MODELING H_2S DISPERSION FROM PROPOSED MENENGAI GEOTHERMAL POWERPLANT

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A Thesis Submitted in Partial Fulfilment of the Requirements for the Award of the Degree of Master of Science in Geothermal Energy Technology, in Geothermal Energy Training & Research Institute, Dedan Kimathi University of Technology.

December, 2018.

DECLARATION

This thesis is my original work and has not been presented in any University/institution for a degree or consideration of any certification.

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G296-03-012/2013

Supervisors' declaration:

We/I confirm that the work reported in this thesis was carried out by the candidate under my/our supervision as University supervisor(s)

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DEDICATION

I dedicate this research to my husband and daughter for their continued support throughout the study period.

ACKNOWLEDGEMENT

I dully thank the entire GDC team for support with the project as well as the Director of Geothermal Training Institute Prof. Nicholas Mariita. Sincere thanks to my supervisors Dr. Douglas Onyancha, Dr. Pacifica Ogolla and Prof Peter Muchiri for accepting to supervise and give guidance until the completion of this work. Moreover, I express my most profound gratitude to my family, friends, relatives, and workmates for their encouragement, sacrifice, and unconditional love during my study. Above all, I glorify the Almighty God for His love, care, and mercy that has seen me to this point.

ABSTRACT

The Hydrogen sulfide gas released from the geothermal operations has a potential impact on the health of the workers and the community living within the vicinity and also the geothermal equipment. Similarly, this gas is a toxic pollutant when released into the atmosphere. Additionally, this gas is corrosive to metal-based materials including brass and iron when dissolved in water. In this regard, there is need to manage the concentrations of hydrogen sulfide in the atmosphere at acceptable levels without detrimental effects to components of the biosphere. The purpose of the research was to assess the concentrations of hydrogen sulfide within the vicinity of the power plant by use of a dispersion model.

The technique is carried out using atmospheric dispersion modeling system (AERMOD) which is a steady-state Gaussian model to determine the hydrogen sulfide concentrations in the atmosphere within the vicinity of the power plant. To achieve this goal, hourly meteorological data were captured and input to the Aermet processor. Since weather conditions heavily influence H_2S concentration, statistical analysis was used to determine a correlation between the weather parameters and H_2S concentration. As such, it provided a basis to determine the likelihood of conditions that may exceed the recommended concentrations and their potential effects on the environment. The prepared background and predictive model when combined show that although operations at Menengai Geothermal Project emit H_2S gas, the concentrations are below the WHO set guidelines of 150 $\mu g\ m^{-3}$ and therefore have a less impact on air quality. This research contributes to theory since no previous modeling on hydrogen sulphide gas has been done in Menengai. The findings are beneficial as part of regulations for air quality standards to reduce global warming and environmental degradation, the introduction of H_2S abatement techniques and reduction strategies.

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ACRONYMS AND ABBREVIATIONS:

ACGIH	American Conference of Government Industrial Hygienists
ATSDR	Agency for Toxic Substances and Disease Registry
H_2S	Hydrogen Sulfide
CO_2	Carbon Dioxide
CH_4	Methane
NCG	Non-Condensable Gases
OSHA	Occupational Safety and Health Administration
PEL-C	Permissible Exposure Limit- Ceiling
REL-C	Recommended Exposure Levels- Ceiling
STEL	Short Term Exposure Limit
TLV	Threshold Limit Value
TWA	Time-Weighted Average
WHO	World Health Organization

CHAPTER ONE
INTRODUCTION

1.1 Research Background

The growing demand for energy has created the need for countries to develop sustainable sources of power to meet the socio-economic development agenda. Consequently, this has forced many countries to look for alternative renewable sources of power. Geothermal power provides solutions since it is clean and sustainable. As such, Kenya has increasingly invested in geothermal energy to ensure a stable supply of energy to facilitate its industrialization agenda enshrined in the vision 2030(Simiyu, 2010).

Geothermal energy is termed as a renewable energy resource because the interior of the earth maintains a limitless supply of heat energy. Sources assert that the pressure in the Earth's interior will retain this status in billions of years to come thus keeping a reliable supply of heat for the present and future generations. Geothermal power plants are specifically designed to capture and convert this heat into electricity. Nevertheless; geothermal development poses a challenge to the environment including surface disturbances, thermal effects, physical, noise, gas emissions and effects due to fluid withdrawal.

1.2 Problem Environment

The global impact of air pollution has been quantified to be quite extensive. Specifically, air pollution has direct and indirect effects on humans. For instance, the human body absorbs the chemicals released from the geothermal sources posing a danger to the respiratory system and the human body at large(Simiyu, 2010). Additionally, the pollutants released from geothermal development can affect the structure and functions of the ecosystems posing a danger to flora and fauna. Sources confirm that the geothermal fluids contain a number of non-condensable gases (NGC) such as CO_2 and CH_4 which are released to the atmosphere courtesy of the diffusive gas discharges (Seaman, 2000).

Release of NCG to the atmosphere at any phase of the geothermal operation changes the chemical composition of the air within the vicinity. Among the NCG emitted, H_2S has a significant effect on the environment. The other gases emitted are CO_2 and CH_4. Studies conducted in various geothermal fields around the world reveal the harmful effects of hydrogen sulfide gas emissions on the nearby towns. Consequently, regulations have been put in place that requires geothermal power plants to reduce the level of emissions (Gunnarsson et al., 2013). This study mainly underscores the impact of the emission of gases from the geothermal steam.

1.2.1 Hydrogen sulfide pollution

H_2S is a colorless gas with characteristic rotten egg smell that distinguishes it from other gases. It is harmless in small quantities (<0.0047 ppm) and soluble in alcohol and water among other liquids.

OSHA records that the permissible exposure limit for hydrogen sulfide is 10 ppm. Also, OSHA confirms that an individual should not experience a peak exposure of 50 ppm for a duration exceeding 10 minutes. At concentrations between 500-100 ppm, hydrogen sulfide causes respiratory paralysis which translates into unconsciousness and asphyxiation. On the same note, World Health Organization, 2000 asserts that inhaling hydrogen sulfide gas at this concentration can cause death.

As noted earlier, it is difficult to recognize hydrogen sulfide gas at low concentrations. However, the unpleasant odor (rotten egg smell) can help in detecting this gas. At concentrations between 500 and 1000 ppm, this gas can cause conjunctival irritation; also known as ‘gas eye.'

Table 1.1 shows the established dose-effect relationships for hydrogen sulfide.

Table 1.1: Health impacts of H_2S (ATSDR, 2006)

H_2S concentration (ppm)	Effects on Humans
0.0047	The concentration at which humans can detect the rotten egg smell of hydrogen sulfide
10-20	The threshold for eye irritation
50-100	This concentration can cause damage to the eye
150-250	This concentration is associated with the paralysis of the olfactory nerves. Victims lose the sense of smell
320-530	This concentration often leads to pulmonary Oedema and can easily cause death.
500	Exposure for 30 to 60-at this concentration leads to dizziness, a headache and staggering. Also, unconsciousness and respiratory failure often follow these events.
530-1000	Causes intense stimulation of the central nervous system and rapid breathing leading to the lack of breath
800	Lethal concentration for 50% of humans after 5minute exposure
>1000	Hazardous concentration even inhalation of a single breath of this cause leads to immediate collapse associated with loss of breath.

As noted earlier, hydrogen sulfide gas results from natural sources such as hot springs, volcanic and natural gas. However, the breakdown of organic matter by the bacteria can also produce this gas (Chou & Organization, 2003).Table 2 describes the chemical and physical properties of hydrogen sulfide.

Table 1.2: Properties of hydrogen sulfide (Chou & Organization, 2003)

Description	Hydrogen Sulfide
Molecular formula	H_2S
Molar mass	34.08g/mol
Melting point	-85.50C
Boiling point	-60.40C
Solubility in water	0.5 g/100 ml at 20 0C
Vapour pressure	1 atm at -60.4 0C
Density	1.39g/l at 25 0C
Explosive limits	4.3-46 vol% in air
Conversion factor	1 ppm = 1.4 mg/ m3 at 250C

Hydrogen sulfide gas affects various parts of the body when inhaled. It also irritates the nose, skin, respiratory tract and the mucous membrane. Dizziness, headache, and stomach upset are associated with inhalation of hydrogen sulfide concentrations at low concentrations. This gas paralyzes the olfactory nerves at high concentrations. In this light, it is hard to detect the characteristic odor at high concentrations since it deadens the sense of smell. Another notable characteristic is that hydrogen sulfide is heavier than air. As such, it accumulates in poorly ventilated areas such as manholes posing a danger to the humans who might access these places for one reason or another. Hydrogen sulfide produced by natural sources such as thermal springs and volcanic gases have led to some fatal accidents claiming lives of humans animals alike (D'Alessandro, Brusca, Kyriakopoulos, Michas, & Papadakis, 2009).

1.2.2 Hydrogen Sulphide standards

Occupational exposure standards establish the maximum levels of chemical substances that the workers should experience in an occupational environment. The table below records the limits of exposure in an occupational environment informed by the safety limits and the international standards.

Table 1.3: International occupational safety guidelines for H_2S exposure

Occupational Standard	Limit Value		Exposure	Averaging Period
	(Ppm*)	(μg m^{-3})		
ACGIH (2009)	10	14200	TLV-TWA	8 Hour
	15	21300	TLV-STEL	15 minute
OSHA (2006)	20	28400	PEL-C	
NIOSH (2005)	10	14200	REL-C	10 minute
European Commission	5	7100	TLV-TWA	8 hour
	10	14200	TLV-STEL	15 minute

According to (Organization & UNAIDS, 2006) ,the toxicity of H_2S varies depending on the dosage and level of exposure and is classified into three categories, namely acute, sub-acute and chronic.

(Chambers & Johnson, 2009) claim that exposure to low concentrations of hydrogen sulfide results in irritation of the eye, nausea, and shortness of breath among other effects. However, prolonged exposure can be fatal and can result in poor memory, fatigue, and loss of appetite. Due to the effects caused by long-term exposure, WHO puts firm guidelines on emissions. Although there are no ambient quality standards for H_2S emissions currently in Kenya, the country uses WHO set guidelines. WHO (Organization & UNAIDS, 2006) confirms that the average daily concentrations permitted within the boundaries of the power station should not go beyond 0.1 ppm. However, American Conference of Governmental and Industrial Hygienists recommend a 10ppm occupational health limit for H_2S in the atmospheric air. Moreover, the National Institute for Occupational Safety and Health contends with this limit. Thus, for staff working in geothermal areas, the concentration should be limited to not more than 10 ppm and exposure levels of no more than 8 hours for staff working five days a week (Webster, 1995).

1.3 Problem Statement

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 atmospheric conditions.

1.4 Research objective

1.4.1 The main objective

The main objective of this study was to model H_2S dispersion around the proposed Menengai geothermal power plant.

1.4.2 Specific objectives

The specific objectives of the study were

i. To map out areas of high H_2S concentrations resulting from the emissions from the power plants using a Gaussian dispersion model.

ii. To assess the effects of weather parameters on H_2S concentration and dispersion.

iii. To recommend abatement methods in these high areas where high H_2S could be expected.

1.5 Significance of the research

Human interventions affect the environment in one way or another. These interventions have led to significant pollution that has brought changes in environmental patterns. As such, the member states of the United Nations have come together to push the agenda of sustainable development. Every development begins and ends with the environment. Geothermal development will have environmental implications on the physical, biological and the social environment. Both the extraction of heat from the interior of the earth and the geothermal fluid has potential effects on the environment. As established earlier, the geothermal fluid contains none condensable gases including hydrogen sulfide gas that has a significant impact on the receiving environment. In this regard, this study was able to give a precise prediction of how many times the conditions favorable for high H_2S events were anticipated per year; in relation to the weather. Therefore, this study explores proper abatement techniques to adopt in future.

CHAPTER TWO
LITERATURE REVIEW

2.1 Kenya's energy system

This research takes into consideration, the current profile of energy in Kenya since the energy composition influences growth and development for geothermal energy. Hydroelectric power dominates the energy production and consumption in Kenya. However, this energy source remains insufficient for the growing economy of Kenya. In line with the Vision 2030 (Commission, 2013), the country will need a reliable and affordable supply of energy. Currently, the country produces close to 2150 MW of power to serve a population of more than 43 million. According to the ministry of energy; Petroleum and electricity dominate the Kenyan energy sector. Besides, wood fuel provides the basic energy needs for most living in the rural and informal sector. Wood fuel dominates the energy scene in Kenya; it accounts for 68% of the total energy consumed by Kenyans. Petroleum and electricity sources accounts for 22% and 9% respectively. Since energy is central to the country's economic agenda, the government has invested in promoting the shift to renewable sources of energy. The ministry of energy asserts that the nation has only explored 5% of the renewable sources to generate energy with much of the power generated come from the wind, solar, geothermal and hydro resources.

