ASSESSMENT OF THE GEOTHERMAL POTENTIAL FOR ENERGY GENERATION IN SRI LANKA

Gihan Sajeew Mathawarna Arachchi

(118352D)

Degree of Master of Engineering

Department of Mechanical Engineering

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August 2015

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DECLARATION

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Name : Dr. Himan Punchihewa

Signature: .... Date: ....

Name : Dr. Mahinsasa Narayana

Signature: .... Date: ....

ABSTRACT

Geothermal energy is the heat extracted from the subsurface of the earth. The heat loss of the earth is higher at plate boundaries compared in the tectonic plates. The global heat loss is about 44TW where volcanic eruptions in the range 2.4 – 4.0 TW.

Sri Lanka has not located geologically favor conditions for geothermal energy development it has nine hot water springs in the eastern and southern region of the country. Out of nine 7 were located in the Vijayan complex. Geochemical analysis of geothermal water of 6 selected hot water springs and the resistivity depth cross sections for few magnetotelluric tested traverses were used for the assessment of geothermal potential in southern and eastern regions of Sri Lanka.

Geothermal energy potential for 1 km^3 reservoir near the six hot springs in southern and eastern of Sri Lanka can be calculated around 5.76 MW in Mahapelessa to 34.86 MW in Marangala. Based on the geochemical analysis, average temperatures of the geothermal reservoirs are around 120-160℃ for MP, KI, KP and NW and for Marangala, Maha Oya 390 and 230℃ respectively. Also the water from Kapurella, Nelum wewa, Maha Oya has representing the characteristics of volcanic water and Marangala as steam heated water.

Available potentials according to the magnetotelluric studies were well beyond the economical depth of exploration so located deep in the available magnetotelluric cross sections. However according to the chemical analysing the presence of intermediate reservoirs in between the traverse can be expected in shallower.

Night time infrared photography can be used to explore the surface hot water accumulations hence can explore new hot springs. Other than the chemical concentrations, isotopes characterization is useful to detect the origin of the geothermal water. To identify the exact dimensions of the reservoirs three dimensional magnetotelluric testing should be done near the hot springs.

ACKNOWLEDGEMENT

I am very much grateful to Dr. Himan Punchihewa and Dr. Mahinsasa Narayana from University of Moratuwa for giving me their utmost support and guidance as supervisors on this research. Without the support of you I could not be able to complete this research properly.

Also I would be very much grateful to Dr. Deepal Subasinghe from National Institute of Fundamental Studies, Who has done many researches in geothermal energy in Sri Lanka and giving me his fullest cooperation and the valuable knowledge resources. Also I would like to thank Mr. Thusitha Nimalsiri who works as a scientist in same organization and giving me his fullest support.

Also I would like to thank the community living near the locations of hot water springs who has helped me for my research works. Finally, I would appreciate everybody, who helped me in numerous ways at different stages of the research, which was of utmost importance in bringing out this effort a success.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CEB	Ceylon Electricity Board
EGEC	European Geothermal Energy Council
EGS	Enhanced Geothermal System
GE	Geothermal Energy
GHP	Geothermal Heat Pump
GSMB	Geological Survey and Mine Bureau
HC	Highland Complex
NIFS	National Institute of Fundamental Studies
IGA	International Geothermal Agency
INEEL	Idaho National Engineering and Environment Lab
KI	Kivulegama
KP	Kapurella
MA	Marangala
MO	Maha oya
MP	Mahapelessa
MT	Magnetotellurics
NW	Nelum Wewa
NWSDB	National Water Supply and Drainage Board
RE	Renewable Energy
SLSEA	Sri Lanka Sustainable Energy Authority
USA	United States of America
VC	Vijayan Complex
WEC	World Energy Council

1. INTRODUCTION

This chapter gives a summary of the energy scenario and its present consequences in global and local context.

1.1 Background

Energy is a vital entity in every aspect of human activities and as well in the activities happening in environment. The sun is the mother of the all energy sources that drives the earth including living and non-living objects. Present man uses various forms of energy derived from the Sun for his day-to-day activities and the development of the humankind is totally based on the availability of adequate quantity and quality of energy sources. The energy requirement of the ancient man was limited mainly for cooking and lighting. After the industrialization in 200 years ago and the invention of fossil fuel reserves; he has been hunting for energy not only for his survival also for the development of the society which he belongs to. The history does not reveal that man has been a great dependent of energy, however the advent of fossil fuels have changed the world dramatically which created so many problems in the present. In case of harnessing and usage of energy have become interesting topics in the modern development world.

Energy can categorised in to two forms, renewable and non-renewable. The fossil fuels are the source of non-renewable energy, therefore gradually depleting or other words takes very long time to reform and soon will be eradicate from the world, within next two or three decades as predicted (Leng , 2009) under present consumption. Due to the increasing demand, the cost for all forms of energy will also increase day by day (International energy agency, 2009). This is a serious issue that every nation will face. On the other hand the environment pollution due to the extensive burning changed the world climate considerably (International energy agency, 2009). Thus the world is altered on this severe issue and gradually shifting to renewable energy (RE) sources, by minimizing the usage of conventional energy sources. One such promising type of RE source is geothermal energy.

1.2 Definition of Geothermal Energy

Geothermal energy (GE) is the heat energy that can be extracted from the interior of the earth. This subsurface heat appears in two forms, as continuous energy current from the mantle to surface (dynamic) and the heat stored in the crust (Stefansson , 2005). The earth is a natural source of heat and as one goes deeper, the temperature rises by as much as 30ºC for each kilometer (Stefansson , 2005). In certain regions of the earth, particularly in volcanic terrains, plate boundaries (Stefansson , 2005) (Stefansson V 2005) the temperature increases quite rapidly than in the normal subsurface. Thermal energy stored in these areas can be extracted economically as geothermal for power generation and various applications depending on the subsurface temperature of the source.

GE is widely regarded as a renewable and clean energy. It is being used in more than 58 countries (International geothermal association, 2014) for electricity generation and for thermal applications including India and Nepal. United States, China and Iceland respectively on the top of tapping geothermal sources for electricity production while Iceland's power needs are mostly met by such energy (International geothermal association, 2014).

1.3 Problem Statement

Sri Lankan economy is heavily depends on fossil fuels. According to the ministry of Power and Energy 2015, 25% of the import cost due to the importation of fossil fuel products also it is approximately 50% of the total export income (Central bank of Sri Lanka , 2014). Conventional renewable energy sources have reached their economically viable capacity and few viable projects yet to be constructed (CEB).Although the country fails to produce present energy demand, the demand is increasing annually (Sri Lanka sustainable energy authority , 2013). Sri Lanka as a middle income country has changed their strategies towards knowledge economy (Ministry of power and energy , 2015) in case substitutes for the fossil fuels should be discovered to reduce the burden for the national economy.

1.3.1 Sri Lanka energy sector

Sri Lankan energy sector mainly depend on local available biomass and imported petroleum fuels. Transport sector is almost fully depending on petroleum and recent developments in the coal power plants reduce the usage of petroleum fuels for electricity generation.

Table 1.1: Primary energy consumption in 2011 and 2012

Primary energy (PJ)	**2011**	**2012**
Biomass	207.0	209.9
Petroleum	205.8	218.5
Coal	13.6	19.1
Major hydro	40.4	27.4
New renewable energy	7.5	7.6
Total	**474.2**	**482.5**

Source: (Sri Lanka sustainable energy authority , 2013)

1.3.2 Electricity sector

Ceylon Electricity Board (CEB) is the statutory body responsible for power generation, transmission and most of the distribution of electricity. Total electrification from the national grid reached 98% in 2015 (Ministry of power and energy , 2015). The total installed capacity owned and operates by CEB is 3,368.0 MW. Total generation in 2012 was 11,878.8 GWh (Ceylon electricity board, 2014). The approximate break down of the said demand is representing in Table 1.2.

Table 1.2: Approximate breakdown of the installed capacities of power plants

Total Grid Connected Capacity (MW)	**2005**	**2008**	**2009**	**2010**	**2011**	**2012**
Major Hydro	1,207.5	1,207.5	1,207.5	1,207.5	1,207.5	1,357.
Thermal Power	1,114.5	1,284.5	1,304.5	1,389.5	1,689.5	1,695.
CEB Wind	3.0	3.0	3.0	3.0	3.0	3.0
New Renewable Energy	85.8	145.9	182.2	217.6	240.7	312.2
Total Installed Capacity	**2,410.8**	**2,640.9**	**2,697.2**	**2,817.6**	**3,140.7**	**3,368.**
Major Hydro (%)	50.1	45.7	44.8	42.9	38.4	40.3
Thermal Power	46.2	48.6	48.4	49.3	53.8	50.3
CEB Wind (%)	0.1	0.1	0.1	0.1	0.1	0.1
New Renewable Energy	3.6	5.5	6.8	7.7	7.7	9.3

Source: (Sri Lanka sustainable energy authority , 2013)

1.3.3 Electricity demand

According to the long term generation expansion planning studies carried out by Ceylon Electricity Board in 2011, the year-on-average annual growth rate of electricity demand is 7.8%.

Table 1.3: Year-on-average annual growth rates of electricity demand

System Parameters	**2000**	**2005**	**2008**	**2009**	**2010**	**2011**
Total Gross Generation (GWh)	6,629.1	8,897.7	10,003.3	9,986.9	10,800.7	11,646.0
Total Grid Connected Capacity (MW)	1,838.2	2,410.8	2,640.9	2,697.2	2,817.6	3,140.7
Year-on-year growth rate (%)	11.5	9.6	1.4	-0.2	8.2	7.8

Source: (Sri Lanka sustainable energy authority , 2013)

Table 1.4: Forecasted electricity demand from 2014 to 2024

CEB Energy Demand	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Forecast	13,995	15,100	16,283	17,556	18,920	20,383
Year	**2020**	**2022**	**2023**	**2024**	-	-
Forecast	21,949	25,429	27,361	29,431	-	-

Source: (Amarawickrama & Hun, 2007)

Sri Lanka as a county try is facing a power deficit at present, which can sustainably met by construction of new RE plants. Recently in 2012 Ceylon Electricity Board added Upper Kotmale hydro power project which is 150MW and plans to add Uma Oya 134MW, Broadlands 35MWand Moragahakanda to the national grid soon. However, Ceylon Electricity Board has set no solid plans in the non-conventional sector beyond these three projects since the potential for large hydro power projects has reached almost its end.

1.4 Aim and Objectives

Geothermal power has not been use for energy generation as a source in Sri Lanka. At present, most hot spring areas are already being used as bathing and tourist attraction places and few are in remote locations. Today geothermal power is an unutilised source of energy in Sri Lanka. Thus the study aims in to develop an approach to facilitate utilisation of GE effectively.

The objectives are;

1. To identify the potential of GE.
2. To study the economics of GE technologies.
3. To develop an approach for the economical utilisation of GE.
4. To estimate the potential of GE in Southern and eastern of Sri Lanka.
5. To identify the possible applications of GE.

1.5 Methodology

In the research mainly it was planned to assess the GE potential in the Southern and Eastern part of Sri Lanka. Six available hot springs in Hambantota, Ampara and Polonnaruwa districts were selected for the study. Geographical positioning of the hot springs was identified by using a global positioning system. Geothermal water in the springs was tested for the anions, cations and few other relevant elements. Maximum temperatures of the spring water were measured by an infrared thermometer. Temperature, potential of the underground resource, viable power plant capacity for 1 m3 reservoir and the levelized power cost for all six hot spring locations were assessed by analyzing the chemical data. Available resistivity depth magnetotelluric scanning data near the five springs and one cross traverse were used to compare the calculated vs. the actual available cross sections of resource distribution. Finally possible applications of geothermal energy were suggested in both thermal and electrical streams.

