more dilution unlike Olkaria I

power plant, the gas is released through the gas ejectors hence resulting into the observed variation in the concentrations.

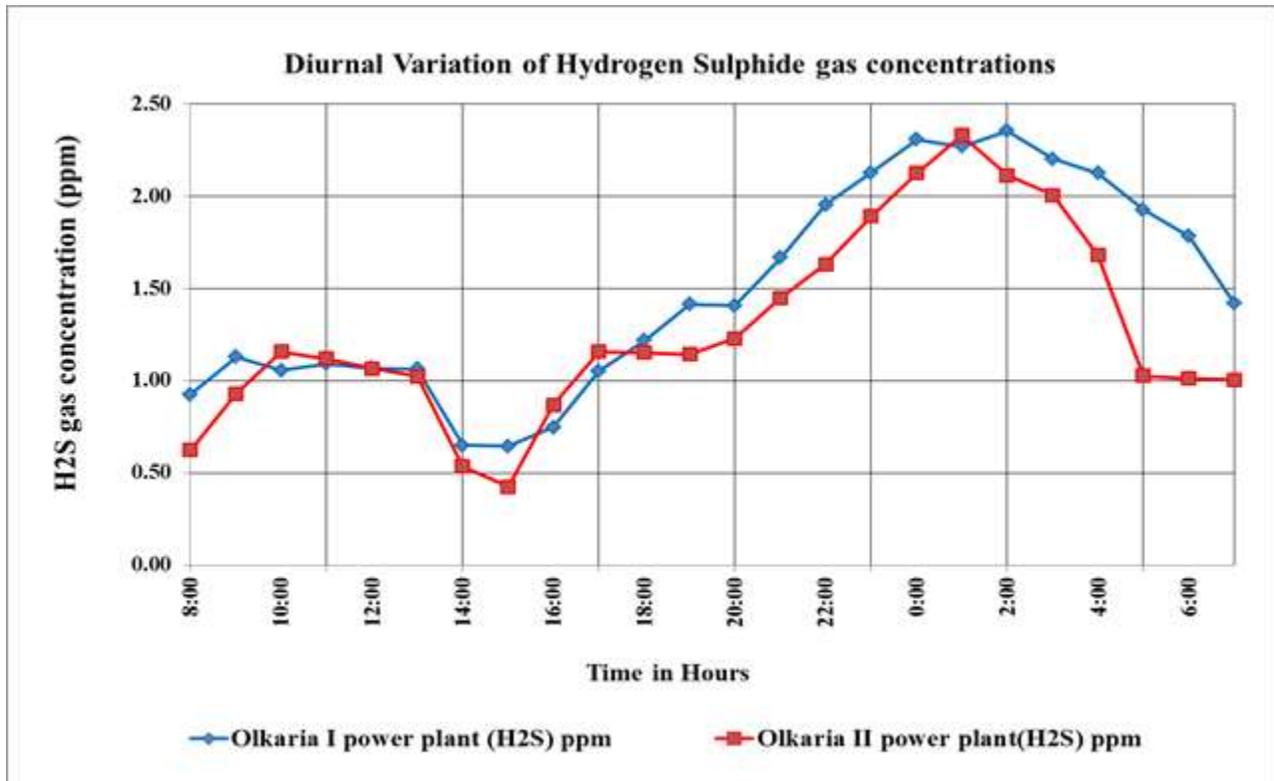


Figure 9: Diurnal variation of Hydrogen sulphide gas concentrations at Olkaria I and Olkaria II power plants for November 2011.

#### 4.1.2 Diurnal Variation of Hydrogen Sulphide Gas Concentration and Prevailing Wind Speed

Diurnal variation of Hydrogen sulphide gas concentration was analyzed in relation to the prevailing wind speeds in the greater Olkaria geothermal area. The graphical analysis (Figure 10) indicates that the observed wind speeds are relatively high (> 4 m/s) between 1200hrs and 1700hrs and this is attributed to the convective activities taking place around this time of the day. Surface wind speed peaks in the early afternoon. During this period the concentrations of ambient Hydrogen sulphide gas is low as there is rapid dispersion of H<sub>2</sub>S gas by wind away from the source point. Between 2000hrs and 0800hrs the prevailing wind speed is low (< 3 m/s) in the area with minimal variation hence resulting to the prevailing high concentration of ambient Hydrogen sulphide gas.

This diurnal analysis indicates that the concentration of Hydrogen sulphide gas in Olkaria geothermal area is highly dependent on the prevailing wind speed for its transport and dispersion. From this analysis the scientist are meant to carry out continuous monitoring of Hydrogen sulphide gas especially when calm condition prevail. Moreover they should sensitize the employees and people living around the power plant so that they are informed of the precautions to take when such conditions prevail.

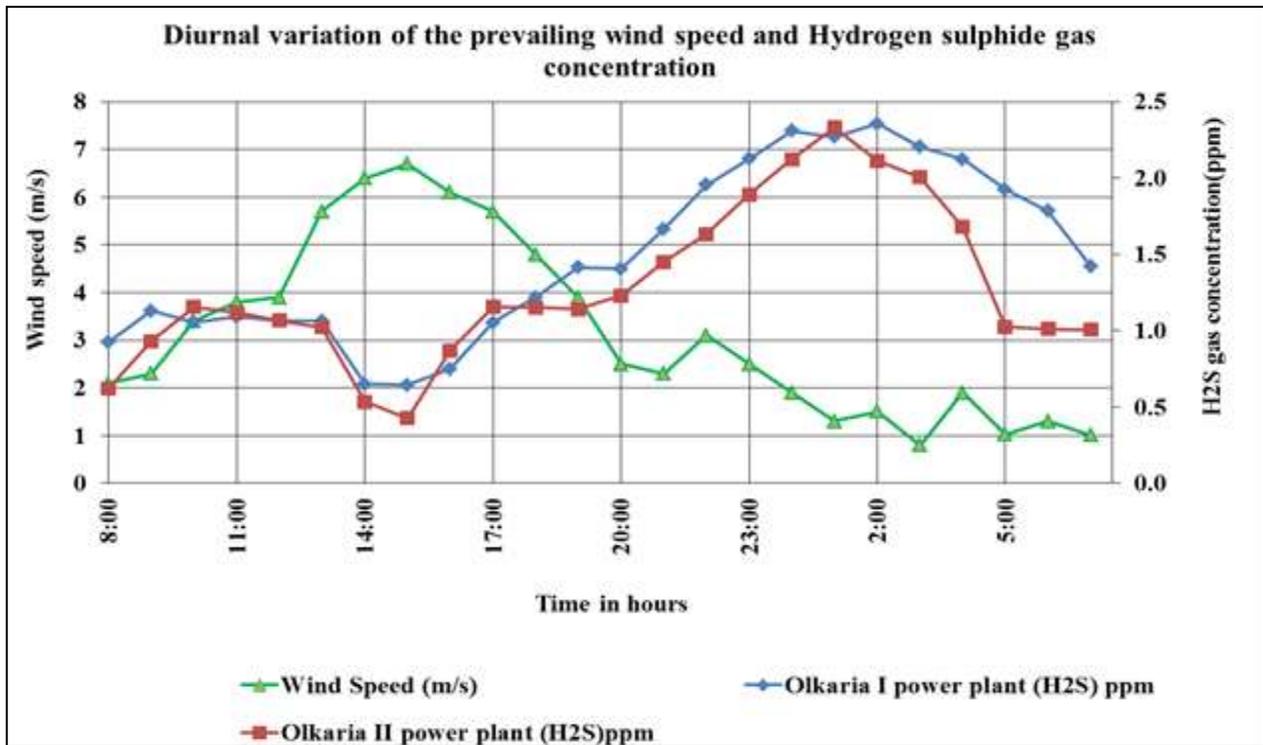


Figure 10: Diurnal variation of Hydrogen sulphide gas concentration in relation to the prevailing wind speed at the Greater Olkaria Geothermal Area for November 2011.