Much of the renewable energy is generated from hydro energy resources and wind energy. Although the potential for geothermal as an energy source has proved to be high, the technologies are still undeveloped. Part of the country vision in achieving economic sustainability is investing in geothermal and solar energy. The World bank (Bank, 2009) claims that Africa as a continent is endowed with natural resources. In this light, they can heavily contribute to the reduction of greenhouse gases if they embrace the technology to tap the clean energy. Sources confirm that the country possesses more than 7000MW of undeveloped geothermal energy resource in the Rift Valley which can significantly boost the country`s potential for power generation and reduce the reliance on other expensive methods of power generation (Bank, 2009).

Kenya's primary resource for generating electricity is hydro resources which account for almost 70% of the electricity generated. Most of the hydroelectric generation plants are located along River Tana and Athi. This venture supplies the country with reliable energy. Petroleum and renewable energy sources supplements other energy needs. Despite this, the growing demand for more and the changing weather patterns have created less flow in the rivers leading to significant drops in the power generated. Moreover, the increased pressure to move to cleaner energy sources has led to increased research and funding for low emission resources and further development of geothermal energy. Also, the current energy demands have made geothermal power production a major power player in Kenya.

2.2 Geothermal Energy system

Geothermal resources are located in the Kenyan Rift Valley that transects the country from North to South .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.

2.3 H_2S emission from Geothermal Power Plants

Geothermal power plants emit geothermal fluids in relatively high amounts. These fluids contain non-condensable gases (NCG) which can significantly change the chemical composition of the air when vented into the atmosphere. Similarly, natural gas discharge from geysers, fumerals, hot pools and natural springs can contain non-condensable gases. Of concern is the level of amounts produced during power generation. These fluids contain high amounts of dissolved gases such as methane, carbon dioxide, nitrogen, and hydrogen. However, the geological status of the site and the environmental factors such as temperature notwithstanding the reservoir composition. (Kristmannsdóttir & Ármannsson, 2003) state that recent geological studies on geothermal discharges indicate that the level of gas concentration in most power plants is controlled by temperature which dictates the equilibrium in the minerals present in the reservoir rock. Similar research done in San Jacinto-Tizate contends to this claim.

(Karingithi, 2002) studied the process of emissions in Olkaria geothermal power plant by using chemical geothermometers to determine the equilibrium between hydrothermal mineral buffers found that dominates the geothermal system and the reactive gases that are emitted from the system. (Zhen-Wu) focused on the secondary analysis of mineral assemblages that influence the concentration of the NCG gases present in Reykjanes Geothermal system, SW Iceland. Both (Karingithi, Arnórsson, & Grönvold, 2010) and (Zhen-Wu) contend that the mineral composition of pyrrhotite, magnetite, prehnite, wollastonite, pyrite, pyrrhotite, prehnite and epidote informs the availability of hydrogen sulfide gas in the geothermal system.

(White, Lawless, Ussher, & Smith, 2008) argue that the presence of five alteration assemblages is usually an indication of possible emissions of H_2S from a geothermal well. The most common of these includes:

1. Interlayered clays, argillic and smectite.
2. Mixed argillic-prophylitic: epidote is experienced at depths between 400 and 600m.

Meaning that instead of a purely phyllic zone, there is a zone of mixed argillic and prophylitic minerals

3. Prophylitic: minerals such as pyrite, chlorite, adularia, calcite, laumontite, quartz, illite, wairakite and prehnite accompany the epidote.
4. High-temperature prophylactic: rare amphibole, implying high temperatures.
5. Contact metamorphic: garnet, amphibole and minor biotite.

The amount of gas present in the geothermal fluid emitted to the environment is dependent on a variety of factors. According to (Fridleifsson et al., 2008) the resource fluid chemistry, the fluid phase, temperature and the plant characteristics influence the level of omission. Gas concentration and composition vary widely but of most concern is the effect of CO_2 and H_2S because of their adverse effects on the environment.

(Gunnarsson et al., 2013) reported that for liquid dominated reservoirs, the most of the non-condensable gases are dissolved in the fluid. In this regard, high concentrations of these gases are registered at the steam phase. Thereafter, the gases are vented and dispersed in the vicinity. In vapor-dominated fields such as Menengai, the waste fluids are re-injected and consequently the NCG in the steam is emitted to the environment. Under these conditions, if not well controlled, the gases affect the air quality and in some cases altering the weather conditions around the power plant site.

Hydrogen sulfide is heavier than air. As such, the gas can accumulate to dangerous levels in poorly ventilated areas. Even at low concentrations, hydrogen sulfide -gas has a distinct rotten egg smell thus can be easily detected at a distance from the source. Reports have shown fatal incidents caused by volcanic eruptions emitting H_2S at high concentrations. H_2S is considered as an irritant and asphyxiate. In humans levels of up to 20 ppm have no general health effects. However, asthmatic persons can only withstand up to 2 ppm (Chou & Organization, 2003). Concentrations of above 200 ppm can cause eye and respiratory irritation while levels of between 500-1000 ppm are considered dangerous and can cause suffocation.

(Muna & Bwire-Ojiambo, 1986) contend that the concentrations of SO_2 and the levels of PH measured in the vicinity of Olkaria power plant does not change. This observation confirms that the hydrogen sulfide gas released is not readily converted to $SO_{2,}$ at the point of release. Similarly, studies done in San Jacinto- Tizate geothermal power plant records low levels of H_2S (between 0.001 ppm and 0.02 ppm) within the vicinity of the power plant. However, researchers have not studied the dispersion and spatial distribution of the emissions from the source, creating the need for setting up air quality guidelines. Nicaragua follows the guidelines for H_2S established by the WHO since they have not established their guidelines for the concentrations of H_2S permissible in the ambient air.

According to a research done by (Bacci, Gaggi, Lanzillotti, Ferrozzi, & Valli, 2000), increase in hydrogen sulfide concentrations beyond one unit of magnitude of the nasal threshold can contaminate the air, spreading its effects to several kilometers from the source. This study was on geothermal power stations at Mt. Amiata (Tuscany–Italy). Therefore, proper abatement measures must be put in place to reduce the potential damages that would accrue from such incidences. Human beings excrete the hydrogen sulfide gas in the body through urinating and expiration process. In this way, there are low chances of the gas building up to toxic levels in humans (Chou & Organization, 2003). However, a further increase in the concentrations of hydrogen sulfide causes eye irritation (at 10 ppm), irritation of the upper respiratory tract membrane (at 50–100 ppm). At a concentration of 150 ppm, it causes loss of smell. In Kenya, researchers have studied the effects of noise and air pollution arising from geothermal exploitation in Olkaria geothermal field. (Kollikho & Kubo, 2001) conducted a study to investigate the effects of geothermal emissions from cooling towers and gas ejector on flowers cultivated within the vicinity of Olkaria. Their results did not show any significant difference in the yield of flowers grown between 600 and 1200 m. Sulfur gas emission causes pollution that may attract the attention of the local environmental agencies. Therefore, geothermal power plants should adhere to the guidelines recommended by the local environmental authorities. On the same note, the international conventions on SO_2 emissions invite the global pollution concern. In this light, the possible conversion rates of hydrogen sulfide gas to SO_2 are of importance.

(Horwell, Patterson, Gamble, & Allen, 2005) focuses crosswise over the city for Rotorua by generating a map on a survey on the dangers of working and living in different parts of the city. Those outcomes about this study provide new knowledge under the subsurface routes about degassing in the Rotorua geothermal field, by demonstrating to the surface statement of the primary upstream zone and the bearing of the conjectured faulting beneath.
(Snyder, Safir, Summerville, & Middleberg, 1995); (Durand & Scott, 2003) argues that indoor exposures to high concentrations of hydrogen sulfide gas in Rotorua have often resulted in deaths. (Milby & Baselt, 1999) also contend with this opinion. This gas is detrimental to human and other animals' life since it paralyzes the olfactory system when one is exposed at levels beyond 150-250 ppm. At this level, it is difficult to detect the gas by smell since the senses are already paralyzed. (Durand & Scott, 2003) claim that H_2S reacts readily with copper causing the corrosion and blackening effect on objects made of copper. In this light, high concentrations of hydrogen sulfide react with copper in the electronic devices and water system causing severe damages. Moreover, the gas readily reacts with rubber thus damaging the electrical casings made of rubber. In the case of rubber, the reaction progresses from browning the materials then turning black and finally damaging the materials completely causing disintegration. Such damages add to the cost incurred to repair and replace the damaged outfit

2.4 H_2S Atmospheric dispersion

Research has shown that the weather conditions affect the concentrations of H_2S. Also, oxidation occurs under favorable conditions. (D'Alessandro et al., 2009) argue that H_2S concentration recorded in the urban areas of Thessaloniki and Sousaki; both in Greece are higher during the summer and lower during winter. The main hydrogen sulfide source in these areas was traffic with the possibility of oxidation. The research further indicates the need for more case studies on H_2S measurements around geothermal power plants.

According to (Kristmannsdóttir, Sigurgeirsson, Ármannsson, Hjartarson, & Ólafsson, 2000) the oxidation of H_2S to SO_2 within the Nesjavellir area, the area is at least slow if any. (Thorsteinsson, Hackenbruch, Sveinbjörnsson, & Jóhannsson, 2013) underscores that H_2S concentration was lower during the day and higher at night and also established that the levels of hydrogen sulfide rose beyond 50 mg/m^3 in Reykjavik and was associated with certain weather conditions. Specifically, he established that the concentrations of hydrogen sulfide gas were higher in low wind conditions coupled with high pressure and low temperature. (Kristmannsdóttir et al., 2000) hold the opinion that the concentrations of this gas decrease with the increase in precipitation. (Patil & Patil, 1990) have also estimated the impact of the emissions in thermal power plants analyzing the emission factors and trace elements present in the power plants.

2.5 Hydrogen sulfide chemistry

Many scholars have studied the chemistry of H_2S since the 1600s. Petrus Johannes Kipp made and invention in the 19th century that transformed the understanding of Hydrogen sulfide gas. The Dutch pharmacist invented an apparatus that would be used to provide hydrogen sulfide. Since then, a lot of research has emerged, and the studies confirm that hydrogen sulfide is a potential source of hydrogen. Similarly, scientists have used semiconductor particulates to decompose hydrogen sulfide to give hydrogen.

Wang proposes another method instead of the decomposition of H_2SO_4 the sulfur-iodine thermochemical water-splitting cycle. The latter is more efficient since it yields more hydrogen gas. Furthermore, the new cycle provides a flexible production ration of H_2 and H_2SO_4. (Ouali, Chader, Belhamel, & Benziada, 2011) conducted a study that examined the processes that are used to produce hydrogen from the hydrogen sulfide component of the geothermal fluid. Similar research underscores that the geothermal resources are rich enough in hydrogen sulfide which can be harnessed to produce significant amounts of hydrogen.

In geothermal plants, hydrogen and sulphur interact under the earth surface at temperatures exceeding 200ºC leading to the formation of the gas. This combination of gases is continuos and proceeds until a state of equilibrium is reached. The higher the temperature, the lower the proportion of hydrogen sulfide in the equilibrium mixture.
The present research has looked at how the varying weather patterns influence dispersion of hydrogen sulfide gas from the power plant. These analyses have helped the researchers to understand hydrogen sulfide concentrations in different weather patterns. In this way, the researchers have recognized the conditions under which hydrogen sulfide concentrations would exceed the required levels.

2.6 Behavior and Life-Time of H_2S 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_2S 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 (Chou & Organization, 2003).

According to (ATSDR, 2006) Hydrogen sulphide gas in the atmosphere, may be oxidized by oxygen (O_2) and ozone (O_3) to give sulphur dioxide (SO_2) 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). (Organization, 2000) 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_2SO_4) and/or sulfate ion ($SO4^{=}$).

There have been relatively few studies of the persistence and conversion of Hydrogen sulphide gas under atmospheric conditions. (Organization, 2000) 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.