1.6 Expected Outcomes

Key outcomes

1. Formation of geothermal energy and the renewable components was identified.
2. World geothermal utilisation and the economics of geothermal energy identified.
3. Potential areas for geothermal energy harnessing in southern and eastern region of Sri Lanka were identified.

4. Potential of geothermal energy based on volumetric capacity generation in Southern and eastern region of Sri Lanka was identified.
5. Possible applications for geothermal energy were identified.

1.7 Chapter Introduction

Chapter 1 provides the background data for the study and the problem statement. It defines the importance of the research by analyzing the energy sector demands with the available energy sources. Also it explains the aims, objectives and the expected outcomes after conducting the research.

Chapter 2 is the literature survey most of the theories related to the study was presented. Literature survey structures by providing overview of the geothermal energy in the world and its applications. Economics aspects and the status of geothermal energy usage of Sri Lanka also discussed in this chapter.

Chapter 3 provides the methodology of the research and explains the main steps used to perform the study.

Chapter 4 is the case study. It includes the identification of potential areas for geothermal energy harnessing and the potential calculations based on geochemical and magneto telluric survey data.

Chapter 5 is the final chapter provides the conclusion and recommendations. Also it discussed about the next step of the research.

2. LITERATURE SURVEY

2.1 Formation of Geothermal Energy

Geothermal energy is the heat extracted from the subsurface of the earth. The earth is mainly structured in to four layers as illustrated in Figure 2.1; crust, mantle, outer core and the inner core (Braile , 2002). The thickness of the earth's crust is location specific ranging from 5-10 km in oceanic regions to 20-70 km for continental and used for the geothermal power excavations. Geothermal Energy is appears in two main forms; a) as continuous energy current from the mantle to surface and b) the heat stored in the crust (Stefansson , 2005). Continuous energy current generated in the core of the earth plays a dynamic power transfer role and the stored heat in the crust is static. Both the dynamic and static components of the terrestrial energy contribute the formation of geothermal resources used by mankind and this dual nature has sometimes confused to clarify whether it is renewable or not.

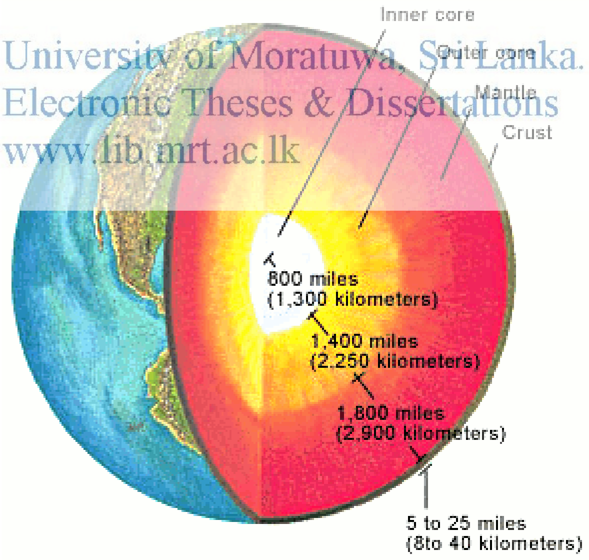

Figure 2.1: Cross section of the earth

Source: (Braile , 2002)

The mantle is liquid and can be divided in to two parts; upper and lower depending on the distance from the center of the earth (Braile , 2002). It contains mainly

Magnesium and Iron rich silicate rocks where the crust is in rich with Silicon dioxide (SiO_2).

Intensity of the terrestrial energy current flowing from the mantle to the surface of the Earth is higher at plate boundaries than within the plates (Stefansson , 2005). At the surface of the Earth, the most obvious manifestations of this energy current are active volcanoes, high temperature geothermal fields and hot water springs. Geothermal assessments have only been carried out for a limited number of countries or regions, while the distribution of active volcanoes in the world is fairly well known (International geothermal association, 2014). As the volcanoes and the high temperature geothermal fields are manifestations of the same energy current, in case it can be useful to map the distribution of active volcanoes and hot water springs to obtain an estimate of the geothermal potential of the world. Theoretical considerations reveal that a huge amount of geothermal energy is stored in the crust of the Earth (Stefansson , 2005). The question is how much of this stored energy, what are the temperature ranges and how much of the energy current is available for the usage of mankind. An empirical relation between the number of active volcanoes and the theoretical potential of high temperature geothermal fields in eight regions of the world established (Stefansson , 1998). This relation is then used to estimate the technical potential of high temperature geothermal fields in the world. By the use of this temperature distribution of geothermal resources in Iceland, USA and China, a lower limit for the potential of low temperature geothermal resources in the world are estimated (Stefansson , 2005).

2.2 Heat Transfer inside the Earth

Terrestrial heat energy transfer from the core to the crust of the earth is takes place mainly in three processes (Stefansson , 2005)

- Thermal conduction: Transfer of energy in the solids without bulk movement; microscopic diffusion and collision of particles.

- Advection of geothermal fluid: Bulk movement of the geothermal fluids which carrying the heat energy. This is usually happened in the hot water springs.
- Advection of magma in the crust which is sometime associated with volcanic eruptions: Bulk movement of the molten and semi molten rocks which carrying the heat energy.

The thickness of the earth's crust varies from the plate boundaries to the crustal plates and it is less in the boundary areas compared with the other areas of the plates (Braile , 2002). In case the heat loss is higher at plate boundaries compared in the tectonic plates. This is due to the simple fact that all three energy transfer and transport processes are at work in the plate boundary regions. Other than the plate boundaries, within the plate thermal conduction is mainly responsible for the energy transfer from the interior towards the surface of the Earth.

The tectonic plates cover about 85% of the surface of the Earth, whereas about 15% of the surface area is classified as boundary regions (Gordon , 1995). The most obvious manifestations of this energy current are active volcanoes and high temperature geothermal fields where plate boundaries are above sea level. Pollack, et al., have estimated the global heat loss at 44 ± 1 TW Based on 24,774 heat flow measurements measures in 20,201 sites located both on continents and sea. Conductive heat flow measurements on the ocean floor were corrected for hydrothermal circulation in young oceanic crust. The average values obtained in the study were 101 MW/m^2 for the oceanic floor and 65 MW/m^2 for the continents (Pollack , et al., 1993). The weighted average for the Earth is 87 MW/m^2 giving a global heat loss of 44 TW as mentioned above. In this study the heat loss through volcanic eruptions and the hydrothermal circulation above sea level, at the continents, were not considered. Therefore it is obvious that global heat loss is therefore somewhat higher than the 44 TW value presented by Pollack and the team.

The average flow rate of magma from volcanoes is estimated by Sigurdsson (Sigurdsson , 2000) in the range $(15 \text{ to } 25 \times 10^{6})\text{km}^{3}/$ million years. By assuming the following parameters: magma temperature = 1300 °C, specific heat of magma = 1 kJ/kg°C, and the latent heat of magma = 400 kJ/kg, we obtain an average heat flow of volcanic eruptions in the range 2.4 – 4.0 TW.

The value 3 TW can be approximately chosen enough to figure as an estimate of the average heat loss of the Earth through volcanic eruptions. The remaining component of the heat loss of the Earth is the heat loss through land based hydrothermal circulation is one of the most important figures for a theoretical estimate of the geothermal potential of the Earth. This component comprises the dynamic part of geothermal activity and it is also related to the renewability of geothermal energy (Stefansson V 2005). The size of this component of the terrestrial energy current might be similar to the heat loss through volcanic eruptions (Stefansson , 2005) since an important feature of the two components, volcanic eruptions and high temperature geothermal fields, is that they are correlated geographically. Active volcanoes and high temperature geothermal fields are concentrated at the plate boundaries of the Earth. Furthermore, these two phenomena are surface manifestations of the same terrestrial energy current. Therefore, it can be expected that there is a correlation between the distribution of active volcanoes and the intensity of high temperature geothermal activity.

2.2.1 Energy storage in the crust

Heat stored in the rocks in the crust down to 3 km depth below the continents was estimated as 12×10^{12}GWh (Electric power research institute, 1978). According to International Energy Agency (International energy agency, 2014) world energy comparison in 2012 is 155,505 TWh. This mean that the heat energy stored in the top 3 km of the crust is equal to the energy consumption by mankind for some 77,000 years at the present rate. The average heat transfer values obtained in the studies were 101 MW/m^2 for the oceanic floor and 65 MW/m^2 for the continents (Pollack , et al., 1993). Considering the radius of the earth as 6371 km and assuming the earth is a sphere, heat loss only from the continents can calculated as 9.946 TW. The time required to fill up this 12×10^{12}GWh storage required approximately 137,730 years.

2.2.2 Geothermal gradient

The geothermal gradient is the rate of change of temperature (ΔT) with depth (ΔZ), in the earth. The usual measuring unit is K/km or °C/km. In geothermal terms, the measurement of T is associated with heat flow, Q, through the simple relation;

$$\mathbf{Q} = \mathbf{K}\frac{\mathbf{\Delta T}}{\mathbf{\Delta Z}} \quad (2.1)$$

Where, K is the thermal conductivity of the rock. The rate of increase with depth (geothermal gradient) varies considerably with both tectonic setting and the thermal properties of the rock. On average, the temperature of the Earth increases with depth, about 25–30˚C/km above the surface ambient temperature (International energy agency, 2009). Higher gradients up to 200°C/km are observed along the oceanic spreading centers and along island arcs. The high gradients are due to molten volcanic (magma) rising to the surface. Low gradients are observed in tectonic subduction zones because of thrusting, cold, water-filled sediments beneath an existing crust.

2.3 Historical Development of Geothermal Energy in the World

Geothermal energy, heat from the interior of the Earth, has been utilized by mankind since its existence. Hot springs and hot pools have been used for bathing and health treatment, but also for cooking or heating. The first relations between man and geothermal energy date back to the Paleolite period (Quaternary times up to 14,000 B.C.), when man might have discovered the advantages of warm springs and started to use them (Stober & Bucher , 2013). Also there are evidences that Paleo Indians lived in North America had used hot water springs for their sanitary and domestic activities more than 10,000 years ago (Kepinska , 2003). Men used to settle in the vicinity of geothermally active places, where they could bathe, rest, cook or use hydrothermal or volcanic products. Natural hot springs were more attractive for them than the volcanic areas. Traces of this could be found on the Japanese islands 11,000 years B.C. (Kepinska , 2003), whereas archaeological findings on the Asian continent show the use of hot springs for bathing as far back as 5,000 years B.C. Greek islands be rich in examples of thermal energy use for therapeutic and cosmetic purposes and medicines produced using geothermal water.

The first industrial use of geothermal energy began near Pisa, Italy in late 18th century. Steam coming from natural vents (and from drilled holes) was used to extract boric acid from the hot pools that are now known as the Larderello fields (International geothermal association, 2014).