#### 4.1.3 Diurnal Variation of Hydrogen Sulphide Concentration and Ambient Air Temperature

A change in concentration of Hydrogen sulphide gas with the prevailing air temperatures was analyzed. Graphical analysis (Figure 11) indicates that the concentration of Hydrogen sulphide gas at a given time of the day is influenced by the prevailing ambient air temperatures in the locality and/or the vicinity surrounding the source of the gas. Between 1100hrs and 1900hrs the H<sub>2</sub>S gas concentration is lower as compared to the period 2100hrs to 0700hrs when the

concentration is higher as displayed in Figure 11. This shows that there is a relationship between H<sub>2</sub>S gas concentration, transport and dispersion and the prevailing daytime and night time ambient air temperatures.

During daytime hydrogen sulphide gas concentrations are relatively lower in relation to the concentrations during the night and even in terms of odour. This can be attributed to the prevailing unstable conditions during the day as a result of heating of the lower atmosphere which increases mixing of the faster-moving air. The air temperatures peak in the afternoons as air keeps net absorbing heat. At nighttime up to early morning the H<sub>2</sub>S gas concentrations are relatively higher due to the prevailing stable conditions as a result of cooling of the lower atmosphere. When there is a temperature inversion the air flow is laminar, leading to little dispersion and the mean concentration rises further. In regards to this kind of a scenario, there should be less activities taking place during the night and early morning hours. In a situation where activities related to generation of geothermal energy must continue, air should be heated especially in confined place where there are people working to avoid accumulation of the sour toxic gas.

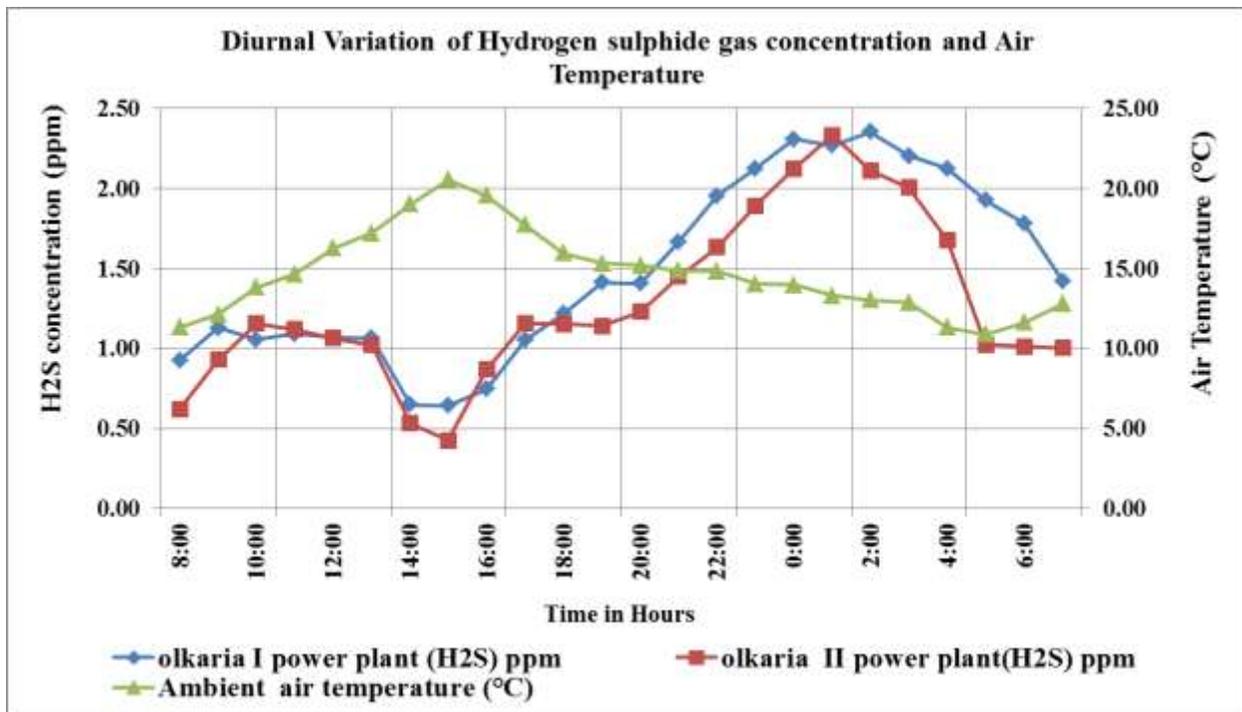


Figure 11: Diurnal variation of Hydrogen sulphide gas concentration with the prevailing ambient Air Temperature for November 2011.

#### 4.1.4 Diurnal Variation of Hydrogen Sulphide Gas Concentration and Relative Humidity

Relative Humidity was considered in this study as one of the parameters that influences the concentration of H<sub>2</sub>S gas concentration in the atmosphere. Results indicated that when the Relative Humidity is higher in the atmosphere the concentration of Hydrogen sulphide gas is also higher as displayed in the graphical analysis below (Figure 12).