Studies carried out by (Sequeira, 1999) noted that H_2S gas can contribute to the formation of acid rain. Studies have shown that part of the H_2S emissions from geothermal plants are oxidized in the air to SO_2. The H_2S gas will oxidize to form elemental sulphur or ultimately, sulphate (SO_4^{-2}), depending on pH. Oxidation to SO_4^{-2} changes the oxidation state of sulphur ion from –2 to +6. Corrosion is another important aspect to keep in mind when there is H_2S 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_2S but also because the sulphide film causes sparking at the brushes which wear away at a startling rate.

(Organization, 2000) 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 mg/m3. 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.

2.7 Health Effects of H_2S 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 (Chou & Organization, 2003) Research work by (Organization, 2000) and (ATSDR, 2006) further noted that the common impact from the existence of H_2S gas in the atmosphere is the annoyance it causes to humans. The detection and perception of odours of H_2S 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_2S gas.

(Latos, Karageorgos, Mpasiakos, Kalogerakis, & Lazaridis, 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_2S 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_2S gas present in the air.

Most human data on the impacts of H_2S 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 can 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 (Chou & Organization, 2003).

Studies by (Chambers & Johnson, 2009) noted that H_2S 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_2S 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 (Organization, 2000), (Chou & Organization, 2003) and (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.

(Organization, 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 μg 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 μg m^{-3}. At higher concentrations (above 225 μg 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 μg 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 μg 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.

2.8 H_2S dispersion modeling

Air pollution modeling is predicting the movement and behavior of pollutants in the atmosphere, using a mathematical theory. The movement and behavior of pollutant are essential factors to consider when adopting a strategy for air quality management. The quality of prevailing meteorology informs air quality simulations, thereby influencing the air quality. Therefore, understanding H_2S dispersion and concentration in Menengai geothermal field demand the analysis of Hydrogen sulfide (H_2S) emissions with the prevailing meteorological variables. Scientists have overtime used advanced models to perform dispersion modeling. These models include; EPA models, Industrial Source Complex (ISC3), American Meteorological Environmental Protection Agency Regulatory Model (AERMOD), CALPUFF, the British Model Advanced Distribution Management System (ADMS) and the Danish model OML (Macdonald, 2003).

Gaussian and other numerical models have been widely used in the simulation of air quality. (Arnold, Dennis, & Tonnesen, 1998) assert that the model mathematically represents emissions; paying attention to the initial concentrations as well as the boundary concentrations of the intended chemical species. In this way, the modeling process estimates the ground level concentrations through understanding the meteorology and atmospheric chemistry combined estimates of the emissions from the source. However, the formula assumes that the meteorological conditions and steady-state conditions remain constant through the dispersion from the source to the receptor. Importantly, the meteorological conditions and the emissions vary. Similarly, hourly model calculations differ from calculations taken another time. Additionally, the forecasts have been used to provide information relating to real-time emissions that have been used to develop abatement strategies aimed at protecting the public from exposure. (Pruchnicki, 1977) in the region of Poland and has been able to describe the air quality standards.

The source inversion based on the simple Gaussian dispersion model was further studied and developed by (Demael & Carissimo, 2008). In their study, (Kho et al., 2007) used the AERMOD dispersion model for predicting air dispersion plumes from diesel power plants. They studied the emissions of nitrogen (NO_2) and sulfur dioxide (SO_2) to determine their effects on the nearby population. (Yousefi, Ehara, & Noorollahi, 2008) also presented a study on the impacts of the emissions on the quality of air in Sabalan geothermal power plant in Iran, focusing mainly on the prediction of H_2S distribution using the Industrial Source Complex Model. (Tuaycharoen, Wongwises, Aram, & Satayopas, 2008) studied the emissions of nitrogen oxides produced from Khanom Power plant found in the southern parts of Thailand. This study used both the RAMS and CALMET-CALPUFF models. These studies have revealed the importance of the application of this mathematical model in analyzing emissions and air quality in urban areas.

Factors e.g characteristics of the emission sources and the relationship between the source of emission, nature of the pollutants and the area receiving the emission receptor, informs the model that research will prefer. (Heckel & LeMasters, 2011) hold the opinion that various researchers have used AERMOD to model the dispersion of multiple gases. Further, (O'Shaughnessy & Altmaier, 2011) contend that AERMOD model has been used in different researches to understand the dispersion and further argue that the researchers have often used this method to determine the concentrations of Hydrogen sulfide gas, based on the measurements. (Cimorelli et al., 2005) contend that the model register better results in moderate and complex terrains. Similarly, AERMOD has registered better performance in situations where the samplers range between two and eight kilometers. According to (Seangkiatiyuth, Surapipith, Tantrakarnapa, & Lothongkum, 2011) AERMOD performs poorly in complex terrains characterized by strong winds especially in modeling locations beyond 50 Km from the source. However, the model performs well when the measurements are taken in stable weather with no strong wind. It assumes the vertical and horizontal concentration distribution to be Gaussian, in a stable boundary layer. However, only the horizontal distribution is assumed to be Gaussian in the Convective boundary layer.

This research analyzes the effects of different weather conditions on the transport of hydrogen sulfide produced from the geothermal power plant. As such, helps in understanding and predicting the possible hydrogen sulfide concentrations under different weather patterns and possible effects. Unlike other models, the AERMOD model is suitable for modeling in both complex and flat terrain

For the past few decades, Gaussian dispersion models have emerged as better alternative tools for air quality management especially in the era when it was difficult to secure high-performance computers for environmental management purposes. Gaussian dispersion model had been used in various air quality studies in both the urban and rural areas. However, extreme environmental pollution such as the Chernobyl disaster pointed out the weaknesses of Gaussian dispersal model thus calling for a more sophisticated approach. Nonetheless, Gaussian plume dispersal model has been commonly used in studies involving both multiple and single sources of air pollution. The calculation is oriented to analyze how atmospheric stability and distance affect the ground level concentration of the pollutant. The software used in this model has an inbuilt set of algorithms to aid in the conversion. The formula below represents a simplified diffusion Equation

$$\frac{dC}{dt} + U\frac{dC}{dx} = \frac{d}{dy}\left(K_y \frac{dC}{dy}\right) + \frac{d}{dz}\left(K_z \frac{dC}{dz}\right) + S$$

.

Where: 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) = means the concentration of diffusing substance at a point (x, y, z) [kg/m3] Ky, Kz = eddy diffusivities in the direction of the y- and z-axes [m2/s]

U = wind velocity along the x-axis [m/s]

S = source/sink term [kg/m3-s]

Gaussian- plume models assume that a steady state of pollution emission and meteorological conditions remain over a short time. However, the conditions can vary within a short time. As such, the formula provides a better representation if the conditions remain constant. The information gained from these forecasts helps environmentalists in determining environmental impacts and developing proper environmental conservation policies

2.9 H_2S Abatement Techniques

(Stephens, Hill, & Phelps Jr, 1980) outline various methods of for removing hydrogen sulfide. The first approach describes the removal of hydrogen sulfide before the stream reaches the turbine and the second method involves the removal of hydrogen sulfide after the turbine. Similarly, (Sanopoulos & Karabelas, 1997) characterizes the suitable H_2S abatement methods depending on the type of flow.

A simple decision tree is given an insight into the best abatement method to choose depending on the compositions of the geothermal steam. It is a diagrammatic summary that details the major considerations and constraints involved with choosing candidate methodologies, before more detailed consideration of preferred options given a plant's site-specific characteristics.

2.10 Deduction from Literature

2.10.1 Relevance

From literature Most GHG emissions are a result of energy use, particularly use of fossil fuels. Likewise, geothermal power generation has also been linked to emission of high levels of carbon dioxide and hydrogen sulfide gases which affect the environment. The correlation between increased energy use and economic growth is unique. This relationship indicates that with further industrial advancement, energy consumption will rise consequently, leading to further environmental deterioration if proper measures are not investigated and employed.

2.10.2 Literature gap

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.

2.10.3 Contribution to the gap

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.

H2S content	Condenser	Plant	Scrubbing with Alkali	Liquid Redox	NCG Injection	Selectox	H2O2 Process	Steam Stripping	Dow-Spec RT_2	Biox
High H_2S content	DC Condenser	Large plant								✓
		Small Plant	✓				✓			✓
	Surface Condenser	Large Plant								✓
		Small Plant	✓				✓			✓
Low H_2S content	DC Condenser	Large Plant				✓		✓	✓	✓
		Small Plant	✓							✓
	Surface Condenser	Large Plant		✓	✓			✓		✓
		Small Plant	✓		✓					✓

Figure 2.1: Proposed H_2S abatement system selection decision tool (modified from (Rodríguez, Harvey, & Ásbjörnsson, 2014).

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Introduction

This section discusses the study area and how the study arrived at the results detailed later. First; it gives the emission data obtained from the power plant, the meteorological data collected from the weather station located at 173363E, 9976379N with an elevation of 2153 m, and the reported H_2S concentration measurements carried out by an automatic gas detector (Jerome® J605 gas detector) around the power plant. Lastly, the Gaussian plume approach that was used in the study.

3.2 Project area

The Menengai Geothermal prospect is found at the central region of the Kenyan rift valley. It borders Lake Nakuru to the north and Lake Bogoria to the south. The Menengai Geothermal Prospect covers approximately 600km^2 characterized by complex geological conditions. Importantly, this zone lies at the triple junction where Nyanza rift joins the Main Kenyan rift. Pyroclasts from the volcanic activities cover the area. The Two rift floor tectonic-volcano axes, i.e., Solai TVA and Molo TVA define the geothermal system of the Mengai Geothermal prospect area. The Solai TVA faults have disturbed the ring structure on the North Eastern end. Studies confirm that one fracture at the SSW of the caldera wall extends southwards. The Molo TVA/Ol'rongai fracture system intersects the caldera on the NNW part. Most the lava filling the Caldera are attributed to the eruptions that released through the fracture openings.

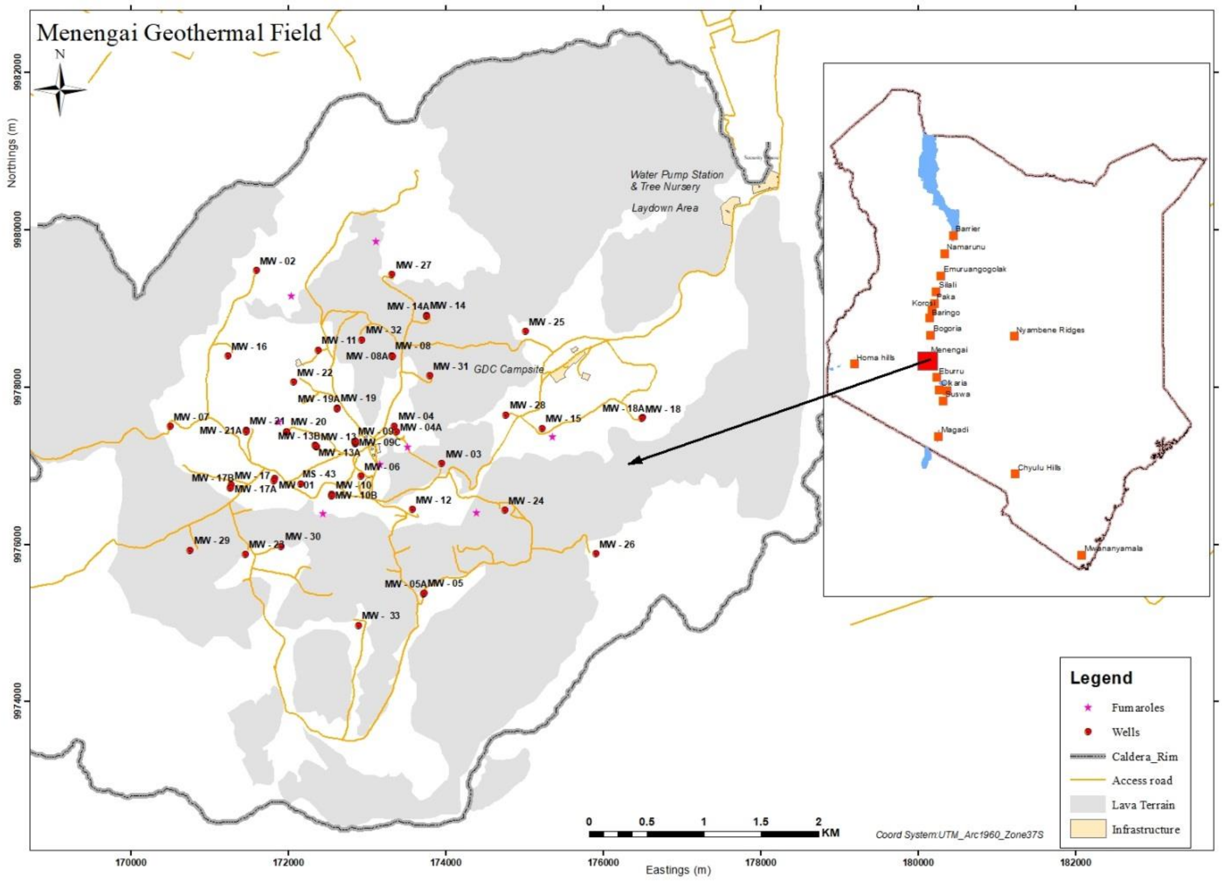

Figure 3. 1: Location of Menengai geothermal field.