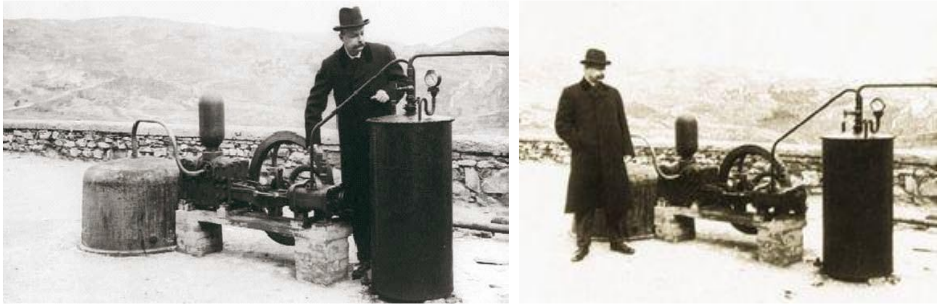

Figure 2.2: First attempt to generate electricity from geothermal at Larderello

Source: (International geothermal association, 2014)

Exploitation of the natural steam for its mechanical energy began at much the same time. The geothermal steam was used to raise liquids in primitive gas lifts and later in reciprocating and centrifugal pumps and winches, all of which were used in drilling or the local boric acid industry (Stober & Bucher , 2013). Between 1850 and 1875 the factory at Larderello held the monopoly in Europe for boric acid production. Between 1910 and 1940 the low pressure steam in this part of Tuscany was brought into use to heat the industrial and residential buildings and greenhouses (Stober & Bucher , 2013). Other countries also began developing their geothermal resources on an industrial scale. In 1892 the first geothermal district heating system began operations in Boise, Idaho (USA). In 1928 Iceland, another pioneer in the utilisation of geothermal energy began exploiting its geothermal water for domestic heating purposes (International geothermal association, 2014).

In 1904 the first attempt was being made at generating electricity from geothermal steam; again, it was to take place at Larderello invented by the Italian scientist Prince Piero Ginori Conti (Stober & Bucher , 2013). The success of this experiment was a clear indication of the industrial value of geothermal energy and marked the beginning of a form of exploitation that was to develop significantly from then on. Electricity generation at Larderello was a commercial success. By 1942 the installed geothermal-electric capacity had reached 127,650 $kW_{e.}$ Several countries were soon to follow the example set by Italy. In 1919 the first geothermal wells in Japan were drilled at Beppu, followed in 1921 by wells drilled at The Geysers, California, and USA with a capacity of 250 kilowatts. In 1958 a small geothermal power plant began operating in New Zealand; in 1959 another began in Mexico, in 1960 in the USA, (Stober & Bucher , 2013)followed by many other countries in the years to come.

However, in 1946 first ground source geothermal heat pump installed at Commonwealth Building in Portland, Oregon. During the 1960′s, pacific gas and electric began operation of first large scale geothermal power plant in San Francisco, producing 11 megawatts (Stober & Bucher , 2013).

In 1973, when oil crisis began many countries began looking for REsources and by 1980′s geothermal heat pumps (GHP) started gaining popularity in order to reduce heating and cooling costs (Stober & Bucher , 2013). As effect of climate change started showing results, governments of various countries joined their hands to fight against it, for which Kyoto Protocol was signed in Japan in 1997, 184 countries had laid out emission targets for rich countries and required that they transfer funds and technology to developing countries. This revolution has created a golden opportunity for the developers and for the scientists to experiment geothermal as a source for energy generation in many parts of the world.

2.4 World Geothermal Assessment

Assessment of the geothermal potential in the world is not as simple as other non-conventional RE sources. Thus it is difficult to understand the potential of underground resource and their distribution than on the ground. Therefore the volumetric assessment method is more or less the only simple assessment method for geothermal resources. This is the assessment method that has been used to estimate the geothermal potential of the United States (Muffler , 1978), Iceland (Palmason , et al., 1985), and the Tuscany region of Italy (Muffler & Cataldi , 1978). Additional estimates have been published for countries like Japan, Indonesia, New Zealand, Philippines, and Mexico. However these estimates are based on more uncertain assumptions than used in the volumetric method.

A more accurate assessment method is the use of geothermal simulation models to estimate the generation capacity of a given geothermal field. A prerequisite for this assessment method is relatively detailed knowledge on the internal conditions in the geothermal reservoir under consideration. Therefore, this method can hardly be applied until several wells have been drilled into a given reservoir and simulation modeling is usually only applied after exploitation has started. Simulation methods can be applied for a single geothermal resource is not as suitable to estimate the geothermal potential of a large region. Comparison of the results obtained by the volumetric method and the simulation method shows that the estimation by the volumetric method tends to be 4 to 5 times larger than the simulation methods (Stefansson , 2005).

Most of the geothermal fields which suitable for electricity generation are located at plate boundaries (Stefansson , 2005). Therefore an estimation of the geothermal potential of plate boundaries would reflect approximate yield of the geothermal electricity generation potential in the world. Valgardur Stefansson in 2005 has analysed the active volcanoes in few countries to determine the high temperature geothermal potential of the particular countries; in fact most of the active volcanoes are located near the plate boundaries.

Table 2.1: Number of active volcanoes and estimated geothermal potential

Country	Number of active	Identified resources MWe for electricity generation
Iceland	33	5,800
USA	133	23,000
Indonesia	126	16,000
Philippines	53	6,000
Japan	100	20,000
Mexico	35	6,000
New Zealand	19	3,650
Tuscany (Italy)	3	700
Total	502	75,150

Source: (Stefansson , 2005)

During the last 10,000 years, 1511 active volcanoes have been identified in the world (Simkin & Siebert , 1994). Using that figures the world geothermal potential is estimated about 240 $GW_{e.}$ Out of the 1511 active volcanoes listed in Simkin and Sibert, 189 volcanoes are not accessible because they are located on the sea. Therefore only considering the 1322 active volcanoes in the continents, the world high temperature geothermal potential calculated as 209 GW_e for electricity generation.

The geothermal potential estimated in Table 2.1 refers to resources suitable for electricity generation, which in most cases mean the extraction of geothermal fluid in excess of 130°C. Also it is evident that this estimate is only valid for the plate boundaries of the Earth. Geothermal fluids with their temperatures lower than 130°C comprises the largest part of the world´s geothermal energy. In order to estimate the magnitude of the geothermal potential with lower temperatures than 130°C, Valgardur Stefansson used the frequency distribution of geothermal resources as function of temperature. From that study he has found that 68% of world total geothermal energy sources are below 130°C. The remaining 32% of the total are resources with temperature higher than 130°C. According to this estimation world low temperature geothermal potential for electricity generation can be calculated as 444 GW_e. Therefore assuming 10% efficiency in converting geothermal heat in to electricity, world low temperature geothermal potential for thermal applications can be calculated as 4440 GW_{th}. This is equal to the value of 38,894 TWh. According to International Energy Agency (International energy agency, 2014) world energy comparison in 2012 is 155,505 TWh.

Surface manifestations as hot springs or fumaroles are usually the most reliable indicators of the existence of geothermal resources at depth in the crust. In other cases, geothermal resources have been identified where no surface manifestations are present. Such resources can be categorised as hidden resources. In general, it is assumed that the number of undiscovered hidden resources is larger than the number of identified resources (Stefansson , 2005). In summary the estimated technically viable potential of geothermal resources is identified as in Table 2.2.

Table 2.2: Technically viable potential of geothermal resources in the world

Category	**Lower limit for the potential of GE resources.**	**World GE potential for identified resources**	**Upper limit for the potential of GE resources**
Resources suitable for electricity generation	0.05 TW_e	0.2 TW_e	1-2 TW_e
Resources suitable for direct use	1 TW_{th}	4.4 TW_{th}	22-44 TW_{th}
Total potential	1.5 TW_{th}	6 TW_{th}	30-60 TW_{th}

(Source: Stefansson V, 2005)

2.5 Geothermal Energy Utilisation in the World.

Many countries were attracted by geothermal energy after the World war two because it to be economically competitive with other forms of energy. It did not have to be imported; it has minimum pollution compared with fossil fuels. In some regions, it was the only energy source available locally. The countries that utilize geothermal for electricity generation up to 2003 were listed in Table 2.3. Table 2.4 gives worldwide geothermal installed capacities and generated energy for non-electric applications in 2000 Also in Table 2.5 illustrate the world summary in 2005.

The most common non-electric use worldwide is heat pumps (34.80%), followed by bathing (26.20%), space-heating (21.62%), greenhouses (8.22%), aquaculture (3.93%) and industrial processes (3.13%) (International geothermal association, 2014).

Table 2.3: Installed geothermal capacities worldwide from 1995 to 2003

No	Country	1995 (MW$_e$)	2000 (MW$_e$)	1995-2000 increse (MW$_e$)	1995-2000 increase %	2003 (MW$_e$)
1	Australia	0.15	0.15	-	-	0.15
2	Austria	-	-	-	-	1.25
3	China	28.78	29.17	0.39	1.36	28.18
4	Costa Rica	55.00	142.50	87.50	159.09	162.50
5	El Salvador	105.00	161.00	56.00	53.33	161.00
6	Ethiopia	-	7.00	7.00	-	7.00
7	France	4.20	4,2	-	-	15.00
8	Germany	-	-	-	-	0.23
9	Guatemala	-	33.40	33.40	-	29.00
10	Iceland	50.00	170.00	120.00	240.00	200.00
11	Indonesia	309.75	589.50	279.75	90.31	807.00
12	Italy	631.70	785.00	153.30	24.27	790.50
13	Japan	413.70	546.90	133.20	32.20	560.90
14	Kenya	45.00	45.00	-	-	121.00
15	Mexico	753.00	755.00	2.00	0.27	953.00
16	New Zealand	286.00	437.00	151.00	52.80	421.30
17	Nicaragua	70.00	70.00	-	-	77.50
18	Papua New Guinea	-	-	-	-	6.00
19	Philippines	1,227.00	1,909.00	682.00	55.58	1,931.00
20	Portugal	5.00	16.00	11.00	220.00	16.00
21	Russia	11.00	23.00	12.00	109.09	73.00
22	Thailand	0.30	0.30	-	-	0.30
23	Turkey	20.40	20.40	-	-	20.40
24	USA	2,816.70	2,228.00	-	-	2,020.00
Total		**6,832.68**	**7,968.32**	**1,728.54**	**25.30**	**8,402.21**

Source: (International geothermal association, 2014)

Table 2.4: Worldwide non-electric use of geothermal energy in 2000

No	Country	Power (MWt)	Energy (TJ/yr)	No	Country	Power (MWt)	Energy (TJ/yr)
1	Algeria	100	1,586	30	Japan	1,167	26,933
2	Argentina	26	449	31	Jordan	153	1,540
3	Armenia	1	15	32	Kenya	1	10
4	Australia	34	351	33	Korea	36	753
5	Austria	255	1,609	34	Lithuania	21	599
6	Belgium	4	107	35	Macedonia	81	510
7	Bulgaria	107	1,637	36	Mexico	164	3,919
8	Canada	378	1,023	37	Nepal	1	22
9	Caribbean Islands	0	1	38	Netherlands	11	57
10	Chile	0	7	39	New Zealand	308	7,081
11	China	2,282	37,908	40	Norway	6	32
12	Colombia	13	266	41	Peru	2	49
13	Croatia	114	555	42	Philippines	1	25
14	Czech Republic	13	128	43	Poland	69	275
15	Denmark	7	75	44	Portugal	6	35
16	Egypt	1	15	45	Romania	152	2,871
17	Finland	81	484	46	Russia	308	6,144
18	France	326	4,895	47	Serbia	80	2,375
19	Georgia	250	6,307	48	Slovak Republic	132	2,118
20	Germany	397	1,568	49	Slovenia	42	705
21	Greece	57	385	50	Sweden	377	4,128
22	Guatemala	4	117	51	Switzerland	547	2,386
23	Honduras	1	17	52	Thailand	1	15
24	Hungary	473	4,086	53	Tunisia	23	201
25	Iceland	1,469	20,170	54	Turkey	820	15,756
26	India	80	2,517	55	United Kingdom	3	21
27	Indonesia	2	43	56	USA	3,766	20,302
28	Israel	63	1,713	57	Venezuela	1	14
29	Italy	326	3,774	58	Yemen	1	15
Total		6,864	91,808	Total		8,281	98,891
Grand Total						**15,145**	**190,699**