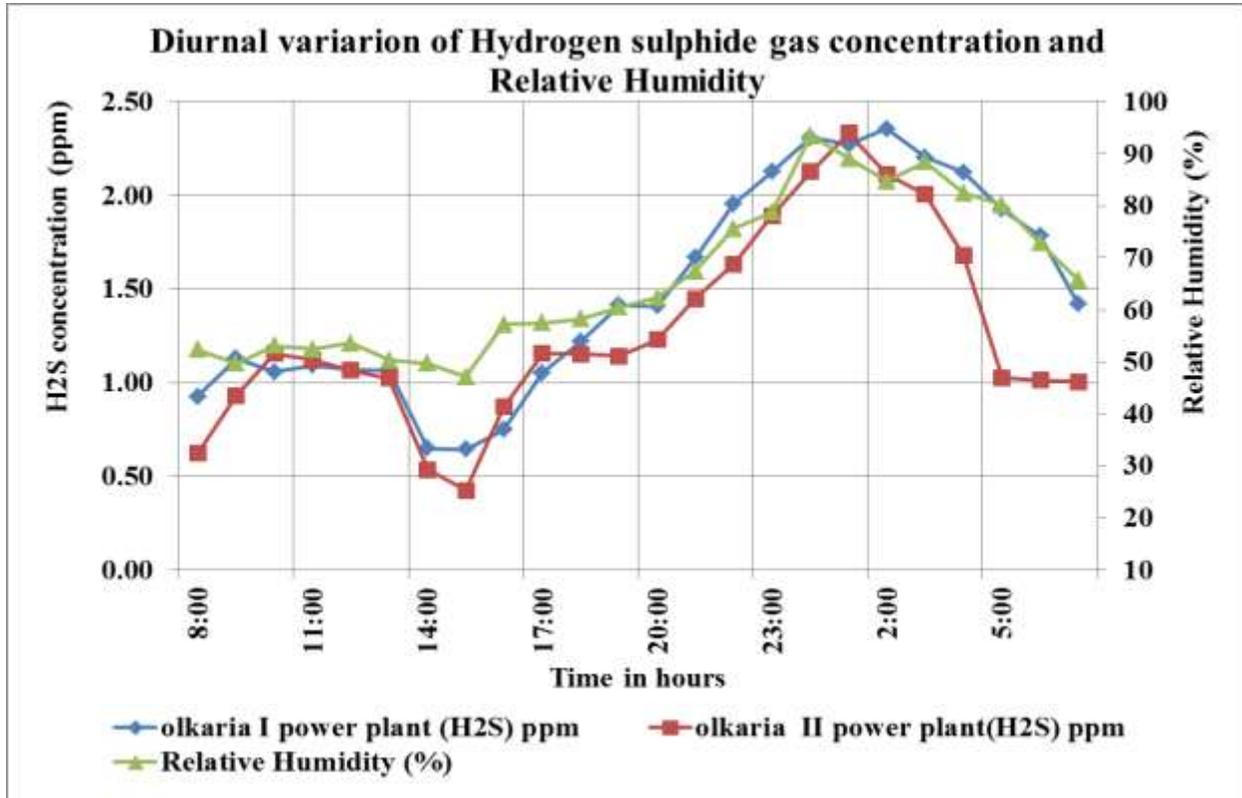


Figure 12: Diurnal variation of Hydrogen sulphide gas concentration and relative humidity for November 2011.

#### 4.2 Correlation analysis of Hydrogen Sulphide Gas and Meteorological Parameters

This section presents results that were obtained from correlation analysis between Hydrogen sulphide gas and prevailing meteorological parameters (Table 5). From the analysis, it was found out that correlation coefficient ranged between -0.36 to -0.59 for air temperature. This shows that there was a negative correlation between Hydrogen sulphide gas concentrations and prevailing air temperature in the greater Olkaria geothermal area during the period of analysis. This shows

that Hydrogen sulphide gas concentrations are high when the prevailing air temperatures are low and the inverse is true.

Correlation coefficient for relative humidity ranged from 0.86 at Olkaria II to 0.96 at Olkaria I. This shows that there is a strong positive relationship between H<sub>2</sub>S gas concentration and relative humidity in the GOGA area. This is an indication that when the Relative Humidity is high in the atmosphere a lot of caution should be exercised during this time when such conditions are prevailing because it is not obvious that rain out or wash out will take place.

Correlation coefficient between wind speed and H<sub>2</sub>S gas concentration showed a negative relationship. This relationship shows that when the prevailing winds speeds are relatively high, H<sub>2</sub>S gas concentrations in the study area are relatively lower and vice versa, indicating that H<sub>2</sub>S concentration is highly dependent on strength of the prevailing wind speed in a given locality. A summary of the correlation results are presented in Table 6;

**Table 6: Correlation Coefficients Between Hydrogen Sulphide Gas Concentration And Prevailing Meteorological Parameters**

	CORRELATION COEFFICIENT(r) VALUES		
ELEMENT	Wind speed (m/s)	Air temperature(°C)	Relative Humidity (%)
H <sub>2</sub> S concentration. at Olkaria I power plant	-0.74407	-0.59448	0.957611
H <sub>2</sub> S concentration. at Olkaria II power plant	-0.57839	-0.36108	0.859268

#### 4.3: Analysis of Seasonal Wind Roses in the Area of Study

Seasonal plots of wind roses for the Greater Olkaria geothermal area were plotted using WRPLOT view software version 7.0.0. The results indicated that during MAM, JJA and OND seasons, the winds are predominantly southeasterly as displayed by the graphical plots in Figure 13a, Figure 14a and Figure 15a respectively. A different scenario is seen in Figure 16a where the winds are randomized in all directions during DJF season. It is noted that there were a number of

calm conditions prevailing in all the seasons analyzed ( figure 13b, 14b , 15b and 16b) hence this is an indication that during this times of the day a lot of monitoring should be carried out to prevent health impacts due to accumulation of the sour gas.

From the results of wind rose plots, it shows that from the month of March to December the gaseous emissions are transported towards North West, hence people should avoid staying downwind for longer periods of times.

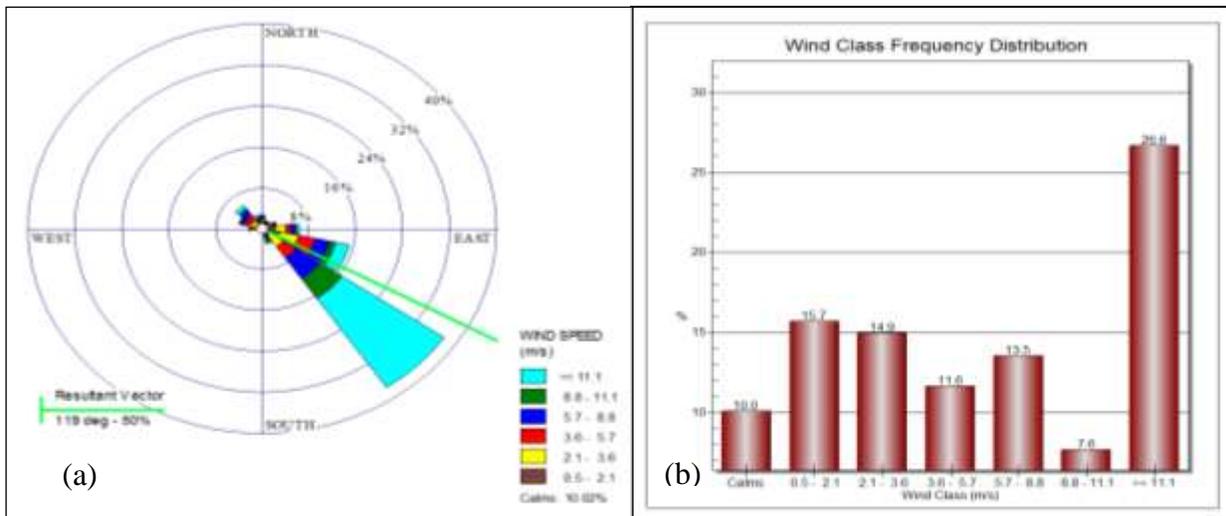


Figure 13 ( a & b): March-April-May seasonal wind rose plot and wind speed class frequency distribution for the year 2011