3.3 Geological setting

The study area is located inside the Kenyan section of the East African Rift system. Menengai is a trachytic central volcano underlain by a high-keyed magma chamber. Geological action began not long preceding 0. 18 Ma (mega-annum); for the Growth of a low - point trachyte magma shield Hosting a volume approximately 30 km³ (Leat, 1984). The shield volcano formation can be dated back to 200,000 years ago. Eruptions of voluminous ash-flow tuffs followed these events with a preceding significant pumice falls. A series of lava flow marks the youngest volcanic manifestations on the caldera floor. Similarly,(Bergner et al., 2009) claim that two ignimbrites are exposed near the Caldera. Importantly, the inside part of the Caldera has seen a number of post-caldera activities and have been associated with the production of lava. Specifically, studies suggest that at least 70 lava flows have been registered as part of the post Caldera activities. Further, pumice deposits responsible for sheet formation and strombolian cinder cones have also surfaced. Fumarolic activity realized in the Caldera, many recent eruption and intense tectonics and large Caldera collapse have weakened the system leading to intense faulting.

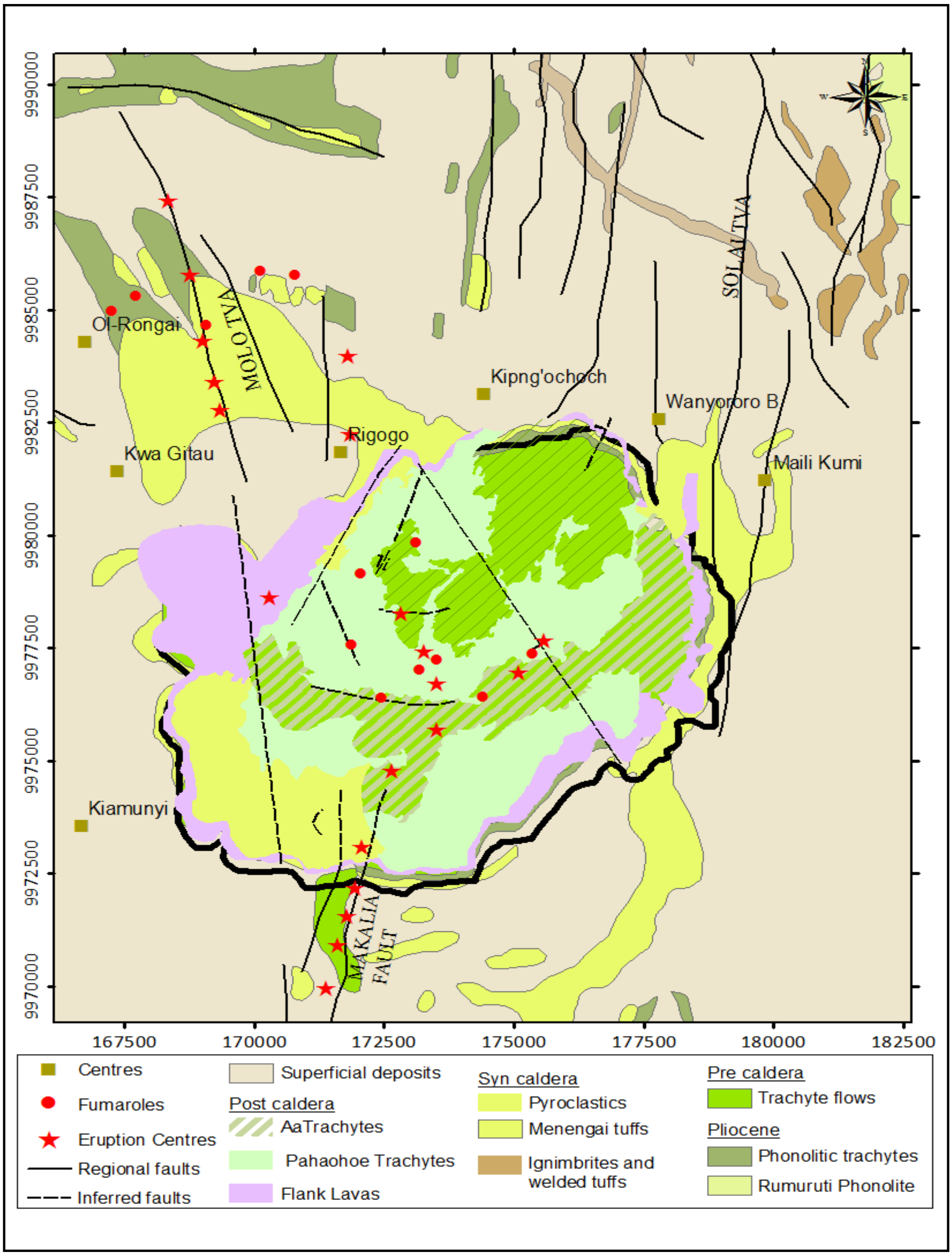

Figure 3. 2: Geological map of Menengai. (modified from (Robertson, Biggs, Cashman, Floyd, & Vye-Brown, 2015)

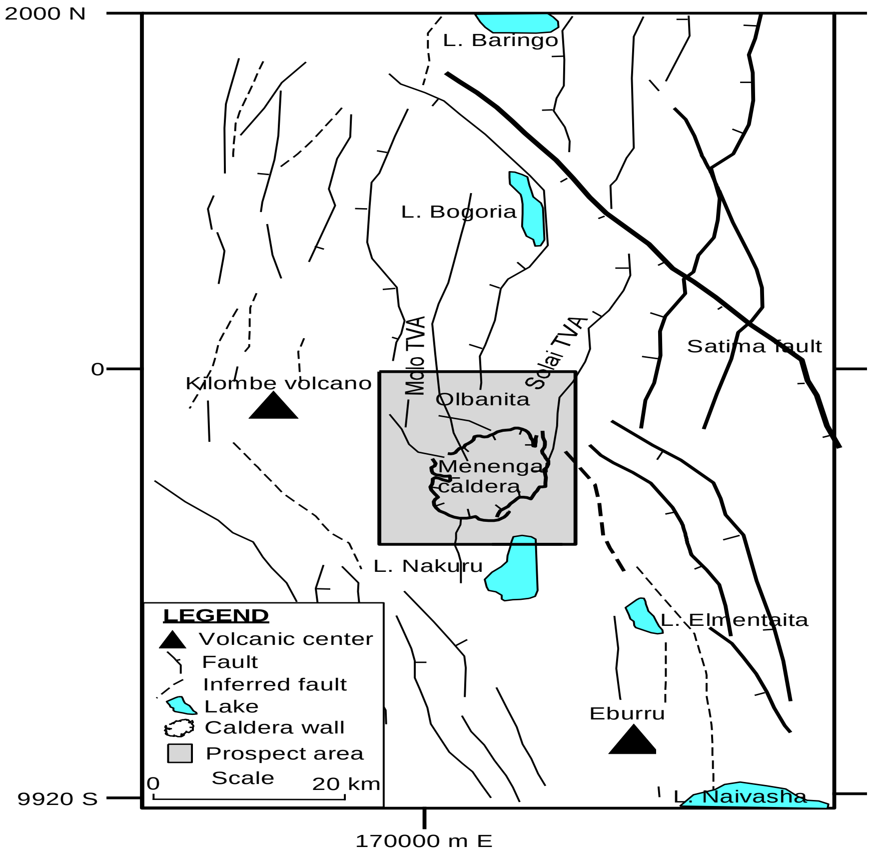

Figure 3. 3: Structural set up of the Kenya Rift floor. (Omenda & Simiyu, 2015)

3.4 Model Description

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

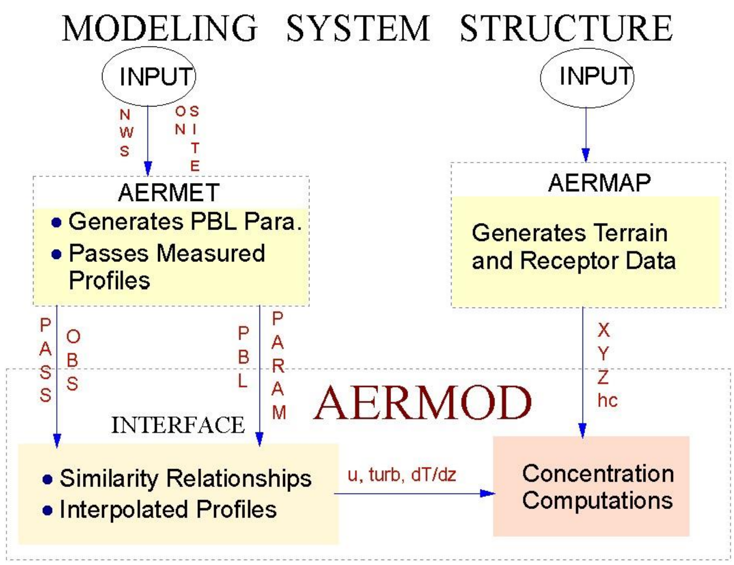

Figure 3. 4: Data flow in the AERMOD modeling system.

Input data

Meteorological data

Hourly surface observations of weather parameters were fed into the AERMET system, to convert the data into the suitable format for AERMOD. Based on the hourly surface data, the wind profile and Vertical temperature gradient were computed by the upper air estimator within AERMET. Surface characteristics are input to AERMET in the forming surface Bowen ratio, roughness, and albedo. The system then calculates the PBL parameters giving the temperature scale (2*), surface heat flux (H), Monin-Obukhov length (L), friction velocity (u*), convective velocity scale (w*) and mixing height (zi). Further, the parameters pass to the INTERFACE where the system utilizes similarity expressions to yield the lateral turbulent and vertical fluctuations (Fw, Fv) and Potential temperature (2) and potential temperature gradient (d2/dz)

3.5 Concentrations of H_2S in the project area

The Menengai geothermal project has an Air quality monitoring program that helps in measuring the concentration levels of H_2S in the ambient air. The baseline measurement sites represent the H_2S background concentration in the study field and the surrounding area. The results obtained from this program are reported on a monthly basis. A Jerome® J605 gas detector with a detection range of 0.003-50 ppm was used for measurements.

Figure 3. 5: Jerome® J605 gas detector

3.5.1 Principle of operation of the instrument

The instrument's microprocessor automatically re-zeroes the digital meter at the start of each sample cycle and holds the meter reading until the next sample cycle is activated.

During the sample mode cycle, a sensor saturation meter on the LCD represents the percentage of sensor saturation, or adsorbed hydrogen sulphide collected on the gold film. With use, the sensor becomes saturated and needs to be cleaned. This is accomplished by a manually activated 45-minute sensor regeneration cycle, which removes the hydrogen sulphide from the sensor. The 45-minute regeneration process includes a cool-down phase, so the instrument is ready for use as soon as the regeneration process finishes.

This study compared the average concentrations recorded every month with the concentrations obtained from dispersion modeling.

3.5.2 Monitoring frequency

The environmental baseline monitoring period and frequency of H_2S concentration were as follows:

- Monitoring period: One year
- Monitoring frequency: Monthly

3.5.3 Measurement duration

For baseline environmental monitoring, continuous measurement for 24 hours (20 minute record interval) was done.

3.5.4 Monitoring equipment installation height

The monitoring equipment was installed at 1.5 m above the ground to consider the effect of air pollution on the human body and the area in which people are most active.

3.5.5 Weather conditions

During measurement of H_2S on the downwind from the source, wind speed and wind direction was considered and recorded.

3.5.6 Selection of the monitoring sites

- Nine sites were selected where we had drilling in progress.
- Seven sites where wells were discharging.
- Five sites where we had the nearest community and social infrastructure facilities.