Source: (International geothermal association, 2014)

Table 2.5: World summary data in 2005

Country	Installed Capacity (MW)	Running capacity (MW)	Annual Energy Produced (GWh /y)	Number of units	Percentage of national installed capacity	Percentage of national energy
Australia	0	0.1	0.5	1	Negligible	Negligible
Austria	1	1	3.2	2	Negligible	Negligible
China	28	19	95.7	13	30 Tibet	30% Tibet
Costa Rica	163	163	1145	5	8.40%	15%
El Salvador	151	119	967	5	14%	24%
Ethiopia	7	7	N/a	1	1%	n/a
France	15	15	102	2	9% Guadeloupe island	9% Guadeloupe island
Germany	0	0.2	1.5	1	Negligible	Negligible
Guatemala	33	29	212	8	1.70%	3%
Iceland	202	202	1406	19	13.70%	16.60%
Indonesia	797	838	6085	15	2.20%	6.70%
Italy	790	699	5340	32	1.00%	1.90%
Japan	535	530	3467	19	0.20%	0.30%
Kenya	127	127	1088	8	11.20%	19.20%
Mexico	953	953	6282	36	2.20%	3.10%
New Zealand	435	403	2774	33	5.50%	7.10%
Nicaragua	77	38	270.7	3	11.20%	9.80%
Papua New Guinea	6	6	17	1	10.9% Lihir island	
Philippines	1931	1838	9419	57	12.70%	19.10%
Portugal	16	13	90	5	25%San Miguel island	
Russia	79	79	85	11	Negligible	Negligible
Thailand	0	0.3	1.8	1	Negligible	Negligible
Turkey	20	18	105	1	Negligible	Negligible
USA	2544	1914	17840	189	0.30%	0.50%
Total	8,912	8,010	56,798	468		

Source: (Bertani , 2005)

2.6 Geothermal Electricity Production

Geothermal power plants use the earth’s heat in the form of underground steam or hot water to spin a turbine and generate electricity. Wells hundreds to thousands of feet deep are used to deliver the hot fluid to the power plant on the surface, where the heat is converted to electrical energy. Nearly all the water is returned to the reservoir through injection wells to be reheated. Currently, geothermal electricity production is limited to certain western states where the hottest resources are closer to the surface. Advances in drilling and energy conversion technologies could make it possible to expand the use of geothermal power plants to other states. The four main types of commercial geothermal power plants are dry steam plants that use resources of pure steam, flash steam, binary cycle plants and back pressure plants that tap reservoirs of hot water. Total installed capacities in 2005 have been classified under the said plant categories as shown in Table 2.6.

Table 2.6: GE power plants distribution

Category	**Installed capacity (MW)**	**No of plants**
Dry steam	2,545	61
Single Flash	3,296	122
Double Flash	2,268	65
Binary/Combined cycle/Hybrid	685	192
Back pressure	119	28
Total	8912	468

Source: (Bertani , 2005)

The highest values of installed capacities are for dry steam and single flash units covering 66% of the total. Figure 2.3 shows the percentage distribution of GE power plants with respect to the installed capacity.

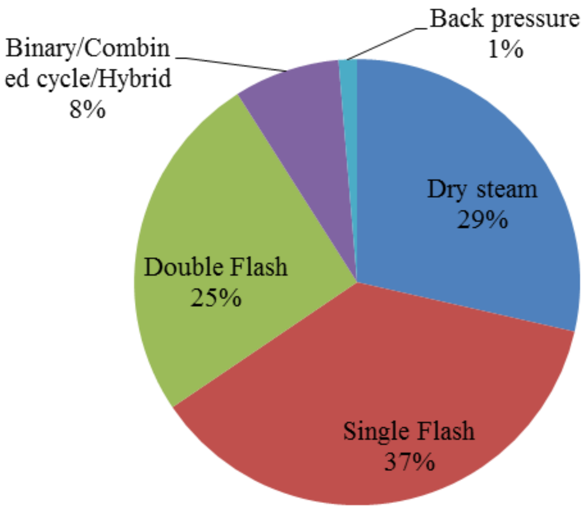

Figure 2.3: Percentage of GE electric power plants by their installed capacity

2.6.1 Dry steam geothermal power plants

The dry steam systems use the hottest reservoirs where steam comes directly from the ground and drives turbines couple to generate electricity. However, these resources are rare and only five such fields have been discovered till 2005. The only commercially developed steam field in the United States is The Geysers, located in Northern California, which began the commercial production of electricity in 1960. Another dry steam geothermal field in Lardarello, Italy, began production in the early 20th century (Kepinska , 2003). These plants emit only excess steam and very minor amounts of non-condensable gases. For dry steam resources either atmospheric exhaust turbines or condensing steam turbines are used.

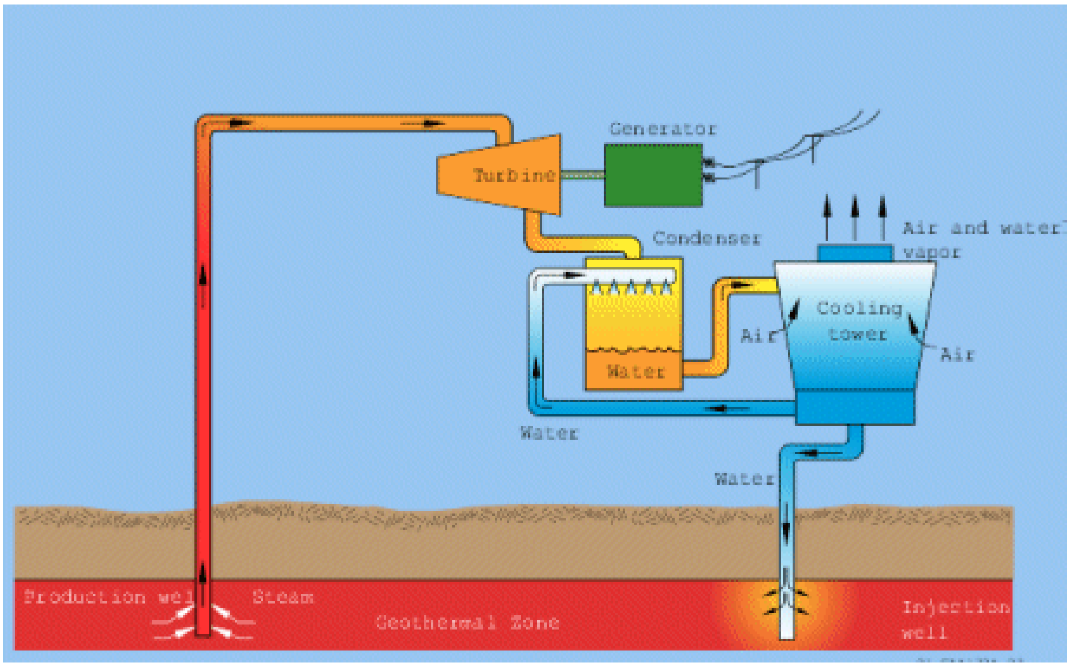

Figure 2.4: Schematic diagram of dry steam geothermal plant (Condensing)

Source: (Idaho Engineering and Environmental Lab, 2015)

Atmospheric exhaust steam turbines are the simplest and, in capital cost, the cheapest of all geothermal cycles. With this type of plant the geothermal steam obtained either directly from dry steam wells, or after flash separation from wet wells, is fed through a conventional axial flow steam turbine which exhausts directly to the atmosphere. Condensing exhaust conventional steam turbine plants are a thermodynamic improvement on the atmospheric exhaust design as, instead of discharging steam from the turbine to atmosphere, it is discharged to a condensing chamber that is maintained at a very low absolute pressure, typically 0.12 bar. Due to the greater pressure drop across a condensing turbine much more power is generated from a given steam flow, at typical inlet conditions, compared with an atmospheric exhaust turbine

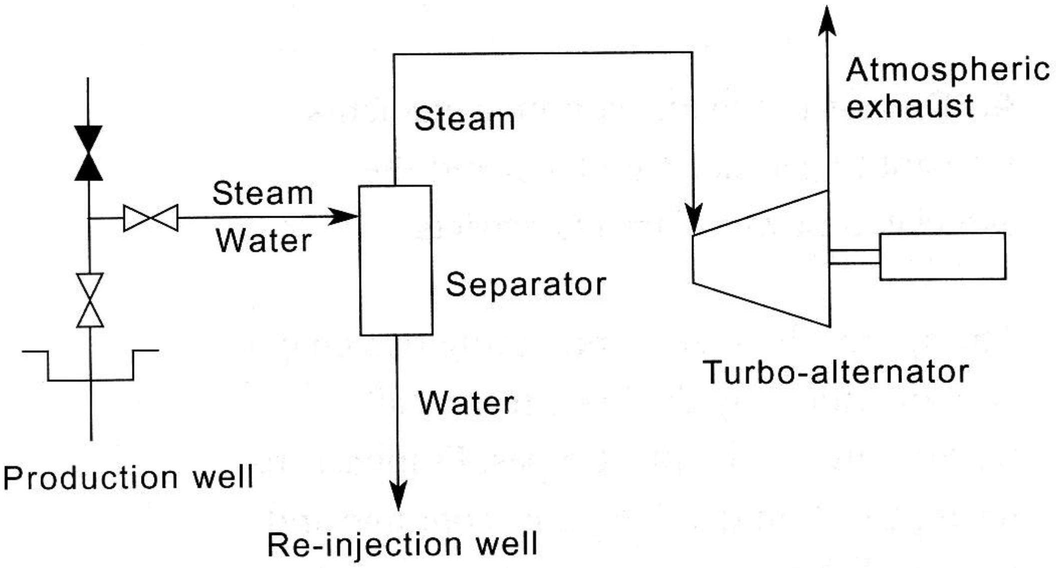

Figure 2.5: Schematic diagram of atmospheric exhaust system

Source: (Ragnarsson , 2006)

2.6.2 Flash steam geothermal power plants

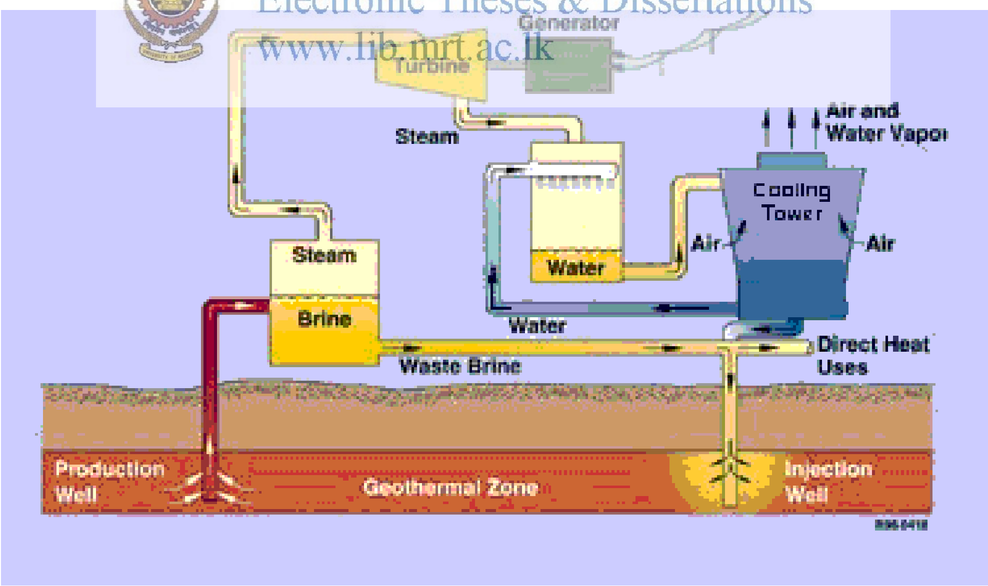

Figure 2.6: Schematic diagram of flash steam geothermal plants

Source: (Idaho Engineering and Environmental Lab, 2015)

Hydrothermal fluids above 182°C can be used in flash plants to make electricity. Fluid is sprayed into a tank held at a much lower pressure than the fluid, causing some of the fluid to rapidly vaporize, or “flash”. The vapor then drives a turbine, which drives a generator. If any liquid remains in the tank, it can be flashed again in a second tank to extract even more energy.