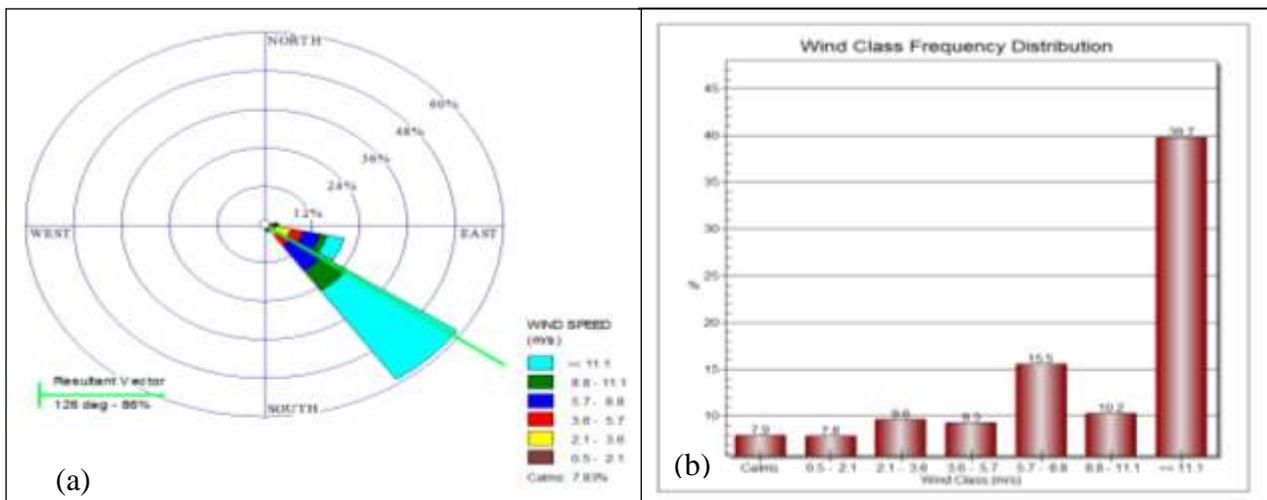


Figure 14 ( a & b): June-July-August seasonal wind rose plot and wind speed class frequency distribution for the year 2011

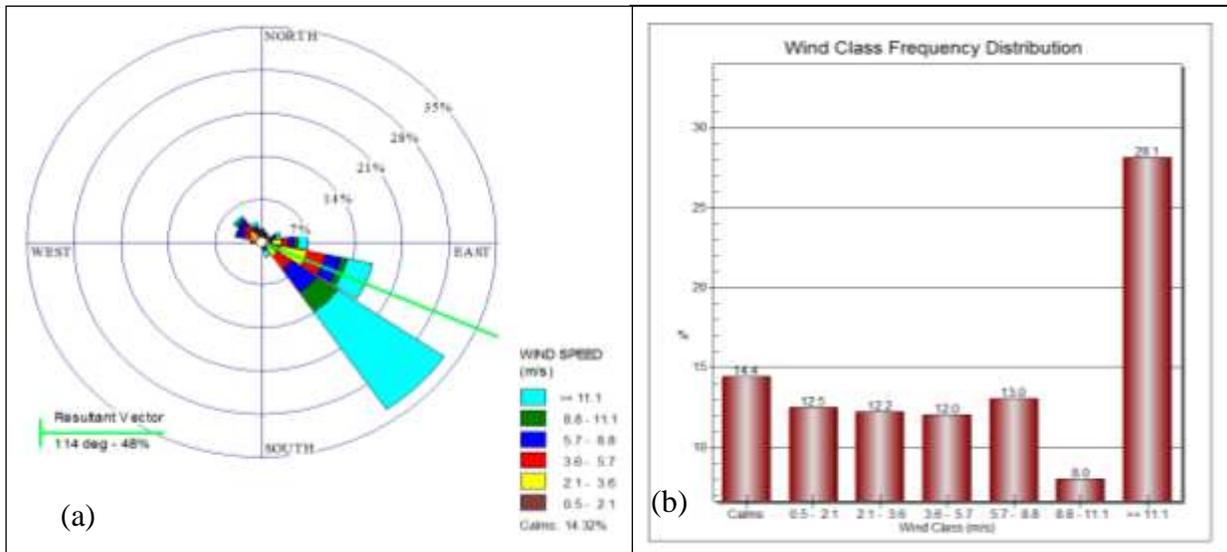


Figure 15 (a & b): October-November-December wind rose plot and wind speed class frequency distribution for the year 2011

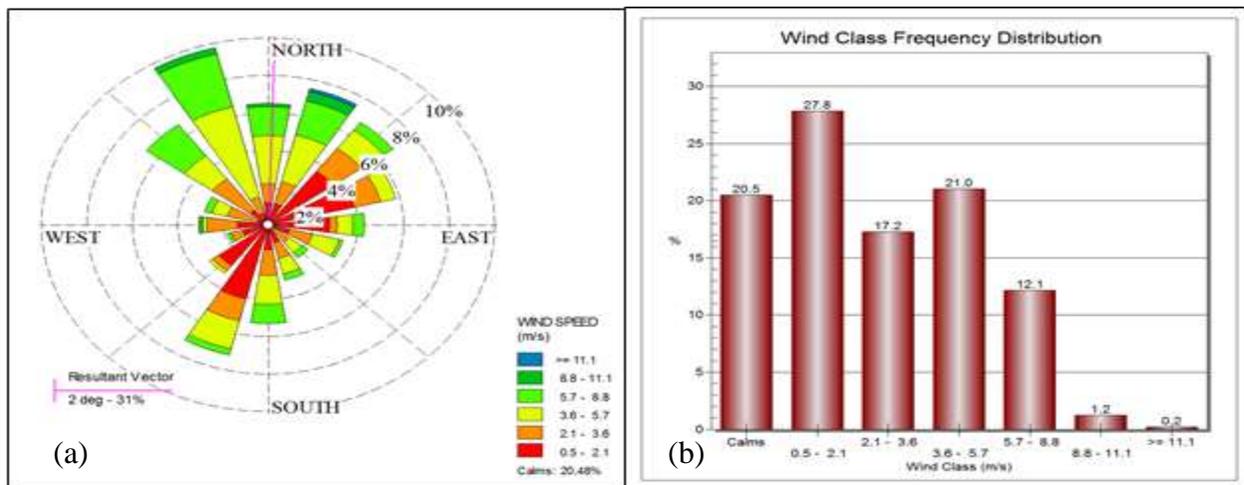


Figure 16(a & b): December-January-February wind rose plot and wind speed class frequency distribution for the year 2011

#### 4.4: Spatial Analysis Of Hydrogen Sulphide Gas Fallout In Olkaria I And Olkaria II Power Stations

To analyze the spatial distribution of Hydrogen sulphide gas fallout in Olkaria I and Olkaria II power stations, spatial maps were plotted using the ninth version of surfer software. From the spatial maps (Figure 17 and 18), it is noted that relatively high concentrations of Hydrogen

sulphide gas were recorded at Olkaria I power plant than as at Olkaria II power plant. This is probably because the route of emission to the atmosphere is through the gas ejectors. A high value of 2.36 ppm of H<sub>2</sub>S gas concentration was recorded at close proximity to the power station with an average diurnal concentration of 1.47 ppm.