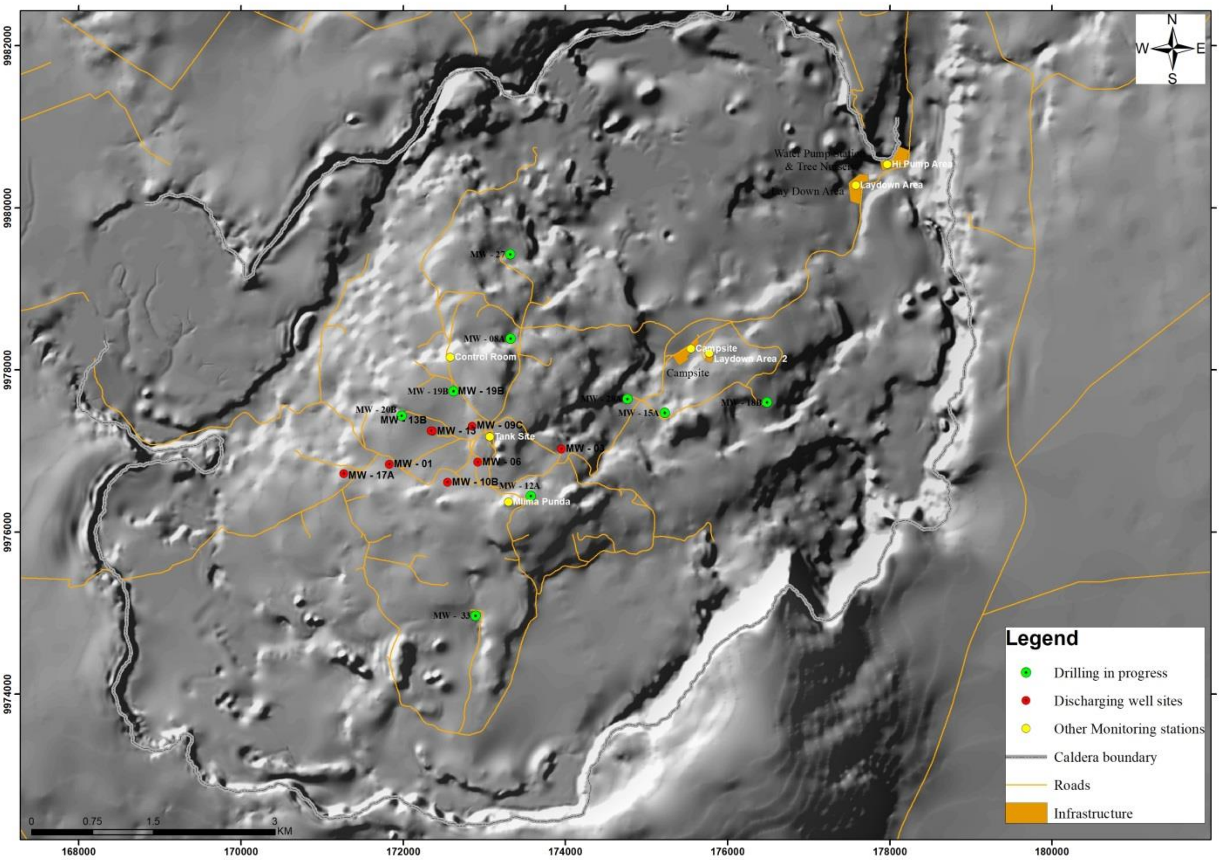

Figure 3. 6: H_2S Monitoring Stations

3.5.7 Quality assurance and maintenance

Before each day's use of the Jerome® J605, the following steps were performed to verify proper instrument operation

- Press the power I/O button to turn the instrument on.
- The display will light up and show instrument serial number and software revision.
- If necessary, press ESC to clear any calibration reminders. (E-mail support@azic.com, to schedule instrument calibration.)
- The digital meter displays 0.000 ppm (or 0.00 ppb, depending on what Range is currently selected).
- Check the battery level as indicated by the battery icon at the top center of the instrument display.
- If the battery meter is empty and flashing, refer to Charging Internal Battery reference manual.
- If the battery meter is not empty, but is flashing, then the instrument is currently charging the battery.
- To ensure the instrument's electronics have stabilized, allow a 5-minute warm up before beginning the next step.

- Perform sensor regeneration. Refer to Sensor Regeneration reference manual Ensure the instrument has been powered on for at least five (5) minutes prior to sampling.
- Use the Zero Air Filter to equilibrate the instrument to ambient air temperature.
- Install the Zero Air Filter in the instrument's intake.
- Sample repeatedly every 15 seconds until the readings stabilize, then removes the Zero Air Filter.
- At the end of each day's use, perform sensor regeneration as described in reference manual. No H_2S is allowed to stay on the gold film sensor overnight!

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Introduction

A simple Gaussian plume approach was employed to analyze the variation in concentration with distances from the source. Three various periods were modeled with regards to the weather patterns for every particular date and the H_2S concentration at the baseline level.

The results and the discussion have been presented together to facilitate and make the thesis more foreseeable. The first part of this chapter shows the results of the AERMOD model. This section also compares the concentrations of H_2S with the guidelines set by the WHO. As established in the literature review the feasibility of geothermal production heavily depends on some specified parameters which affect the sensitivity of the model.

4.2 AERMOD model results

Meteorological information for the period January-December 2013 were used to model three different periods in AERMOD.

4.2.1 Highest 24-hour average

The results from AERMOD shows the highest concentration averaged in 24 hours. Contours depend on the highest 24h average concentration by the receptor, established at various circumstances prevailing in different areas (Figure 7). The spatial conveyance of the plume for 24 hours averaging time stretches over a wide area found H_2S concentrations of up to 25.5 μg m^{-3}. The highest concentrations were recorded near plant building hitting a peak value of 25.5 μg m^{-3}.

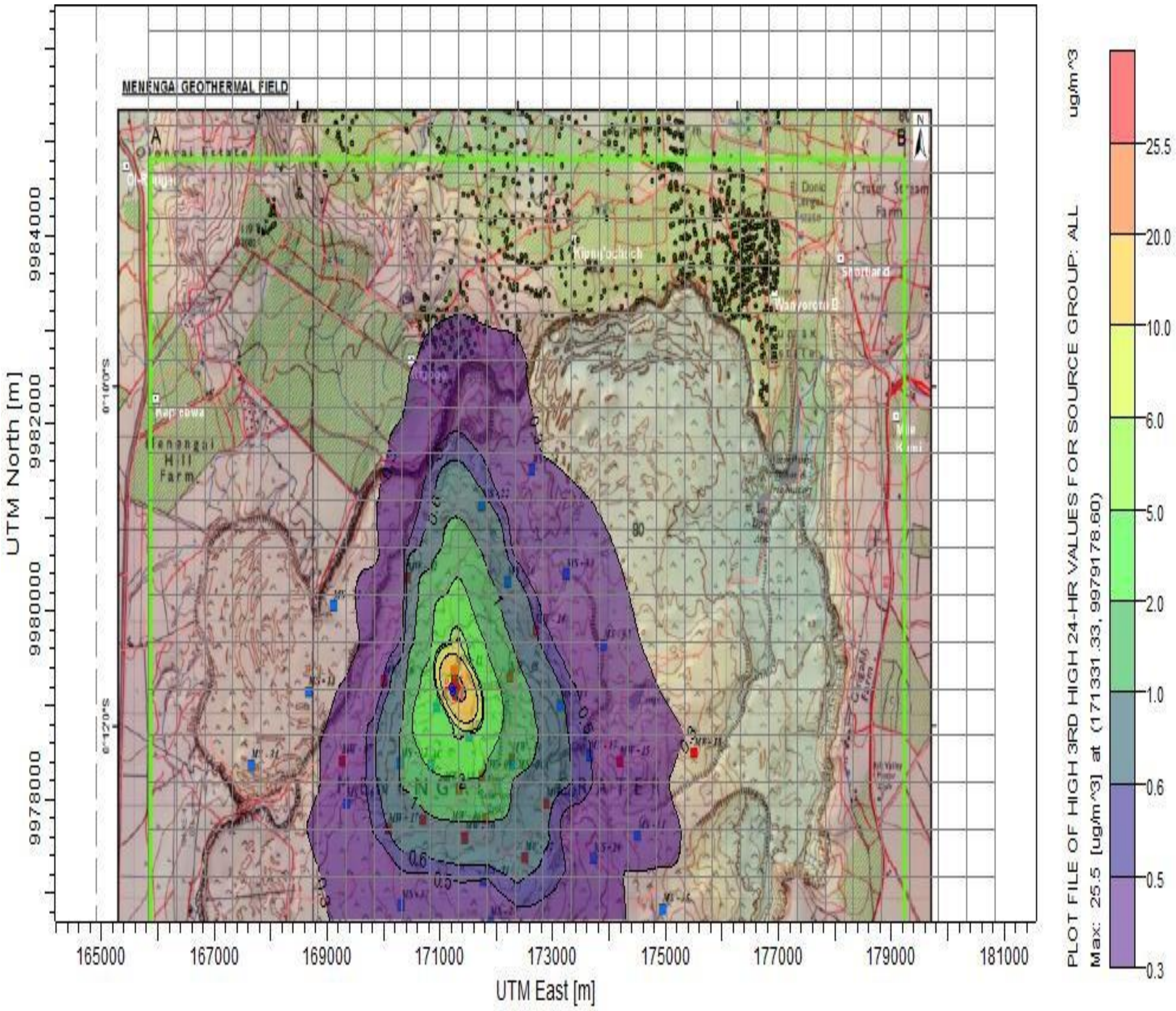

Figure 4. 1: Highest H_2S 24- hour average concentration at any given location for the modeled the year 2013.

4.2.2 Highest 8-hour average

The study also modeled the highest concentration in 8-hour averaging. According to the study, none of the exposure limits averaged in 8 hour- time in the study are the exposure standards limits established by the World Health Organization (7100-14200 μg m^{-3}).

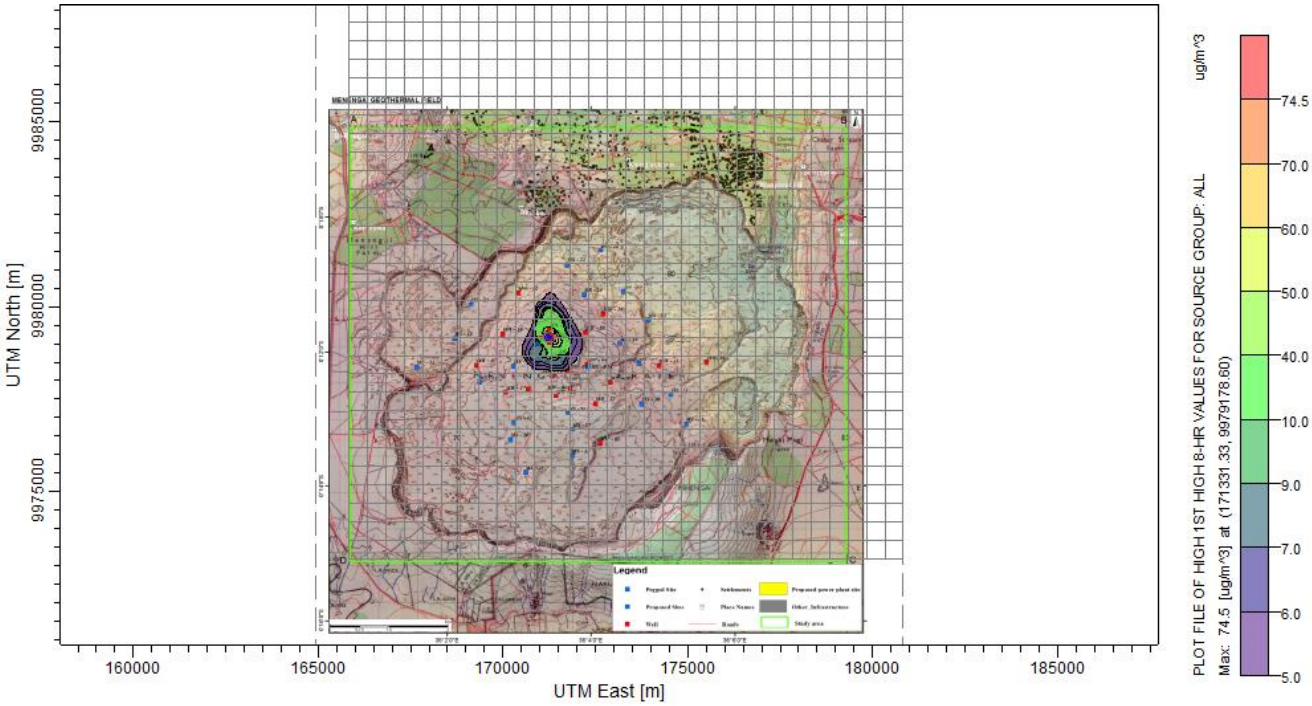

Figure 4. 2: Highest H_2S 8- hour average concentration at any given location for the modeled the year 2013

4.2.3 Highest 1-hour average

One hour unit is the least averaging time that can be modeled in AERMOD. For a one-hour average, a single hour with the highest concentration amid the displayed year was taken by the receptor to assemble the concentration contours.