Flash power plants can be distinguished in single flash and multiple flash plants: Single flash in a single flash plant the liquid dominated brine steam mixture will be flashed in a separator before the dried steam will be fed to the condensing steam turbine. Condensing cycles have more auxiliary equipment compared to atmospheric exhaust units. This significantly increases the costs of the total plant as well as construction and installation time. Furthermore, the presence of non-condensable gases in the geothermal steam, which accumulate in the condenser, requires the installation of a gas extraction system, which will in smaller quantities emit Green House Gasses such as NO_2 and CO_2. However in very small quantities compared to a fossil fuel fired power plant. These types of power plants operate in California, Japan, Hawaii, Nevada and Utah.

Multiple flash

The above sections consider conventional steam turbines supplied with geothermal steam obtained either directly from dry steam wells, or after flash separation from wet wells. However in the case of lower enthalpy well discharge it can become attractive to flash the separated water from the first separator to a lower pressure and obtain an additional geothermal quantity of steam, at a lower pressure. Multi-flash systems are similar to the single-flash apart from additional flash tanks for the production of further steam from the hot water coming from the separator. The steam produced during the first flash stage is sent to the first stage of the turbine, while the steam produced from the following flashes is admitted in intermediate turbine stages. The decision regarding the use of a multiple flash system is a simple economic one, whereby the value of the increased generation should be compared against the increased capital cost of the additional flash separation plant.

2.6.3 Binary geothermal power plants

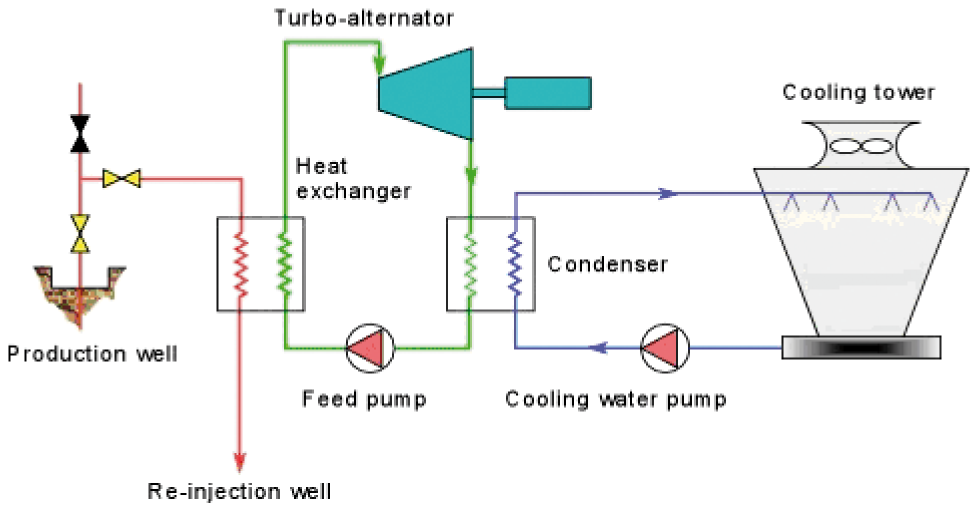

Figure 2.7: Schematic diagram of binary GE power plant

Source: (European geothermal energy council, 2014)

This rapidly expanding technology uses geothermal resources with temperatures as low as 90°C. As illustrated in Figure 2.7, rather than flashing the geothermal fluid to produce steam, this type of power plant uses heat exchangers to transfer the heat of the water to another working fluid that vaporizes at lower temperatures. This vapor drives a turbine to generate power, after which it is condensed and circulated back to the heat exchangers. This type of geothermal plant has superior environmental characteristics compared to the others because the hot water (which tends to contain dissolved salts and minerals) is never exposed to the atmosphere before it is injected back into the reservoir. Binary power plants were introduced in the mid-1980s and are the fastest growing generating technology currently with more than 350 MW of binary generation capacity in California, Hawaii, Nevada and Utah (Bertani , 2005).

Enhanced geothermal system

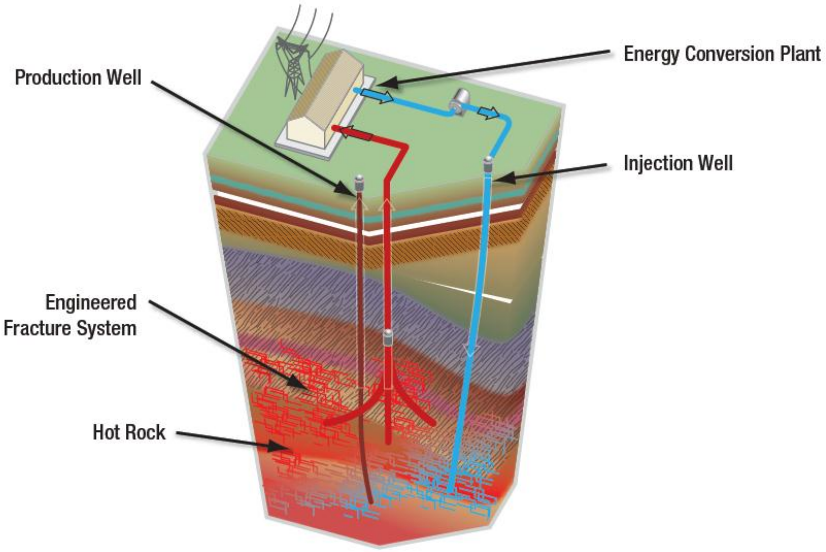

Figure 2.8: Cross sectional diagram of an enhanced geothermal system

Source: (U.S. Department of energy , 2008)

Various studies have estimated the developmental potential from identified hydrothermal resources to be in the range of tens of thousands of megawatts. After some 30 years of exploration, the estimated total potential has not increased significantly, leading some analysts to conclude that the occurrence of natural hydrothermal reservoirs is limited. The natural hydrothermal resource is ultimately dependent on the coincidence of substantial amounts of heat, fluids, and permeability in reservoirs and the present state of knowledge suggests that this coincidence is not commonplace in the earth. An alternative to dependence on naturally occurring hydrothermal reservoirs involves human intervention to engineer hydrothermal reservoirs in hot rocks for commercial use. This alternative is known as Enhanced Geothermal Systems (EGS). EGS reservoirs are made by drilling wells into hot rock and fracturing the rock sufficiently to enable a fluid (water) to flow between the wells. The fluid flows along permeable pathways, picking up in situ heat, and exits the reservoir via production wells. At the surface, the fluid passes through a power plant where electricity is generated. Upon leaving the power plant, the fluid is returned to the reservoir through injection wells to complete the circulation loop

(Figure 2.8). If the plant uses a closed-loop binary cycle to generate electricity, none of the fluids vent to the atmosphere. The plant will have no greenhouse gas emissions other than vapor from water that may be used for cooling (European geothermal energy council, 2014). Basic requirements for an EGS can list as;

- Identify and exploit the natural fracture networks hosted in basement rocks
- Boost their conductivity/connectivity via massive stimulation techniques to favor the creation of large fractured rock volumes and related heat exchange areas
- Complete a heat extraction system based on a multi production/injection well array
- Circulate large amounts of water via pumping/ lifting/buoyancy into this man-made geothermal reservoir to maximize heat and power production
- Achieve adequate heat recovery and system life to secure system sustainability

2.6.4 Combined cycle geothermal power plants

Figure 2.9: Combined cycle power plant installed in Hawaii, USA

Source: (GeothermEx, Inc, 2005)

A further improvement to utilize the potential of a high or medium temperature resource is the combination of a flash power plant with a binary cycle power plant. This will increase the efficiency of the power plant at higher investment costs.

2.6.5 Hybrid power plants

Hybrid systems, which combine a geothermal power plant with another type of power plant, offer the flexibility of determining the optimal steam temperature independent of the geothermal resource temperature. This adds increased reliability to the system design. Hybrid systems can increase efficiency, and therefore create more electricity without expanding the use of the geothermal resource. In a typical hybrid configuration, the source for the first heat exchangers is geothermal and the energy source for additional heat exchanger(s) usually identify as super heater could come from any other source, including biomass, hydropower or even coal. The generating capacity of the combined power station would in this case be boosted by the additional heat/power source.

In countries like Indonesia, biomass (sugar cane or rice hulls) or hydropower are available and could be combined to geothermal power in a hybrid power station using 100% renewable energy (International geothermal association, 2014).

2.7 Geothermal Applications

Geothermal energy is used for various non-electric applications in the world. In Figure 2.7, 1995 to 2005 data are divided among the various uses in terms of the capacity and energy utilisation.