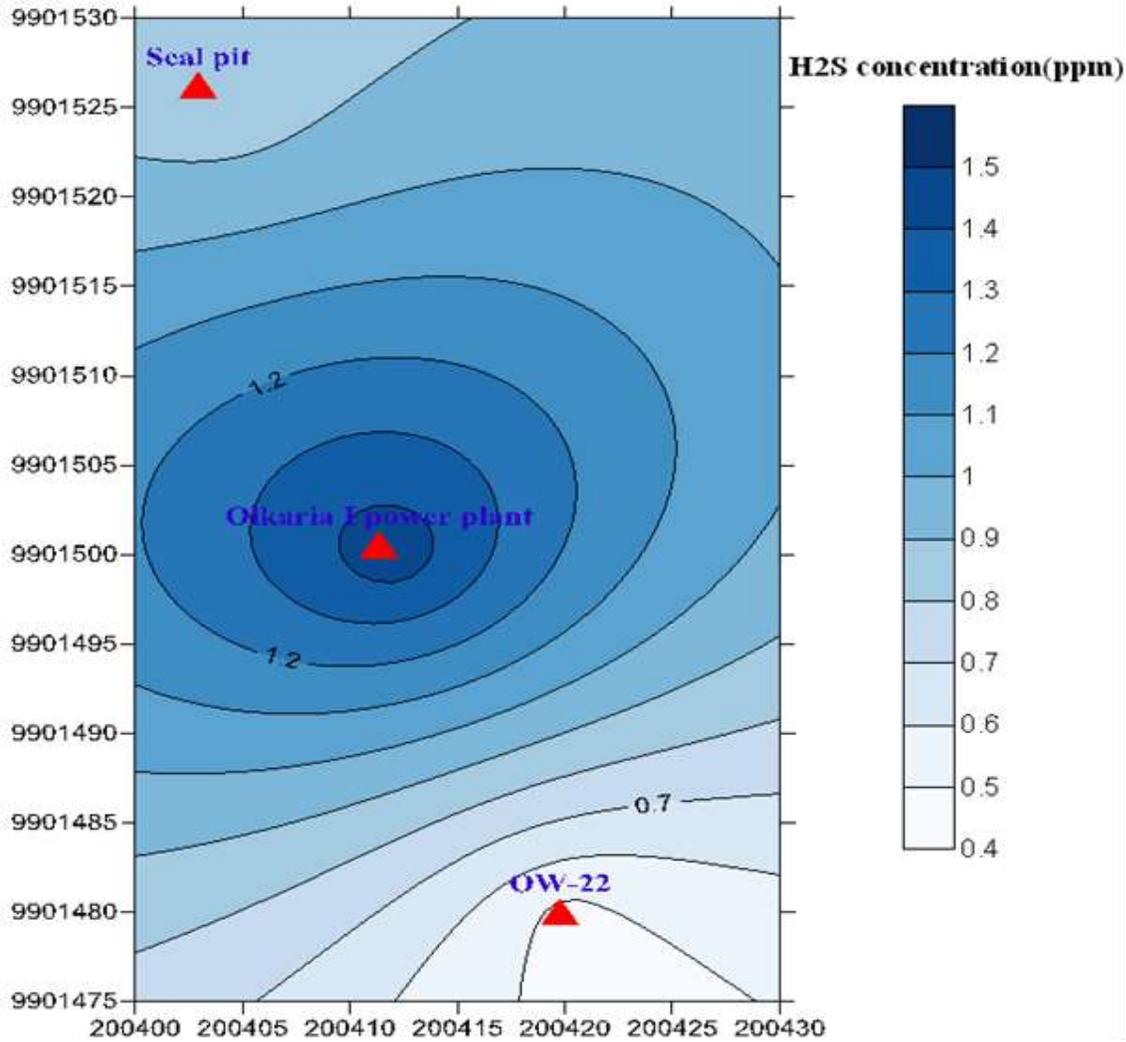


Figure 17: Spatial variation of H<sub>2</sub>S gas (ppm) at Olkaria I power station

The highest recorded concentration of H<sub>2</sub>S gas at Olkaria II power plant was 2.03 ppm. From the analysis, the diurnal average concentration of Hydrogen sulphide gas was 1.26 ppm (Figure 18). It was further noted that the gas was transported and dispersed away such that the concentration at the Kenya Wildlife Service gate which is approximately 600 m from Olkaria II power station was as low as 0.001 ppm which could hardly be sensed through smelling.