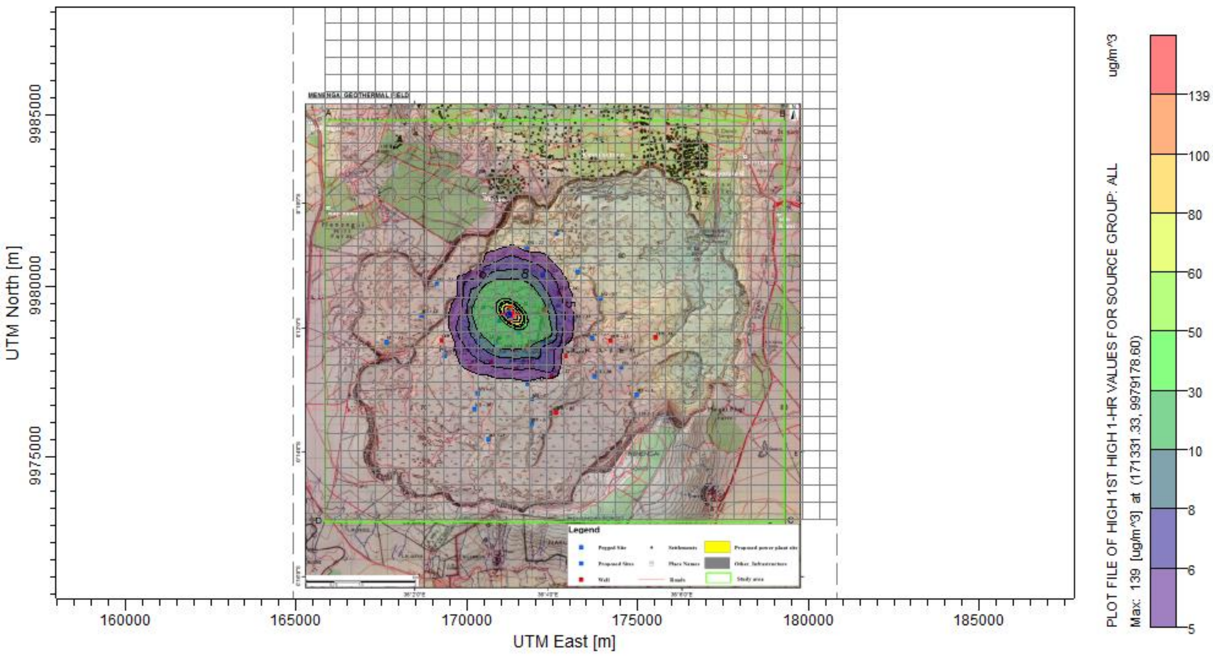

Figure 4. 3: Highest H_2S 1- hour average concentration at any given location for the modeled the year 2013

The high concentration levels were recorded at the site between the powerhouse and the cooling tower; during the entire averaging times. This can be related with building downwash impacts

since the development of air over and around the structures produces territories of stream dissemination, which can prompt high ground level focuses in the building wakes.
Hourly concentrations nearly meet the WHO ambient air guideline of 150 μg m^{-3} averaged over 24h.

The results above indicate that Menengai geothermal power plant does not significantly influence the chemical composition of the air within the vicinity. AERMOD model demonstrates that an H_2S outflow, for the most part, influences the air quality close to the project area. The encompassing towns are situated outside of the most well-known plume pathway; however, when displaying short averaging circumstances over an entire year, the focus is anticipated at some populated spots.

When comparing results from the AERMOD model with the measured averaged concentrations, the model anticipated low focuses for most of the points.

Natural release of H_2S from fumaroles in the undertaking territory is not represented in the demonstrating; notwithstanding, these regular sources can influence the deliberate focus utilized for correlation with the model outcomes.

4.3 Influence of meteorological parameters on the transport and distribution of H_2S.

4.3.1 Diurnal variation of H_2S with prevailing wind speed.

Diurnal variation of hydrogen sulfide gas was analyzed in relation to the prevailing wind speed in Menengai geothermal area. The graphical analysis in figure 10 indicates the concentration of hydrogen sulfide gas is low as there is a rapid dispersion of hydrogen sulfide gas by the wind away from the source point.

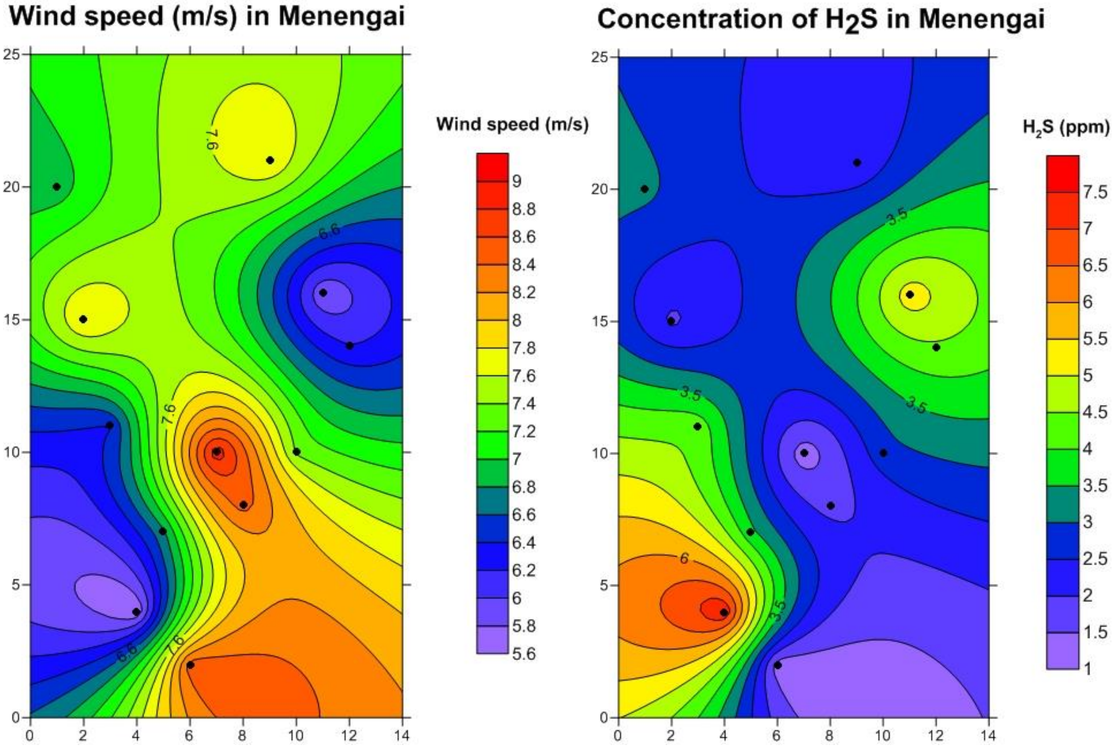

Figure 4. 4 : Diurnal Variation of H_2S with the prevailing wind speed

4.3.2 Diurnal Variation of H_2S with Relative Humidity.

Relative humidity was considered as one of the parameters that influence hydrogen sulfide concentration in the atmosphere. From the graphical analysis, it showed that periods when there was high H_2S, the relative humidity was significantly low this may be attributed to solubility of the gas in water.

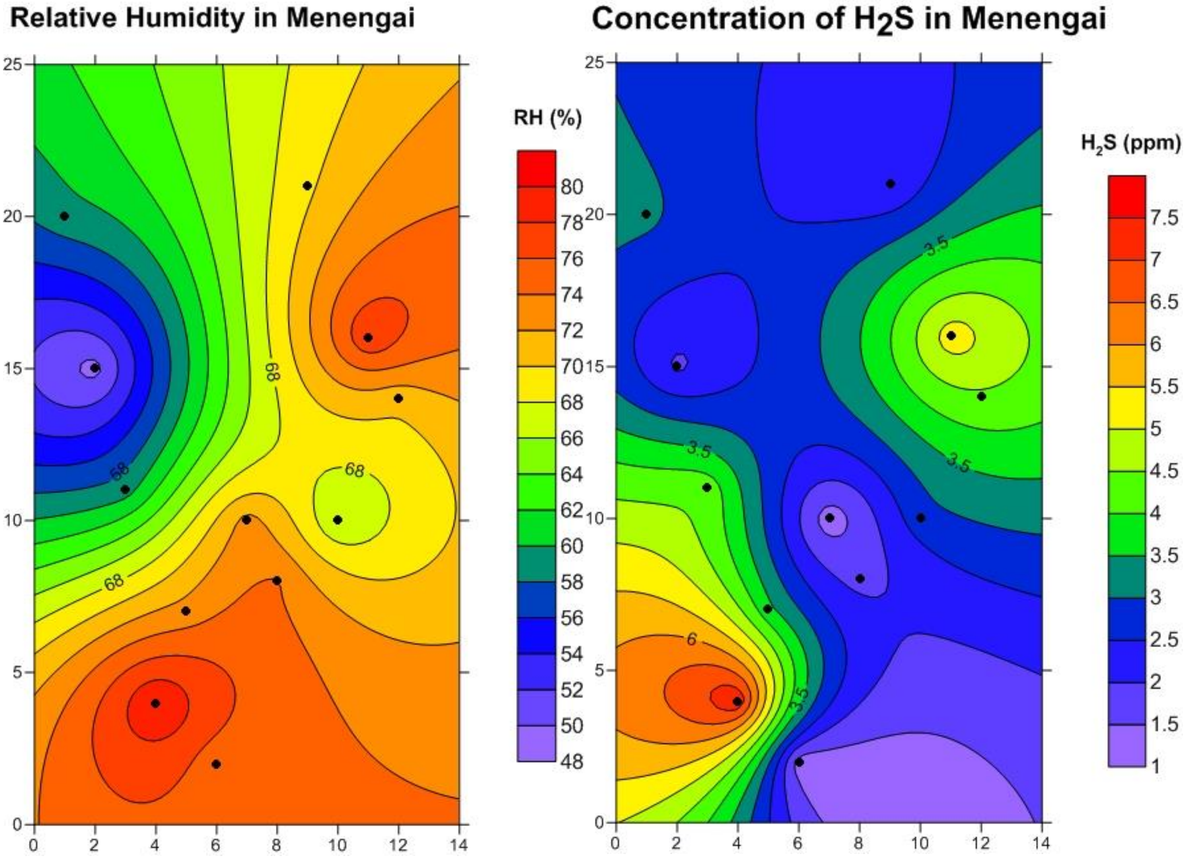

Figure 4. 5: Diurnal Variation of H_2S with Relative Humidity.

4.3.3 Diurnal Variation of H_2S with air temperature.

Change in concentration of hydrogen sulfide gas with the prevailing air temperature was analyzed. Figure 12 below indicates that the prevailing air temperature in an area influences the concentration of hydrogen sulfide gas.