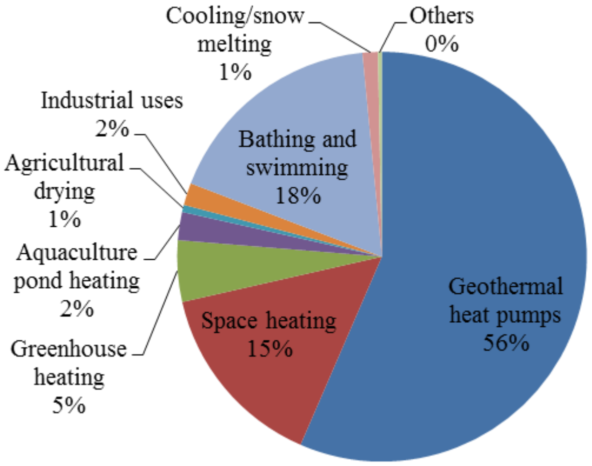

Figure 2.10: GE applications as a percentage of capacity (MWt) in 2005

Table 2.7: Summary of the various worldwide direct use categories 1995-2005

Geothermal Application	Capacity (MW_t)			Utilisation (TJ/y)		
	1995	2000	2005	1995	2000	2005
Geothermal heat pumps	1,854	5,275	15,723	14,617	23,275	86,673
Space heating	2,579	3,263	4,158	38,230	42,926	52,868
Greenhouse heating	1,085	1,246	1,348	15,742	17,864	19,607
Aquaculture pond heating	1,097	605	616	13,493	11,733	10,969
Agricultural drying	67	74	157	1,124	1,038	2,013
Industrial uses	544	474	489	10,120	10,220	11,068
Bathing and swimming	1,085	3,957	4,911	15,742	79,546	75,289
Cooling/snow melting	115	114	338	1,124	1,063	1,885
Others	238	137	86	2,249	3,034	1,045
Total	8,664	15,145	27,826	112,441	190,699	261,417

Source: (Lund , et al., 2005)

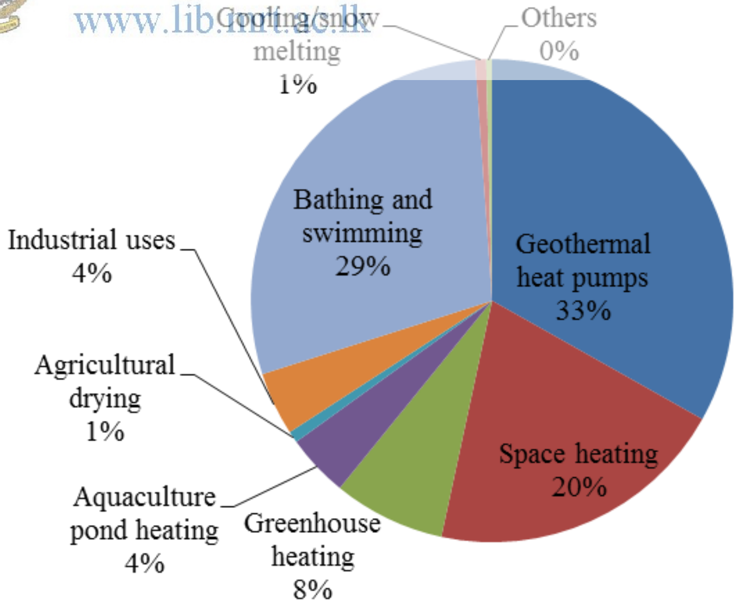

Figure 2.11: GE applications as a percentage of utilisation (TJ/y) in 2005

Lindal diagram

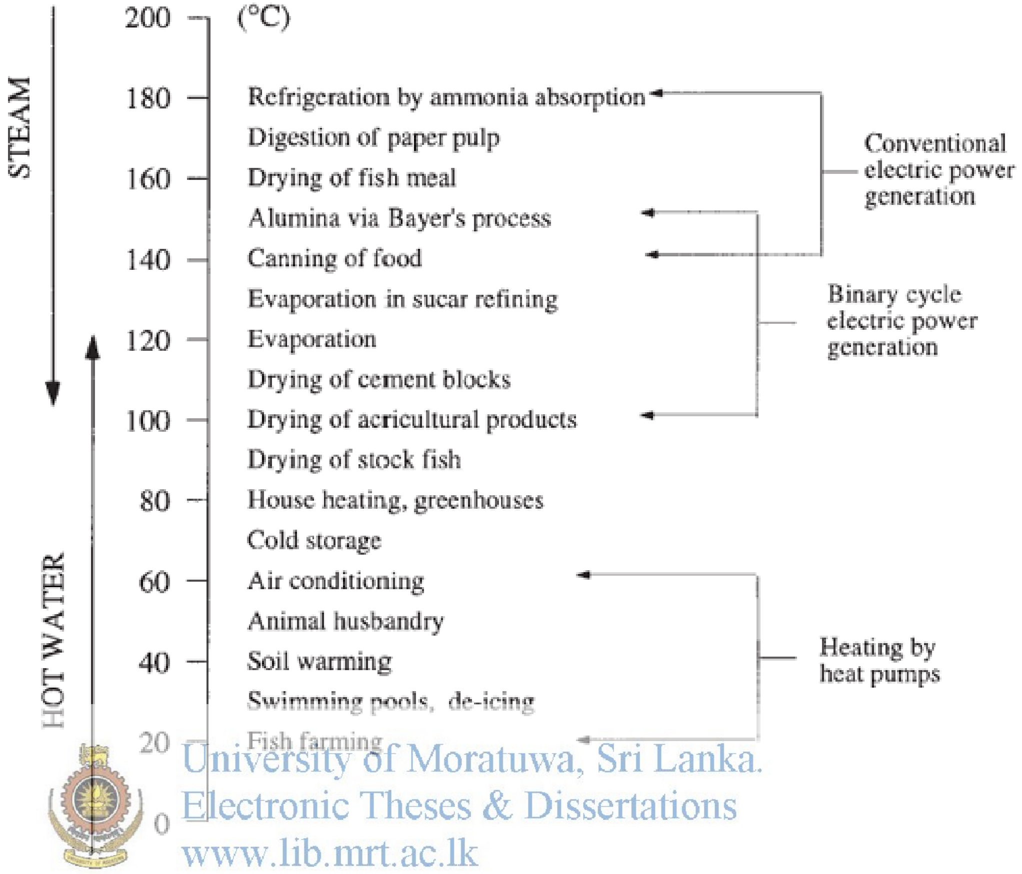

Figure 2.12: Lindal diagram

Source: (International geothermal association, 2014)

The Lindal diagram is developed to determine the possible applications of geothermal energy resources depending on the temperature limits. Also it provides applicable energy conversion techniques.

2.7.1 Geothermal heat pumps

Geothermal heat pumps works in the same way as a refrigerator but in the opposite direction. Usually they are used to heat areas by absorbing heat from a GE resource. GE heat pumps are frequently suggests when the temperature of the resource is not much enough for direct application. Geothermal heat pumps have the largest energy use and installed capacity, accounting for 33% and 56% of the word-wide utilisation and capacity. The installed capacity is 15,723 MW_t and the annual energy use is 86,673 TJ/yr with a capacity factor of 0.17 in the heating mode (Lund , et al., 2005).

2.7.2 Space conditioning

Space condition refers to the alteration of the climate in an enclosed space by either heating or cooling. The use of geothermal energy for space conditioning is popular in cold countries. In Iceland where about 90% of the houses are heated using geothermal water (Lund , et al., 2005). The heating of buildings is accompanied by the supply of hot water for domestic uses such as washing. In tropical climates, geothermal energy could be used to cool building for the comfort of the occupants. This is done by the use of vapor absorption machines, which use hot water as the source of energy in order to circulate a refrigerant medium within the system.

Vapor absorption systems are of two types. Lithium Bromide and water cycle, where water is the refrigerant while lithium bromide used as the absorbent. This configuration is used mainly for air conditioning where temperatures do not go below 0°C as this would result in freezing of the refrigerant. The second configuration is the water, ammonia cycle where ammonia is the refrigerant. This is mainly used for the applications which achieve temperatures below 0°C.

2.7.3 Agriculture and Green house heating

The major application of geothermal energy in agriculture is the heating of greenhouses in order to control the climate, mainly temperature and relative humidity. The temperature of the water supplied to the greenhouse depends on the heating demand and ranges from 40-100°C (Vasilevska , 2007). The water is distributed in steel pipes which could be placed under the soil, on the soil or on benches, between rows of plants or suspended in the greenhouse space.

About 900 ha of greenhouses are presently heated with geothermal energy, about 50% of which are located in Mediterranean countries. That is about 14% of the total geothermal direct application in the world (European geothermal energy council, 2014). After the initialization in France, Macedonia, Greece and several Central/East

European countries in late 70's and early 80, and development of a set of different heating technologies accommodated to the requests of different types of greenhouse constructions, cultures (flowers and vegetables) and available temperatures of geothermal water, a process of continual development all over the world is in flow. Present knowledge enables competitive economical solutions both for the simple and sophisticated greenhouse constructions and growing technologies and easy incorporation in centralized integrated or district heating projects.

In order to produce fast maturing and high quality plants, certain growing conditions must be maintained as close as possible to the optimum. These include nutrients and climatic conditions such as temperature and humidity. It is for this reason that Oserian flower farm in Kenya utilizes thermal energy from one of its geothermal wells leased from KenGen to heat its greenhouses (Kiruja , 2011). Kenya is a tropical country in which annual temperatures remain relatively constant throughout the year. However during the cold months and at night, the temperatures could drop considerably. These temperatures may drop below the optimal value for growing flowers and result in formation of dew on the flowers and the leaves, a situation that could encourage the growth of fungi which destroy the quality of flowers. However, final success of the applied technical solutions and economy of exploitation still depend very much on quality of initial technical design of the heating system.

2.7.4 Industrial uses

The industrial uses of geothermal energy are numerous and involve mainly heating and cooling. They depend to a large extent on the economic activities around the geothermal resource. Drying or dehydration of agricultural produce is one of the major industrial applications of geothermal energy. The products that can be dried include grains, fruits, and vegetables. Eburru in Kenya, the local community uses steam from a shallow borehole for drying pyrethrum (Kiruja , 2011).

Dairy processing is yet another application of geothermal energy where fresh milk from the farmers can be pasteurized using hot geothermal water. A series of plate heat exchangers are used to keep the milk and heating water separated during pasteurization. Concentration of milk, one of the stages in milk powder production, requires temperatures below 100°C. This is done in a falling film evaporator and the evaporation temperature can easily be obtained from geothermal water (Kiruja , 2011). Geothermal heat is used in various industries all around the world for the heating applications and some of the applications can be listed as;

- Animal products processing after production in order to preserve them.
- Skins and fides from animals are treated by tawing and tanning at temperatures of about 40°C in order to produce good quality leather.
- Pulp, Paper and wood processing.
- Process heating, pre heating of boiler water.
- Extraction of salt by evaporation.
- Distillation in liquor and hydrocarbon industry.
- Chemical extraction process.

2.7.5 Aquaculture

Fish farming in warm water is a proven geothermal energy direct application in many countries; Italy, France, Hungary, Greece, U.S.A., China and others. Problems of development are more connected to the biological than to the technological problems. Recently, also the algae growing are developed in Bulgaria and Greece and shall be probably a promising field for future development (European geothermal energy council, 2014).

2.7.6 Bathing, swimming and balneology

Bathing is one of the earliest known uses of geothermal energy. Ancient Romans, Turks and Japanese have bathed in geothermal water for over 1000 years (International geothermal association, 2014). Not only is bathing in geothermal water a recreational activity even today, but also believed to have therapeutically effect on the human body.

Some of the health benefits derived from bathing in geothermal water include treatment of high blood pressure, skin diseases, diseases of the nervous system and relieving the symptoms of rheumatism. The use of geothermal energy to heat swimming pools is a common practice especially in the cold countries such as Iceland where almost all outdoor swimming pools are geothermally heated all year round. Steam baths and saunas have also been designed to utilize geothermal fluids to provide steam and heat. Relaxing in these facilities is also associated with some health benefits;

- improving blood circulation
- cleaning and rejuvenating the skin
- easing muscle tension
- promoting feelings of relaxation and well-being
- enhancing detoxification processes

2.8 Economics of Geothermal Energy

2.8.1 Determination of the cost for geothermal energy

Both capital cost and operations and maintenance (O & M) costs of geothermal power have declined substantially over the last decade (Entingh & Mcveigh , 2003). In consideration of this development, it is worthwhile assessing the overall cost of geothermal power today which may enables new players to enter to the field. The power cost considered here is levelized cost in Sri Lanka rupees per kilowatt-hour (LKR/kWh) over the project life, the initial capital cost being depreciated (Amortized) over a period of 30 years; make-up well drilling cost is not take advantage of and is considered an operating expense. The capital cost includes the cost of money (that is, the cumulative present value of all future interest payments) but does not include any transmission line cost or any unusually site specific costs of regulatory compliance or environmental impact mitigation. In this study considered power cost (cost for generate 1 kWh) rather than tariff or project profitability because, unlike price or profitability, cost is substantially independent of the corporate culture of the developer and operator, financing mechanism, local market forces and government policies. Furthermore, cost calculations in this study ignore any royalty burden, tax liability or tax credit. Therefore the values of economic parameters assumed in this study reflect the setting in the United States in 2005, the conclusions arrived at should be applicable at least qualitatively, if not quantitatively, to geothermal power projects worldwide. In the present energy scenario over the relative integrity of various forms of renewable energy, power cost is an objective gauge of judgment that should favor geothermal; yet there is considerable difference of opinion as to what it truly is and can be. Hence the justification for this analysis; the analysis considers a power capacity range of 5 to 150 MW with 50 MW as the base case. Power cost consists of three components:

- Capital cost component (including cost of money)
- O&M cost component (not counting debt service, which is included under the capital cost component)
- Make up well drilling cost component.