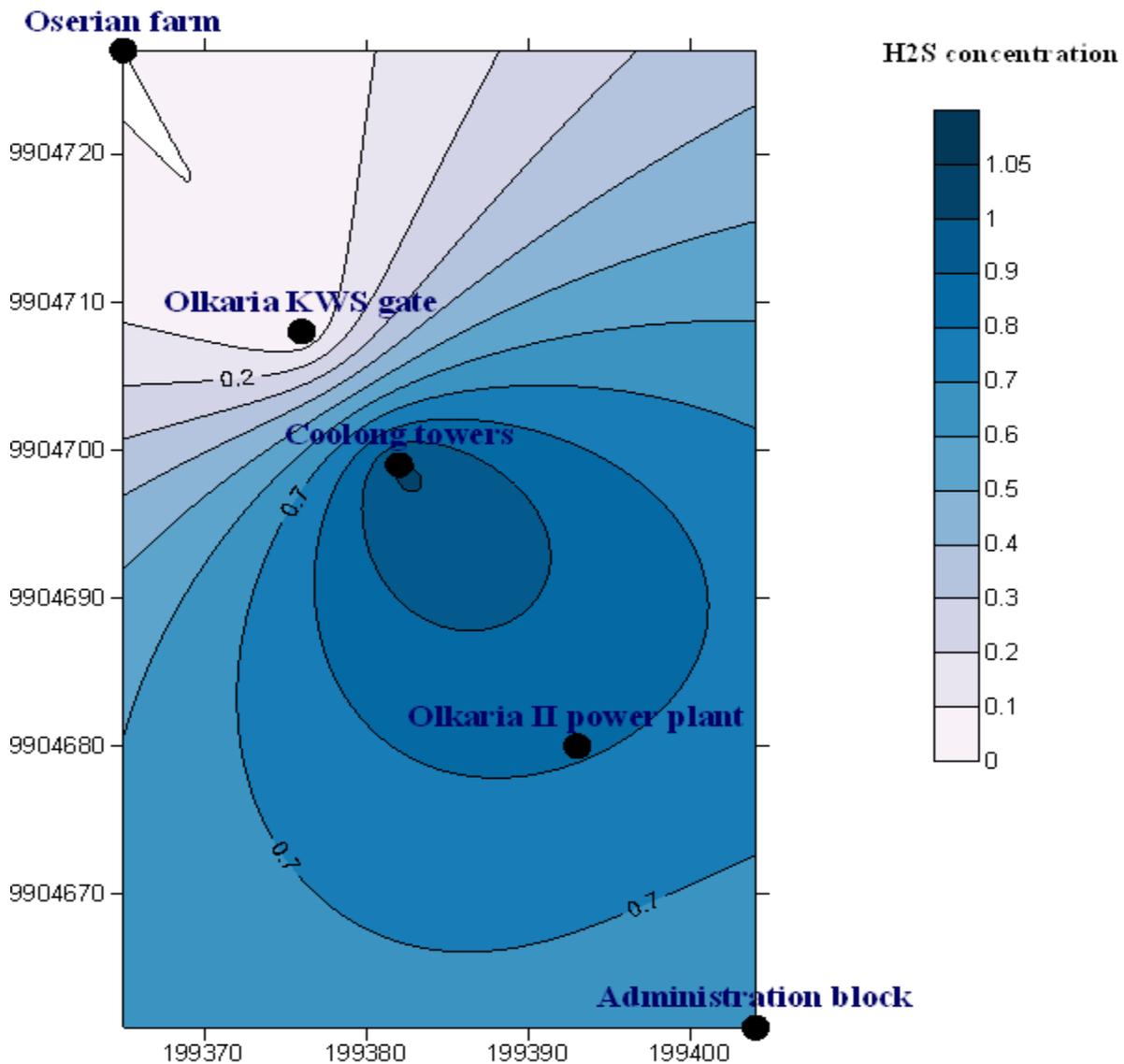


Figure 18: Spatial variation of H<sub>2</sub>S (ppm) at Olkaria II power station

Spatial maps (Figure 17 and Figure 18) shows that higher concentrations of H<sub>2</sub>S gas were recorded close to the stations. Comparing the two figures, it can deduced that the power station with the cooling towers (Olkaria II power plant) achieved better dispersion that the one that has gas ejectors (Olkaria I power plant). From this spatial analysis it can be recommended that future power plants to be designed should consider use of cooling towers be incorporated into the designing of the plants.

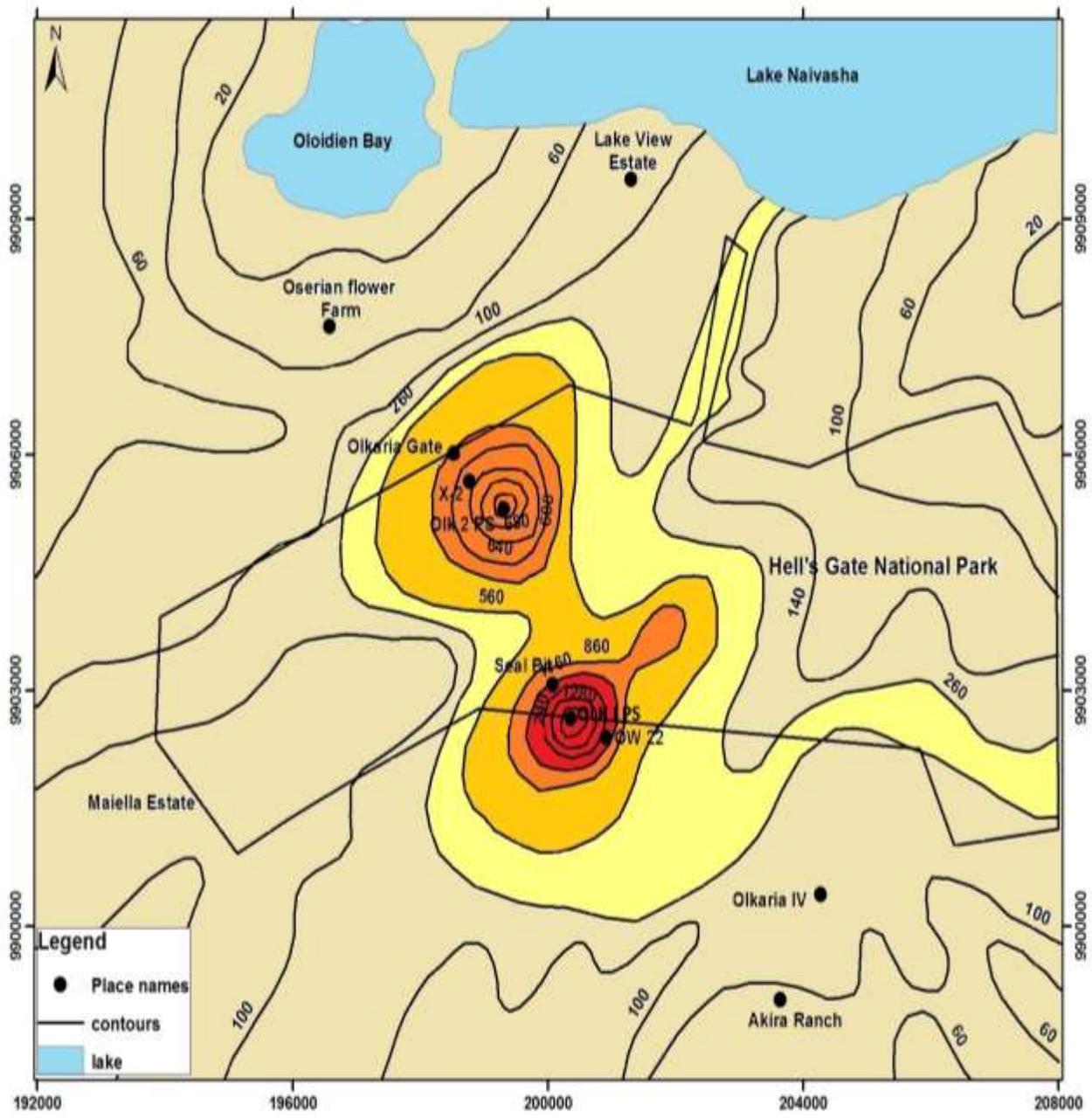
## **4.5 Modeling Results For Hydrogen Sulphide Gas Dispersion for Olkaria I And Olkaria II Power Stations**

The Hydrogen sulphide gas transport and dispersion modeling for Olkaria I and Olkaria II power plant was done using Aermod software. The result indicates that generally high concentrations of H<sub>2</sub>S gas were predicted to occur near Olkaria I and Olkaria II power plants. It was further noted that higher concentrations of H<sub>2</sub>S gas were recorded at Olkaria I power plant in comparison to those recorded at Olkaria II power plant. The averaging times that were considered in this study are one-hour averaging period (1-hr), eight-hour averaging period (8-hr) and twenty four- hour averaging period (24-hr). The AERMOD model outputs the H<sub>2</sub>S gas concentrations in  $\mu\text{g m}^{-3}$ .