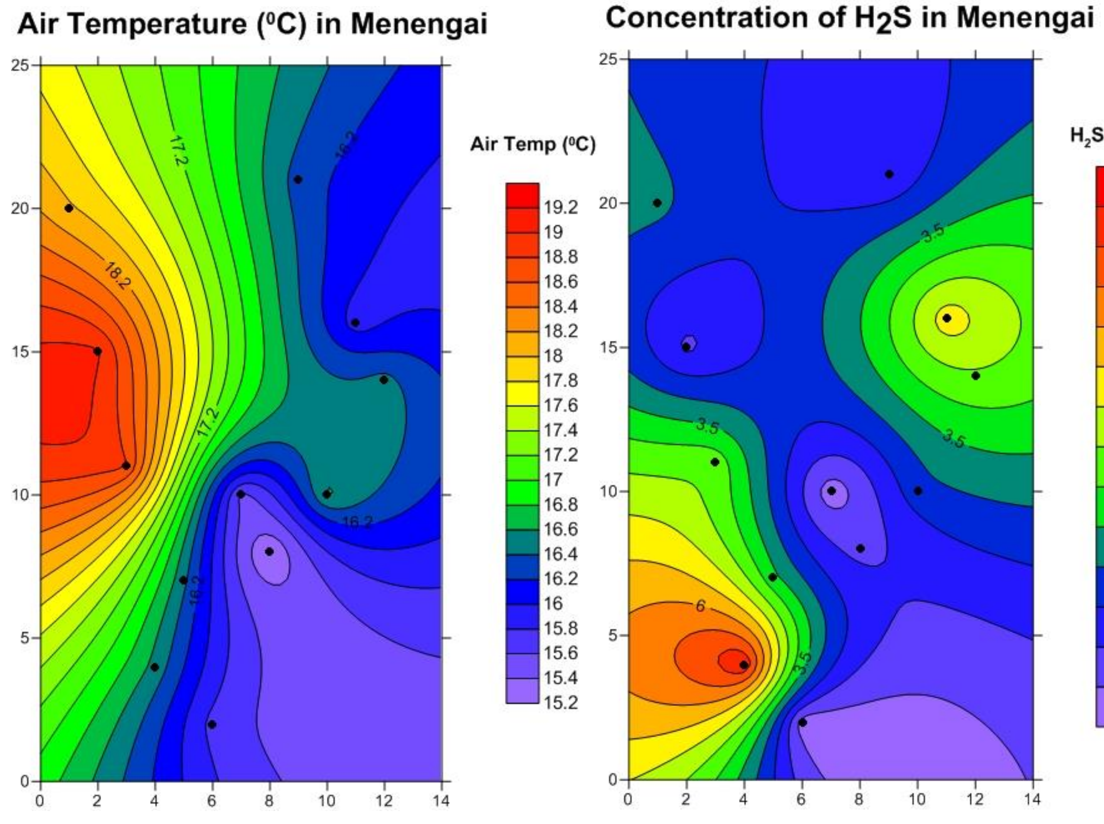

Figure 4. 6: Diurnal Variation of H_2S with air temperature.

When modeling the Menengai geothermal power plant using weather data from 2013, results from the influence of meteorological parameters on the concentration and distribution of hydrogen sulfide showed there is a clear relationship in a given season of the year. Increased wind speeds and high ambient air temperature can lower the concentration levels of H_2S as the air becomes turbulent and the plume is dispersed away.

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1 Review of research objectives

The main objective of this study was to model H_2S dispersion around Menengai geothermal field and studies the influence of weather parameters on its concentration and distribution.

The specific objectives were:

- To map out areas of high H_2S concentrations resulting from the emissions from the power plants using a Gaussian dispersion model.
- To assess the effects of weather parameters on H_2S concentration and dispersion.
- To recommend abatement methods in these high areas where high H_2S could be expected.

This chapter, therefore, explored the outcome of the research and whether the set objectives were achieved and recommendations given.

5.2 Key findings

Understanding the atmospheric steadiness as informed by the prevailing weather conditions and the season is essential for the best possible interpretations of the modeling results. Amid stable conditions, high pollutant concentrations can be expected away from the emitting source and low concentrations near the source. In contrary, high concentrations occur closer to the sources during unstable conditions due to the turbulence caused by the rapid overturning of air.

5.3 Conclusion

Naturally, the geothermal fluid contains a certain percentage of different non-condensable gases. Drilling of the geothermal energy releases these gases into the atmosphere. One of the important gas is hydrogen sulfide hence the need for this research.

This study successfully used the AERMOD to establish the impact of H_2S concentration in the Menengai region. The corresponding concentrations of H_2S obtained from AQMS (Air Quality Monitoring Stations) were used to validate the simulated model. It was established that the emissions from the power plant do not have any significant effects on the environment. Hydrogen sulfide dependency on different weather parameters was also analyzed. In this light, the easements associated high concentrations of H_2S to low precipitation, low speed of air and high air stability. In addition, the plumes that had wider spread were measured during unstable conditions. In this regard, we can make the following conclusions.

1. The concentrations of H_2S within the area do not exceed the hourly threshold established by the World Health Organization
2. Hourly concentrations recorded are higher when wind speeds are the least

The results obtained from this study can be used to predict the concentrations of H_2S thus informing major decisions made in the planning process for a geothermal power plant. However, further research should be done to establish the effects of long-term exposures of the low-level concentrations to flora and fauna.

5.4 Recommendations

From the tree diagram analysis, the recommended abatement technique is the BIOX process (downstream process). In this regard, the system compresses mixing them with condensate before reaching the cooling tower. In the presence of oxygen, the oxidizing biocide used to control the biological growth in the cooling tower helps to convert the dissolved hydrogen sulfide gas into water-soluble sulphates. (Gallup, 1992) argues that this process reduces both primary and secondary emissions of hydrogen sulfide from the cooling towers reports. Additionally, the concentrations of NH_3 in the steam do not affect this process. Moreover, both large and small power plants can install acquire this process since it requires relatively capital to install and operate. However, the attainable removal efficiencies may not be as high as other methods.

5.5 Research contribution

This research provided the underlying logic of the occurrence of hydrogen sulphide gas by explaining the transport, dispersion and associated impacts of Hydrogen sulphide gas in Menengai. Secondly, the research aided in sense-making by helping us 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 atmospheric conditions. Thirdly, the research provided guidance for future research by helping identify constructs and relationships that are worthy of further research.

5.6 Future research

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. Secondly this study explores proper abatement techniques to adopt in future.

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APPENDIX- A section of Meteorological data used in this research

WindDir_Deg	Wind Speed M/sec	Air TempDeg C	RH %	Solar RadW/m^2	BP_mbar_Avg	Rain_m_Tot	AVG_Cloud_Height	Opaque
163	4.3	15.7	82	0.00	789	0.00	450	7
142	4.3	15.8	83	0.00	789	0.00	450	7
175	2.2	15.3	82	0.03	789	0.00	450	7
171	2.8	15.1	86	0.09	789	0.00	450	7
178	3.0	14.7	90	0.02	788	0.00	450	7
184	4.0	14.2	92	0.03	789	0.00	450	7
184	4.2	14.0	94	0.00	789	0.00	450	7
181	4.0	14.0	93	6.20	789	0.00	450	7
184	4.2	14.3	90	62.69	789	0.00	450	7
109	3.7	16.2	69	248.80	790	0.00	450	7
8	6.9	17.6	64	390.10	790	0.00	450	7
352	7.4	18.0	66	363.10	790	0.00	450	7
360	8.0	18.5	65	457.80	790	0.00	250	7
5	9.0	19.1	56	436.70	789	0.00	250	7
359	7.4	19.7	57	415.50	788	0.00	150	7
3	9.1	20.1	54	607.20	787	0.00	150	7
6	10.6	20.4	51	703.20	787	0.00	150	7
6	9.5	20.5	50	468.30	787	0.00	75	7
353	8.6	20.1	57	168.80	787	0.00	75	7
355	7.7	19.2	59	15.75	787	0.00	75	7
4	7.7	18.4	65	0.01	787	0.00	250	7
9	5.5	18.0	66	0.00	788	0.00	250	7
359	6.5	17.2	68	0.00	789	0.00	450	7
21	4.4	17.0	70	0.00	789	0.00	800	7
27	3.6	16.7	71	0.00	789	0.00	800	7
304	4.1	16.0	76	0.00	789	0.00	800	7
338	6.4	15.6	78	0.00	789	0.00	1250	7
239	4.9	15.2	78	0.03	789	0.00	800	7
298	4.0	15.5	83	0.02	789	0.00	250	7
287	4.1	15.2	80	0.00	789	0.00	250	7
283	3.2	15.5	82	0.00	789	0.00	450	7
283	3.4	15.5	78	5.37	789	0.00	250	7
309	3.8	16.0	75	79.19	790	0.00	450	7
355	6.2	17.4	70	354.00	790	0.00	450	7
10	8.4	18.1	59	471.00	791	0.00	450	7
3	10.1	19.0	53	571.60	790	0.00	450	7
356	9.6	20.0	54	816.00	790	0.00	450	7
349	9.3	20.7	45	906.00	789	0.00	450	7
354	10.0	21.5	49	963.00	788	0.00	450	7
352	11.0	21.7	45	699.40	787	0.00	450	7
1	11.4	22.1	42	683.10	787	0.00	450	7
353	10.3	22.2	43	476.10	787	0.00	450	7
358	11.3	21.4	39	190.00	787	0.00	450	7

358	8.0	20.2	46	28.56	787	0.00	450	7
2	6.4	19.3	53	0.02	788	0.00	450	7
344	7.0	18.6	57	0.01	789	0.00	450	7
42	6.3	17.7	65	0.00	789	0.00	250	7
337	4.3	17.5	68	0.01	789	0.00	250	7
334	5.0	17.1	72	0.00	789	0.00	150	7
336	4.8	16.6	73	0.00	790	0.00	150	7
349	4.6	16.1	77	0.00	789	0.00	150	7
117	3.0	15.8	76	0.00	789	0.00	75	7
72	1.9	16.1	72	0.01	789	0.00	75	7
309	2.5	16.1	77	0.00	789	0.00	75	7
281	4.0	15.4	81	0.00	789	0.00	250	7
290	4.8	15.3	80	8.44	789	0.00	250	7
331	4.4	16.1	70	71.30	790	0.00	450	7
36	5.8	17.4	57	347.70	791	0.00	800	7
15	8.0	18.0	54	578.10	791	0.00	800	7
1	9.8	18.9	48	719.50	791	0.00	800	7
358	10.7	20.0	44	859.00	790	0.00	1250	7
3	14.2	20.3	44	859.00	790	0.00	800	7
5	11.8	20.8	44	898.00	789	0.00	250	7
360	11.5	21.3	44	837.00	788	0.00	250	7
1	11.0	21.4	43	593.80	788	0.00	450	7
2	11.5	21.0	39	329.60	788	0.00	250	7
6	9.8	20.4	42	87.20	788	0.00	450	7
25	8.8	19.1	46	19.96	789	0.00	450	7
31	8.0	17.9	45	0.03	789	0.00	450	7
47	7.4	17.4	45	0.00	790	0.00	450	7
24	5.1	17.2	51	0.02	790	0.00	450	7
242	3.1	16.5	53	0.00	791	0.00	450	7
212	2.9	16.9	47	0.00	791	0.00	450	7
198	2.8	17.1	52	0.01	790	0.00	450	7
25	2.7	16.2	52	0.03	790	0.00	450	7
63	2.8	15.8	51	0.04	790	0.00	450	7
111	1.8	16.0	51	0.00	789	0.00	450	7
169	3.0	15.9	56	0.00	789	0.00	450	7
203	3.0	15.2	56	0.02	790	0.00	450	7
49	4.0	15.1	54	4.85	790	0.00	450	7
47	2.9	15.3	50	80.80	791	0.00	250	7
356	3.9	16.7	49	322.80	791	0.00	250	7
6	6.2	17.3	49	565.10	791	0.00	150	7
353	9.3	18.3	46	770.10	791	0.00	150	7
1	12.0	19.2	45	897.00	791	0.00	150	7
0	11.4	20.0	44	879.00	790	0.00	75	7
357	10.6	20.5	37	870.00	789	0.00	75	7
347	9.9	21.1	38	764.20	789	0.00	75	7
353	8.7	21.3	40	606.00	788	0.00	250	7
342	9.3	21.2	37	327.90	788	0.00	250	7
357	8.2	20.8	43	174.70	788	0.00	450	7