All the calculations based on the actual costs ascertain in developed geothermal projects in California, USA.

2.8.2 Costing of geothermal electric systems

Factors that affect the cost of geothermal energy harnessing can be grouped into four main categories (Sanyal , 2005):

- Economy of scale
- Well productivity characteristics
- Development and operational options
- Macroeconomic climate.

In general, economy of scale allows both unit capital cost and unit O&M cost (in LKR/kWh) to decline with increasing installed capacity. The unit capital cost is estimated to vary from LKR 216,000/kW to LKR 337,500/kW (1 USD= LKR 135) depending on project size and other project specific criteria (Sanyal , 2005). For the smallest project size of 5 MW considered here, have assumed a unit capital cost of LKR 337,500/kW and for the largest considered project size of 150 MW a cost of LKR 216,000/kW. Within the above range of values, unit capital cost declines exponentially with plant capacity (Sanyal , 2005). This assumption leads to the following correlation between unit capital cost in LKR/kW (C_d) and plant capacity in P MW (Sanyal , 2005).

$$\mathbf{C_d} = \mathbf{337,500} \times \mathbf{e^{-0.003(P-5)}} \quad (2.2)$$

Operation and maintenance cost approximately ranges from LKR2.7/kWh for a 5 MW plant to LKR1.89/kWh for a 150 MW plant (Sanyal S.K., 2005). Assuming an exponential decline in unit O&M cost in LKR/kWh (C_o) with plant capacity in P MW.

$$\mathbf{C_o} = \mathbf{2.7} \times \boldsymbol{e^{-0.0025(P-5)}} \quad (2.3)$$

Well productivity characteristics affect geothermal power cost in mainly two ways (Sanyal , 2005):

- If well productivity is higher, fewer wells are needed to supply a plant, thus reducing power cost
- A higher rate of decline in well productivity with time calls for more make-up well drilling, and therefore, leads to higher power cost.

Assuming an average initial productivity of 5 MW per well. It is noted that geothermal wells generally undergo harmonic decline in well productivity with time (Sanyal , 2005).

$$\mathbf{W} = \frac{\mathbf{W_i}}{(\mathbf{1+ D_i t})} \quad (2.4)$$

Where W_i is initial productivity, D_i is initial annual decline rate in productivity and W is productivity in year *t*. The harmonic decline trend implies a decline rate that slows down with time. The annual decline rate (D) in productivity in year *t* being given by equation (2.5) (Sanyal , 2005).

$$\mathbf{D} = \frac{\mathbf{D_i}}{(\mathbf{1+D_i t})} \quad (2.5)$$

If the total production rate from a field is small enough to be entirely compensated by natural recharge or if only a small fraction of the productive reservoir is being exploited, the decline rate in well productivity would be insensitive to increases in the installed capacity. These situations are much less common. Most of the practical scenarios decline rate increases with increasing installed capacity (Sanyal , 2005). This sensitivity of productivity decline to installed capacity is very much site-specific to be quantified by a generally applicable correlation.

With the presence of initial decline rate and particular production rate, the new initial decline rate for the change in plant capacity can be determined by using equation 2.6 (Sanyal , 2005).

$$\mathbf{D_i'} = \frac{\mathbf{W_i'}}{\mathbf{W_i}} \times \left(\frac{\mathbf{lnW_i'}}{\mathbf{lnW_i}}\right)\mathbf{D_i} (2.6)$$

For an example: Assume initial decline rate for a base case of 50MW plant is 5% and the initial decline rate of a 40MW plant can be calculated as 3.77%. WhereD_i', and W_i' are decline rate after changing the capacity and the new capacity of the plant respectively. D_i and W_i are for the initial design of 50MW.

There is certain resource development and operational options that affect power cost. The developer of a geothermal project has the option to size the power plant while the operator of the project has the option to either allow generation to decline with time or to maintain generation by make up well drilling; the operator can also run the plant beyond its amortized life.

While the unit capital cost for a given plant capacity, as given by equation (2.2), includes initial drilling cost, the unit O&M cost given by equation (2.3) does not include make up well drilling cost. In order to estimate the make up well drilling cost as a function of time, it is necessary to estimate the initial number of wells required for a given plant capacity. This estimate was based on a typical initial productivity of 5 MW per well plus the customary need for at least one stand by well and a minimum of 10% reserve production capacity at all times. With the above assumptions it follows that the installed plant capacity can be maintained without any make up well drilling for up to t_c years following plant startup, as given in equation (5) and (6) (Sanyal , 2005).

$$\mathbf{t_c} = \frac{\mathbf{1}}{\mathbf{D_i}}\left[\frac{\mathbf{W_i N_{wi}}}{\left(\mathbf{1+\frac{r}{100}}\right)\mathbf{P}} - \mathbf{1}\right] \ (2.7)$$

Where D_i is initial annual harmonic decline rate, W_i is initial productivity per well (MW), N_{wi} is initial number of wells (including at least one stand-by well), P is plant capacity (MW), and r is minimum production capacity reserve required (%).

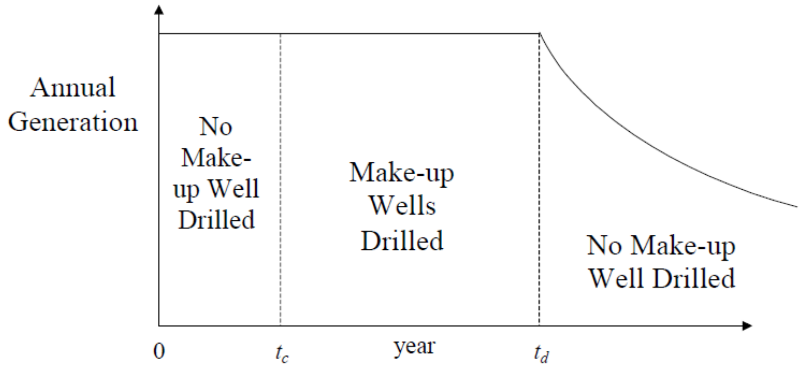

Figure 2.13: Generation and make-up well drilling of a project

Source: (Sanyal , 2005)

Figure 2.13 represents the schematic generation and make-up well drilling histories of a typical power project. Generation can be maintained without make-up well drilling up to year t_c, as given by equation (2.7). Then generation is maintained by make-up well drilling up to year t_d in response to decline in well productivity according to equation (2.4), the initial annual harmonic decline rate being given by equation (2.6). After year t_d no make-up well is drilled and generation is allowed to decline as per equation (2.4) and (2.6).

Levelized cost of geothermal power ($\bar{C}$) can be determined by calculating capital power component of levelized cost ($\bar{C}_{CAP}$), O & M component of levelized cost ($\bar{C}_{O\&M}$) and levelized cost for drilling make up wells ($\bar{C}_{MW}$) over the plant life (Sanyal , 2005). Exchange rate considered as 1USD = LKR 135.

$$\bar{C} = \bar{C}_{CAP} + \bar{C}_{O\&M} + \bar{C}_{MW} \quad (2.8)$$

$$\bar{C}_{CAP} = \frac{100D(t_d)}{G\{D(t_d)t_d + \ln[1 + D(t_d)(n - t_d)]\}} \times \left\{\frac{iC(1+i)^n}{(1+i)^n - 1}\right\}\left\{\frac{(1+I)^n - 1}{I(1+I)^{n-1}}\right\} \quad (2.9)$$

$$\bar{\mathbf{C}}_{\mathbf{O\&M}} = \mathbf{C}_{\mathbf{ov}} + \frac{(\mathbf{t_d})}{\mathbf{n}} \times \mathbf{C}_{\mathbf{ofi}} + \frac{\mathbf{C_{ofi}}}{\mathbf{n}}\{(\mathbf{n} - \mathbf{t_d}) + \frac{\mathbf{Dt_d(n-t_d)^2}}{\mathbf{2}}\} \quad (2.10)$$

$$\bar{C}_{MW} = \frac{100C_{wi}N_{wi}D(t_d)D(t_c)(t_d-t_c)}{G\{D(t_d)t_d+\ln[1+D(t_d)(n-t_d)]\}}, \mathbf{D(t_d) \neq 0} \quad (2.11)$$

$D(t)$= Annual productivity decline rate in year t

G= Initial annual generation in kWh

N= Power plant life

C= Total capital cost

I= Annual inflation rate

C_{ofi} = Fixed portion of the annual O & M cost at plant start-up divided by initial annual generation (US¢/kWh)

C_{ov} = Variable portion of the annual O & M cost divided by initial annual generation (US¢/kWh)

N_{wi} = Number of initial production wells

C_{wi} = Drilling cost per initial production well

Table 2.8: Analysed development scenarios of geothermal projects

Plant capacity (MW)	(Unit capital cost LKR/kW)	Total capital cost LKR Million	O & M cost (LKR/kWh)	Initial harmonic decline rate (%)	No. of initial production wells	Years before makeup well drilling is required (t_c)
5	337,500	1,688	2.70	0.2	2	>30
10	333,180	3,321	2.67	0.6	3	>30
20	322,650	6,453	2.61	1.5	5	9
30	313,065	9,396	2.54	2.6	7	2
50	294,840	14,742	2.42	5	11	0
75	273,375	20,520	2.27	8.3	17	0
100	253,800	25,380	2.13	11.8	22	0
125	235,440	29,430	2.00	15.4	28	0
150	218,430	32,765	1.88	19.2	33	0

Source: (Sanyal , 2005)

2.9 Geothermal Energy in Sri Lanka

2.9.1 Sri Lanka country profile

Sri Lanka, formerly called Ceylon, is an island in the Indian Ocean located in Southern Asia, southeast of India, in a strategic location near major Indian Ocean sea lanes. The total area of the island is 65,610 km^2 approximately, with 62,705 km² of land and 2,905 km² of water located between north latitude 5° 55' - 9° 50' and east longitude 79° 31' - 81° 53' (Central bank of Sri Lanka , 2014). Its coastline is 1,340 km long. The highest point is Piduruthalagala mountain at 2,525 m (Central bank of Sri Lanka , 2014). Natural resources include limestone, graphite, mineral sands, gems, phosphates, clay, and hydro power. The multi ethnic and multi religious population is at present close to 22 million inhabitants. The government is run by the Democratic Socialist Republic of Sri Lanka. The main industries of the island are manufacturing, based on textiles & apparel and tea. Mineral resources currently developed in Sri Lanka are limestone, graphite, mineral sands, gems and phosphate.