### **4.5.1 Concentrations Averaged Over One-Hour Period**

One-hour averaging period was done so as to find out the predicted concentrations of H<sub>2</sub>S gas emitted around the source in 1 hour and its transportation away. The results averaged over one-hour period shows that the highest predicted H<sub>2</sub>S concentration was  $1240 \mu\text{g m}^{-3}$  (Figure 19). This highest concentration occurred close to Olkaria I power station which is one of the permanent sources of Hydrogen sulphide gas. This is attributed to gaseous emission from Olkaria I power plant and Olkaria II power plant which are the permanent continuous point sources. Moreover from the Figure 19, it shows that at that particular time the plume was mainly dispersed towards Northeast. The plume was transported away from the source such that at a distance of about 700 m towards the Olkaria domes (downwind) the concentration had reduced to  $142 \mu\text{g m}^{-3}$ . This is an indication that the prevailing atmospheric conditions contributed in transporting and diluting the gas away from the source.

At Olkaria II power plant the scenario was different as it is observed in Figure 19. The plume from the cooling towers was dispersed generally in all directions. This is attributed to the prevailing atmospheric conditions at that given time and the way the gas is being released into the atmosphere.



#### 4.5.2 Hydrogen Sulphide Concentrations Averaged Over Eight- Hour Period

The results for the predicted H<sub>2</sub>S gas concentrations averaged over 8-hour period showed that the highest concentration was 294 µg m<sup>-3</sup>. This was noted to occur close to Olkaria I power plant. The Hydrogen sulphide plume produced from Olkaria I power station was transported and dispersed to the Northwest.

At Olkaria II power station the plume was noted to concentrate near the station though the H<sub>2</sub>S gas concentrations were relatively lower giving 171 µg m<sup>-3</sup> compared to emissions at Olkaria I power station (Figure 20). Hence continuous monitoring should be carried out to avoid related health impacts given that Hydrogen sulphide gas is heavier than air thus it can accumulate in low lying areas.

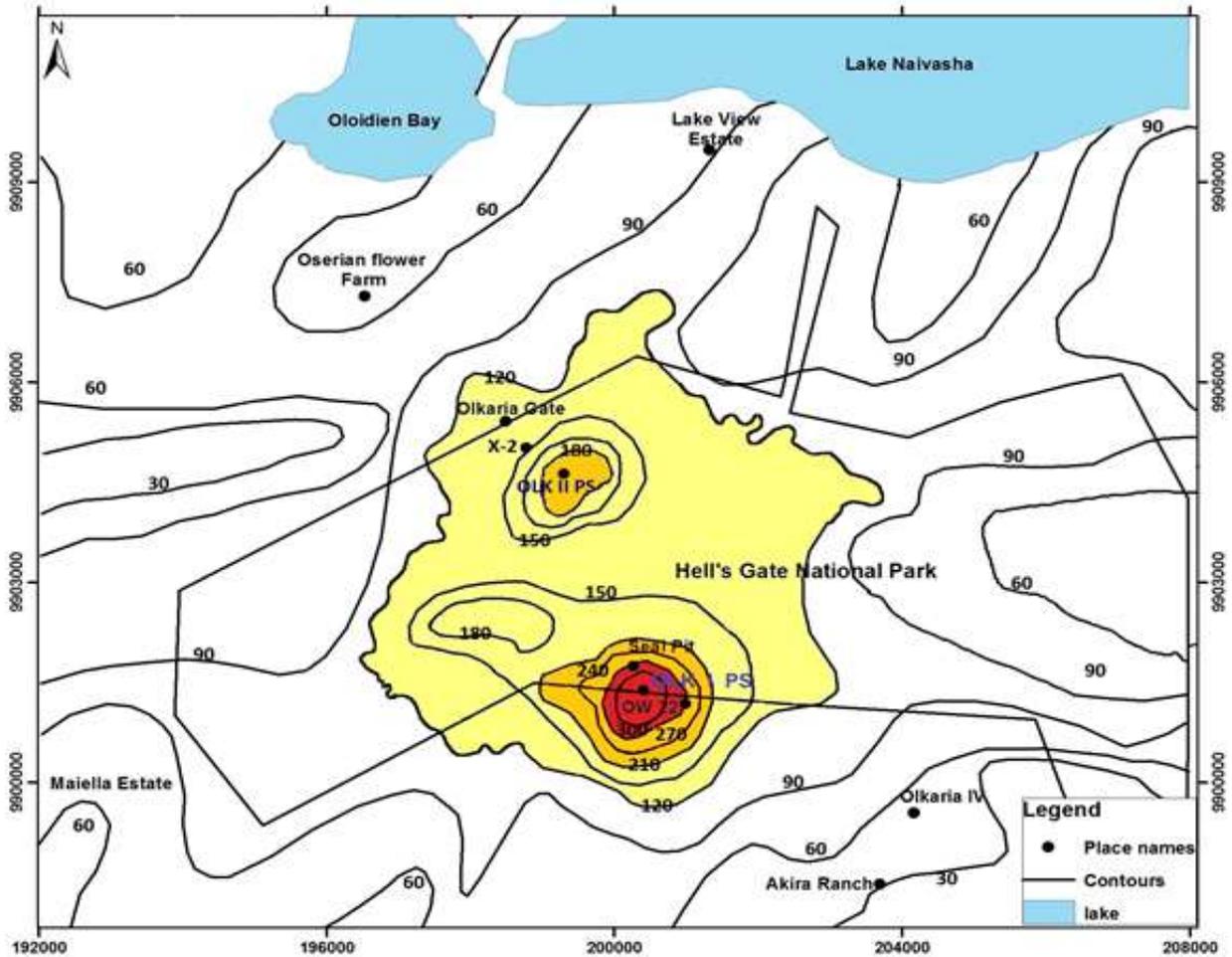


Figure 20: Predicted eight-hour averaged H<sub>2</sub>S gas concentration (µg/m<sup>3</sup>) due to emission from Olkaria I and Olkaria II power plants

### 4.5.3 Hydrogen Sulphide Concentrations Averaged Over Twenty Four - Hour Period

The 24-hour averaging was done so as to determine the concentration of H<sub>2</sub>S gas in a given day. From the modeling results, the highest predicted 24-hour averaged concentration was 102 µg m<sup>-3</sup> which is in proximity to Olkaria I power station (Figure 21).