13	7.2	19.6	49	13.23	789	0.00	800	7
30	7.4	18.3	50	0.10	789	0.00	800	7
37	7.0	17.3	56	0.01	790	0.00	800	7
42	6.3	16.8	56	0.01	790	0.00	1250	7
25	6.0	16.2	62	0.02	790	0.00	800	7
289	3.8	15.7	65	0.01	790	0.00	250	7
250	3.0	15.2	65	0.05	790	0.00	250	7
305	2.1	15.1	65	0.00	790	0.00	450	7
290	1.5	15.0	65	0.00	789	0.00	250	7
279	2.5	14.4	70	0.03	789	0.00	450	7
243	2.3	14.1	71	0.02	790	0.00	450	7
229	3.0	13.9	72	0.00	790	0.00	450	7
213	3.5	13.6	74	5.19	790	0.00	450	7
195	4.9	13.6	72	46.11	791	0.00	450	7
196	5.6	15.3	61	362.30	791	0.00	450	7
127	5.7	18.2	54	594.90	791	0.00	450	7
13	7.5	19.1	49	773.50	791	0.00	450	7
6	8.5	20.3	43	882.00	790	0.00	450	7
347	10.0	21.3	43	941.00	789	0.00	450	7
345	9.1	22.1	43	929.00	789	0.00	450	7
358	8.3	22.6	39	851.00	788	0.00	450	7
1	9.2	23.0	41	618.40	787	0.00	450	7
6	8.7	22.5	42	324.10	787	0.00	450	7
7	6.3	22.1	44	126.10	787	0.00	250	7
12	3.7	21.5	46	28.65	787	0.00	250	7
155	4.1	20.6	51	0.14	788	0.00	150	7
30	5.5	19.8	57	0.04	789	0.00	150	7
50	6.1	18.5	62	0.02	789	0.00	150	7
49	3.8	18.4	64	0.00	790	0.00	75	7
307	4.3	17.2	69	0.02	790	0.00	75	7
302	3.9	16.2	72	0.02	789	0.00	75	7
247	3.1	16.2	73	0.01	789	0.00	250	7
292	3.2	16.1	73	0.03	789	0.00	250	7
339	2.6	15.7	73	0.03	789	0.00	450	7
79	2.0	15.8	75	0.03	789	0.00	800	7
275	2.2	15.5	75	0.01	790	0.00	800	7
289	2.9	15.1	78	4.73	790	0.00	800	7
306	3.4	15.6	77	78.08	791	0.00	1250	7
300	4.1	16.6	69	272.80	792	0.00	800	7
334	4.8	17.8	64	353.90	792	0.00	250	7
11	6.0	18.9	60	599.80	792	0.00	250	7
25	7.1	20.1	53	536.60	791	0.00	450	7
6	7.5	20.5	54	365.40	790	0.00	250	7
353	11.1	21.3	54	526.90	789	0.00	450	7
338	6.3	20.8	47	203.20	789	0.00	450	7
47	4.5	22.3	48	488.00	788	0.00	450	7
143	6.2	22.2	54	345.50	788	0.00	450	7
340	8.4	18.9	73	93.30	788	2.60	450	7

113	10.5	18.5	76	22.05	789	0.00	450	7
336	11.2	16.6	54	0.06	789	0.00	450	7
173	5.8	17.6	60	0.01	790	0.00	450	7
190	7.8	15.9	81	0.04	790	0.00	450	7
178	7.9	15.6	76	0.01	790	0.00	450	7
174	8.2	15.5	73	0.03	790	0.00	450	7
165	7.2	15.5	66	0.01	790	0.00	450	7
166	7.4	15.8	77	0.03	789	0.00	450	7
154	10.3	15.7	77	0.01	789	0.00	450	7
145	6.3	15.4	76	0.02	789	0.00	250	7
138	5.6	15.7	71	0.01	790	0.00	250	7
161	3.3	15.7	76	0.03	790	0.00	150	7
197	2.6	15.5	71	4.25	791	0.00	150	7
261	2.7	16.3	69	67.07	791	0.00	150	7
223	3.3	17.9	67	357.50	792	0.00	75	7
27	5.9	18.7	49	611.60	792	0.00	75	7
356	8.8	19.8	55	790.90	792	0.00	75	7
350	11.4	20.6	46	818.00	791	0.00	250	7
350	10.4	21.4	47	921.00	790	0.00	250	7
356	10.9	22.1	41	882.00	789	0.00	450	7
358	12.0	22.8	41	736.20	788	0.00	800	7
353	11.1	23.2	39	699.90	788	0.00	800	7
6	10.3	22.4	55	283.20	787	0.00	800	7
190	10.3	18.5	70	22.25	788	0.20	1250	7
189	8.3	17.5	62	9.46	789	0.00	800	7
179	8.1	18.0	58	0.01	789	0.00	250	7
298	8.9	15.9	83	0.17	790	0.00	250	7
273	4.3	15.8	78	0.05	791	0.00	450	7
216	3.7	15.8	76	0.07	791	0.00	250	7
159	4.6	16.5	73	0.02	791	0.00	450	7
167	4.0	16.2	71	0.01	791	0.00	450	7
150	4.3	16.1	75	0.03	790	0.00	450	7
168	5.2	15.3	82	0.08	790	0.00	450	7
179	7.0	14.4	84	0.13	789	0.00	450	7
192	5.2	13.8	86	0.11	790	0.00	450	7
183	5.7	13.8	81	0.12	790	0.00	450	7
169	5.2	14.1	77	5.06	790	0.00	450	7
175	5.0	14.6	77	31.72	791	0.00	450	7
158	3.9	16.8	62	328.20	791	0.00	450	7
180	3.9	18.4	68	430.10	792	0.00	450	7
296	5.4	20.0	52	850.00	792	0.00	450	7
332	8.3	20.6	48	672.90	791	0.00	450	7
2	8.8	21.2	47	700.10	790	0.00	450	7
330	10.1	21.5	44	686.30	790	0.00	250	7
326	9.8	22.5	41	634.80	789	0.00	250	7
330	11.3	22.5	42	502.20	788	0.00	150	7
3	8.7	22.3	40	303.10	788	0.00	150	7
9	9.0	22.5	40	198.80	788	0.00	150	7

2	9.0	21.3	52	27.81	788	0.00	75	7
57	8.6	19.4	56	0.11	789	0.00	75	7
167	5.9	18.1	67	0.09	790	0.00	75	7
207	4.2	17.2	72	0.02	791	0.00	250	7
317	7.3	16.5	89	0.11	791	0.00	250	7
316	8.5	15.1	95	0.12	791	0.00	450	7
318	6.3	14.5	100	0.11	791	0.00	800	7
330	7.1	14.3	100	0.08	790	0.00	800	7
344	5.7	13.9	100	0.11	790	0.00	800	7
323	5.5	13.7	100	0.05	790	0.00	1250	7
314	4.9	13.6	100	0.10	790	0.00	800	7
318	3.1	13.6	100	0.10	791	0.00	250	7
308	3.7	13.3	100	4.24	791	0.00	250	7
279	2.9	13.9	100	92.10	791	0.00	450	7
285	3.1	14.4	91	230.90	792	0.00	250	7
319	3.0	17.3	65	563.70	792	0.00	450	7
279	4.5	19.9	61	918.00	792	0.00	450	7
303	5.6	20.5	56	613.00	791	0.00	450	7
333	8.1	20.6	49	497.00	791	0.00	450	7
19	9.1	21.8	44	762.50	790	0.00	450	7
352	10.4	22.7	41	893.00	789	0.00	450	7
326	10.3	21.9	43	152.20	788	0.00	450	7
234	6.4	22.1	38	338.60	788	0.00	450	7
323	11.1	21.5	69	143.10	788	0.20	450	7
345	12.6	17.2	85	5.99	789	0.00	450	7
324	10.5	14.8	94	0.08	790	0.00	450	7
305	9.6	14.2	96	0.06	790	0.00	450	7
318	7.9	14.1	94	0.04	791	0.00	450	7
314	7.3	14.2	94	0.02	791	0.00	450	7
290	5.2	14.1	94	0.03	791	0.00	250	7
288	4.1	14.2	92	0.03	791	0.00	250	7
293	3.5	14.6	91	0.04	791	0.00	150	7
326	3.4	14.2	92	0.01	790	0.00	150	7
339	3.5	14.0	94	0.05	790	0.00	150	7
301	2.5	13.9	95	0.06	790	0.00	75	7
206	4.0	13.5	96	0.15	790	0.20	75	7
185	6.1	13.0	96	4.43	791	0.00	75	7
180	5.6	13.6	89	53.44	791	0.00	250	7
182	5.4	15.1	84	289.10	792	0.00	250	7
208	4.8	17.6	60	594.60	792	0.00	450	7
296	4.0	18.9	64	373.80	791	0.00	800	7
10	6.3	20.4	53	726.50	791	0.00	800	7
16	8.8	21.0	52	679.30	790	0.00	800	7
357	8.1	21.6	54	666.70	790	0.00	1250	7
334	7.4	21.5	50	341.00	789	0.00	800	7
302	5.7	21.6	51	258.30	788	0.00	250	7
278	6.2	22.3	52	177.70	788	0.00	250	7
300	3.1	21.9	49	83.00	788	0.00	450	7

167	7.1	19.5	74	19.58	789	2.80	250	7
176	6.6	17.5	64	0.24	789	1.20	450	7
193	5.6	18.1	61	0.00	789	0.00	450	7
255	5.8	17.4	79	0.04	790	0.00	450	7
272	5.4	16.4	73	0.02	790	0.00	450	7
286	4.5	16.4	77	0.00	790	0.00	450	7
281	4.2	15.9	79	0.00	790	0.00	450	7
292	4.0	15.5	82	0.00	790	0.00	450	7
4	2.5	15.0	74	0.04	790	0.00	450	7
146	3.1	15.2	84	0.00	789	0.00	450	7
177	4.5	14.4	86	0.05	789	0.00	450	7
191	3.9	14.5	86	0.04	790	0.00	450	7
180	3.6	14.3	88	5.28	790	0.00	450	7
188	5.7	14.0	84	67.44	791	0.00	450	7
190	4.9	15.5	74	264.90	791	0.00	450	7
175	5.6	18.6	55	619.90	792	0.00	250	7
357	4.9	20.5	56	812.00	791	0.00	250	7
12	7.0	21.0	51	941.00	791	0.00	150	7
3	8.9	21.5	55	894.00	790	0.00	150	7
348	9.9	22.0	49	815.00	789	0.00	150	7
347	9.0	22.2	50	435.00	789	0.00	75	7
357	8.8	21.6	44	157.20	788	0.00	75	7
343	7.5	22.6	39	359.30	788	0.00	75	7
353	7.5	21.8	47	100.10	788	0.00	250	7
29	7.6	20.6	50	14.40	788	0.00	250	7
28	5.4	19.3	52	0.08	789	0.00	450	7
28	5.6	18.9	53	0.00	789	0.00	800	7
307	4.6	17.9	64	0.04	790	0.00	800	7
317	3.5	17.4	63	0.00	790	0.00	800	7
65	3.6	17.6	68	0.01	790	0.00	1250	7
299	1.7	17.4	71	0.00	790	0.00	800	7
311	2.4	16.8	71	0.00	789	0.00	250	7
336	4.5	16.3	73	0.00	789	0.00	250	7
360	4.4	15.8	73	0.00	789	0.00	450	7
243	2.1	15.8	74	0.07	789	0.00	250	7
202	4.2	15.1	75	0.09	789	0.00	450	7
190	4.9	14.5	75	3.95	790	0.00	450	7
210	3.7	15.3	76	61.68	790	0.00	450	7
266	3.6	17.2	62	236.80	791	0.00	450	7
354	5.2	18.8	56	609.00	791	0.00	450	7
6	9.2	19.3	57	794.00	790	0.00	450	7
356	11.6	20.6	38	798.80	790	0.00	450	7
11	12.9	22.2	35	848.00	789	0.00	450	7
17	13.6	23.3	33	914.00	789	0.00	450	7
12	12.1	22.9	35	480.80	788	0.00	450	7
14	13.4	23.0	33	316.90	788	0.00	450	7
8	12.0	22.9	35	361.80	788	0.00	450	7
13	13.0	22.0	36	125.50	788	0.00	450	7

21	10.7	21.0	45	18.99	788	0.00	450	7
28	14.9	19.8	54	0.05	788	0.00	250	7
30	11.6	18.8	58	0.01	789	0.00	250	7
54	9.2	18.2	63	0.00	789	0.00	150	7
56	8.4	17.6	68	0.00	789	0.00	150	7
22	8.1	16.6	65	0.04	790	0.00	150	7
355	4.6	15.8	68	0.08	790	0.00	75	7
9	4.3	15.1	68	0.03	790	0.00	75	7
17	3.1	15.1	67	0.00	790	0.00	75	7
353	2.2	14.8	73	0.00	790	0.00	250	7
297	3.5	14.3	75	0.00	790	0.00	250	7
285	4.1	13.7	76	0.00	791	0.00	450	7
290	3.9	13.5	74	5.42	791	0.00	800	7
283	2.6	15.4	55	63.41	792	0.00	800	7
17	4.2	16.8	48	261.50	792	0.00	800	7
26	5.8	18.5	43	626.90	792	0.00	1250	7