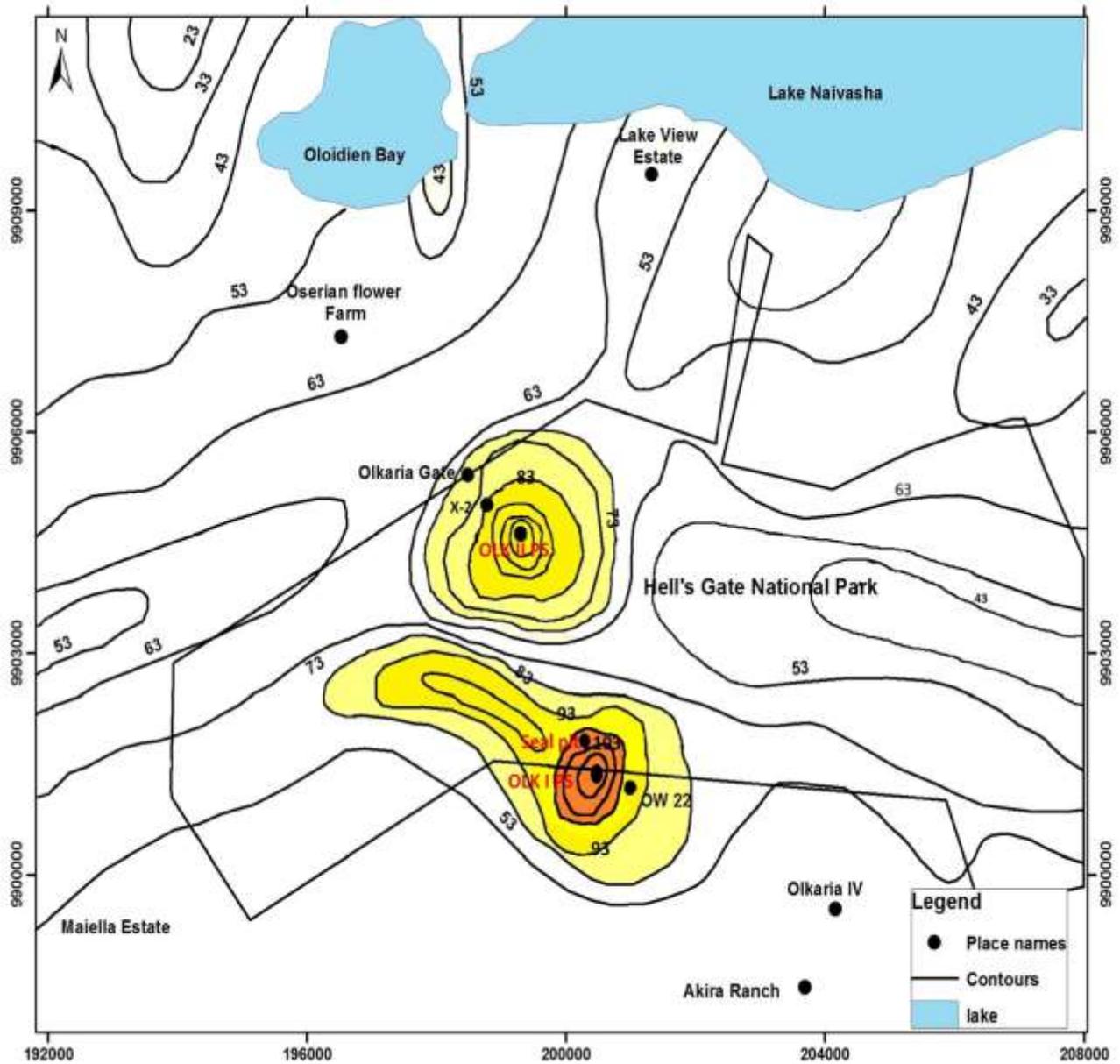


Figure 21: Predicted twenty four -hour averaged H<sub>2</sub>S gas concentration (µg/m<sup>3</sup>) due to emission from Olkaria I and Olkaria II power plants

Hydrogen sulphide plume produced from Olkaria I power station (Figure 21) was transported and dispersed in the northwest direction. At Olkaria II power station the highest predicted H<sub>2</sub>S gas concentration was 83 µg m<sup>-3</sup>. Given the guidelines on 24-hour averaging time by (WHO 2000), the dispersion model results indicated that 24-hour average H<sub>2</sub>S gas concentrations due to emissions from Olkaria I and Olkaria II power stations were below the WHO threshold limit value of 150 µg m<sup>-3</sup>.

Results from Figure 19, 20 and 21 shows that the concentrations of Hydrogen sulphide gas at Olkaria I power plant is higher than those at Olkaria II power plant. This is because the route of emission of NCGs to the atmosphere is through the gas ejectors (chimneys) unlike at Olkaria II power plant is through the cooling towers thus achieving greater transport and dispersion.

However, though the WHO threshold limit for 24 hour concentration of Hydrogen sulphide gas has not been exceeded, continuous monitoring should be carried out at the vicinity of the power plant especially the operation areas. This is because Olkaria IV power plant and the extension of Olkaria I power plant will be operating in the near future thus increasing the concentrations of the gases in the atmosphere.

## CHAPTER FIVE

### 5. CONCLUSIONS AND RECOMMENDATIONS

This chapter provides conclusions from the results and recommendations for further work.

#### 5.1 CONCLUSIONS

Hydrogen sulphide gas concentrations vary widely in the Greater Olkaria geothermal area. Considering the gross output of H<sub>2</sub>S gas at the power plants being constant, the concentrations of H<sub>2</sub>S gas at a given locality would depend on the prevailing weather conditions particularly wind speed and also the distance away from the source.

Meteorological parameters are important elements that contribute to the air quality in a given locality. Meteorological parameters that were assessed in relation to the transportation and dispersion of H<sub>2</sub>S gas away from the source showed that there is a clear relationship between prevailing meteorological conditions and the concentration of H<sub>2</sub>S gas at a given time around the power stations. This is confirmed by the graphical and correlation result obtained in the study. Generally it can be concluded that increased wind speeds, high ambient air temperature would greatly reduce the ambient concentration levels of Hydrogen sulphide gas as the air becomes more turbulent and the plume is dispersed away.

In the averaging times that were considered, the highest predicted H<sub>2</sub>S gas concentrations at Olkaria were close to the main gas emission sources and reduced rapidly away with distance. The results from temporal analysis suggest that H<sub>2</sub>S concentrations are high between 2000hrs and 0600hrs local time. In regard to this a policy statement on Hydrogen sulphide concentrations should be put in place by the company. Moreover, continuous monitoring done when the winds remain calm, ambient air temperatures are low for an extended period of time. Results from spatial analysis and AERMOD dispersion model showed that concentrations of H<sub>2</sub>S gas decrease away from the source.

The results obtained in this study can go a long way in carrying out the monitoring in the power plants and the surrounding areas. Hence it is very useful in sensitizing the workers and people

living around the power plant. The main objective of this study was therefore achieved in that the prevailing meteorological conditions were found to influence the concentration of Hydrogen sulphide in terms of transport and dispersion at any given time around the power plants.

## **5.2 RECOMMENDATIONS**

The recommendations presented in this study are:

- ❖ Information on the concentration, transport and dispersion of Hydrogen sulphide gas is very important hence it should be disseminated to the public and especially those working in the power plant to ensure that they are informed for their safety.
- ❖ The times with high H<sub>2</sub>S gas concentration can be predicted by using a current weather forecast.
- ❖ For proper and accurate dispersion modeling to be done, continuous data sets should be available. There is need for continuous long term data collection for both meteorological parameters and Hydrogen sulphide gas. This is because meteorological fields supplied to air-quality models may contain significant uncertainties and inaccuracies which adversely affect air quality simulations.
- ❖ Research needs to be done to find out if Hydrogen sulphide can be reinjected with brine so as to eliminate environmental pollution totally from artificial sources.

## ACKNOWLEDGEMENTS

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