Climate

The tropical climate of Sri Lanka is characterised by the rainfall originating from the Southwest and Northeast monsoons, starting April, May (lasting 5 months) and November (lasting 3 months) respectively. Normally Southwest monsoon gives the main rainfall in the Southwestern part of the island while the Northeast gives the heaviest rains in the Northeast. The average rainfall varies from about 1000 mm to more than 5000 mm per year. Temperature varies from 24.4 ^{0}C to 31.7 ^{0}C in the low country and 18.3 ^{0}C to 26.6 ^{0}C in hilly areas.

Seismicity

Sri Lanka lies in the Indo-Australian tectonic plate, seemingly far away from any of the plate boundaries (Dissanayake , 2005). The nearest active plate boundaries to Sri Lanka are the Sumatra subduction zone to the east and the extensional /transform fault structures of the central ridge to the west zones located approximately 2000 km away from Sri Lanka; hence, any earthquakes in these structures are unlikely to be of geothermal significance in the island. Although numerous large earthquakes have occurred in the past within the South Asian region, few of them were reported within Sri Lanka.

Geology

More than 90% of Sri Lanka is made up of highly crystalline, non fossiliferous rocks which lie on Precambrian age (National Institute of Fundamental Studies, 2010). Some of it dating back 2 billion years. Rest 10% is in the north western region Jurassic, Miocene and Quaternary sedimentary formations underlie the northwestern part of the country and extend south in a relatively narrow belt along the west coast. Thabbowa, Andigama and Pallama areas defined as Jurassic and Miocene in Jaffna limestone and low percentage in beach and sand deposits as Quaternary.

The metamorphic rock surface was created by the transformation of ancient sediments under intense heat and pressure during mountain building processes. The theory of plate tectonics suggests that these rocks and related rocks forming most of south India were part of a single southern landmass called Gondwanaland. Beginning about 2000 million years ago, forces within the Earth's mantle began to separate the lands of the Southern Hemisphere, and a crustal plate supporting both India and Sri Lanka moved toward the northeast. About 45 million years ago, the Indian plate collided with the Asian landmass, raising the Himalayas in northern India, and continuing to advance slowly to the present time. Sri Lanka does not experience earthquakes or major volcanic events because it rides on the center of the plate.

As presented in Figure 2.14 Precambrian age rocks running to North and North East. It can be sub divided in to four major geological units. Highland complex, Vijayan complex, Wanni complex, Kadugannawa complex are the four main geological units.

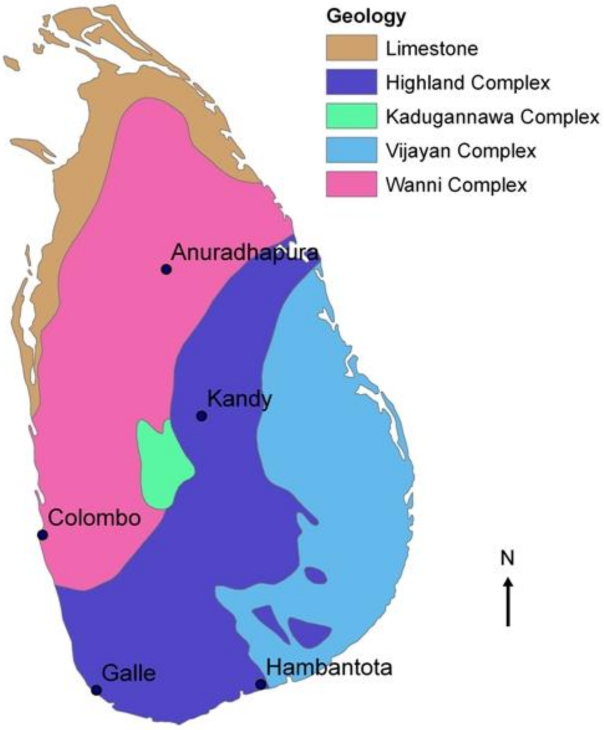

Figure 2.14: Geology map of Sri Lanka

Source: (National Institute of Fundamental Studies, 2010)

Highland series is broad and running across the center of the island from southwest to northwest. It composed of inter-banded metamorphic rocks. The granulite facies rocks of the Highland Series (Charnokitic gneiss, Marble, Quartzite, Quartzofeldspathic gneiss) make up most of the island and the amphibolite facies metamorphism (gneisses, granites, and granitic gneisses) of the Vijayan Series occur in the eastern and southeastern lowlands. Vijayan series has low temperature and pressure compared to Highland series (National Institute of Fundamental Studies, 2010). Kadugannawa complex is in folded within HC and contains Granulite facies metamorphism. The origin of these rocks not yet discovered but it has high temperatures and pressures associated with the process of metamorphism.

Highland Vijayan boundary is a trust zone and also well demarcated. Outliers can be seen as Buttala and Katharagama Klippen (a geological feature of thrust fault terrains) due to trusting of HC over VC (National Institute of Fundamental Studies, 2010). This is a mineralized belt (Magnetite, Serpentine, Vein quartz, Cu-magnetite) which has salient geological features. Seven out of nine identified geothermal springs are located in this boundary region.

Proven data of the geothermal gradient and heat flow along the boundary of the Highland Vijayan complexes (thermal spring belt) of Sri Lanka are still not available. However, a 2.5 km deep borehole on Mannar Island indicates an above normal geothermal gradient of 34.2°C/km (Fonseka , 1994).

Gravity

Figure 2.15 illustrates the Bouguer gravity anomaly map of Sri Lanka. It can be clearly observed that along the Highland and Vijayan boundary Bouguer gravity anomaly values gives high negative values. Particularly in the hot water spring locations of Eastern province these observed values giving more deviation from the predicted values based on the theories. The strength of the gravitational field is directly proportional to the mass and therefore the density of subsurface materials. Anomalies in the earth's gravitational field result from lateral variations in the density of subsurface materials and the distance to these bodies from the measuring equipment (Maritta , 2007). Therefore according to the variation of the observed gravity with the anomaly it can be expected that a low dense volume under the area of Highland and Vijayan boundary. Also, geothermal activity is usually associated with fault structures that provide preferential pathways through the subsurface for the circulation of geothermal fluids. Often, these fault structures do not represent themselves at the surface because they are covered by younger sedimentary cap-rock sequences and the gravity of these areas is lesser than the theoretical expected values (Maritta , 2007).

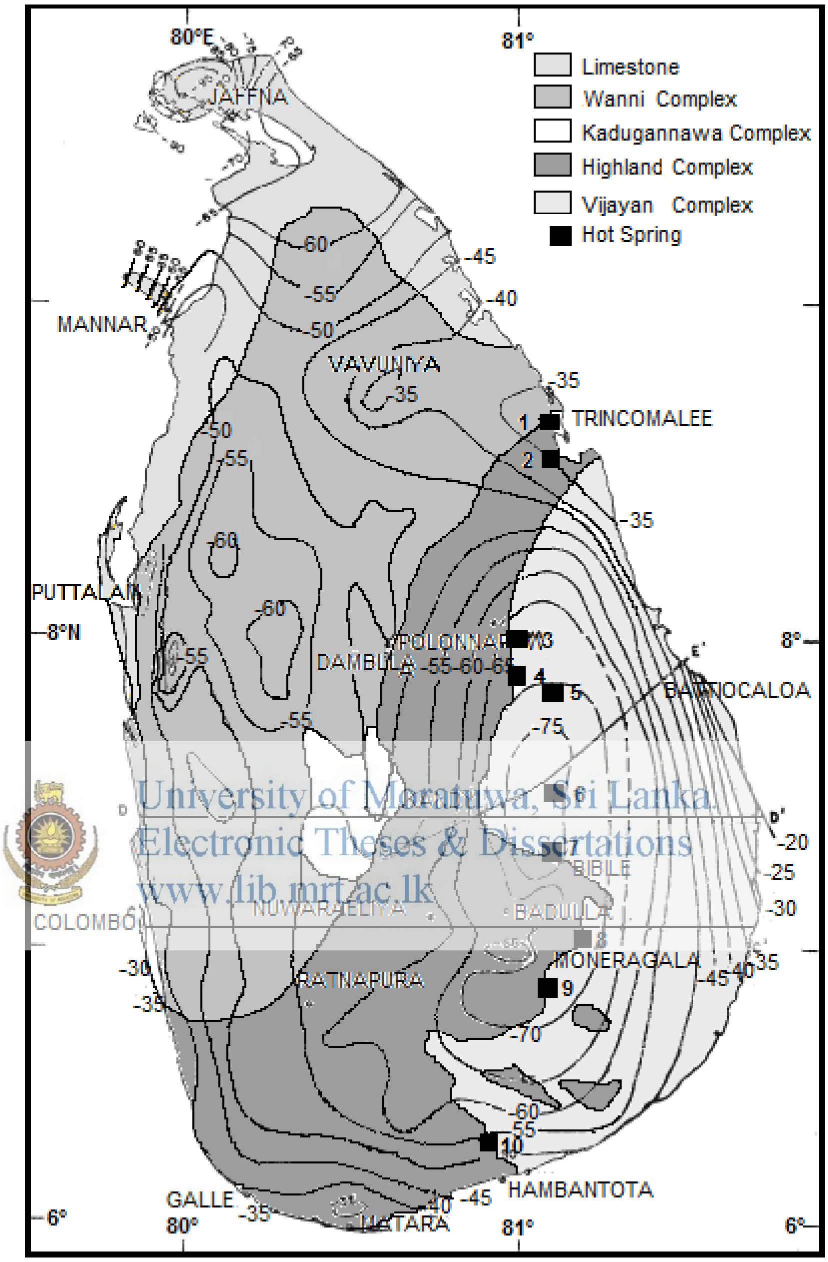

Figure 2.15: Bouguer gravity map marked with hot water springs

Source: (Fonseka , 1995)

2.9.2 Hot water springs

Sri Lanka is not located an active volcanic region or situated within proximity to an active plate margin. However several hot water springs can be identified in the country giving a positive indication of the potential for development as a sustainable energy resource. Surface manifestation of thermal springs has been recorded from ancient times and even ruins of a spa can be seen near Marangala hot water spring. The hot water springs manifest in nine locations from Mahapelessa of Hambantota district to Rankihiriya in Trincomalee district. In some locations more than one spring is available with different temperatures.

a) Mahapelessa (Madunagala)

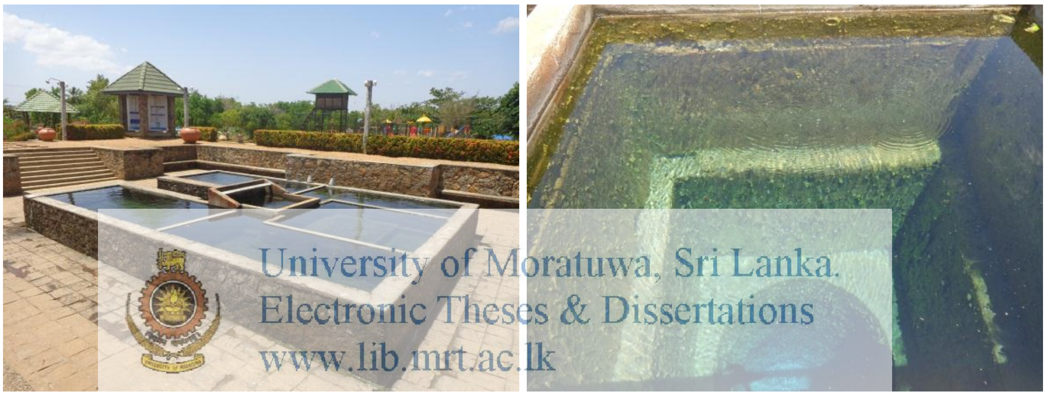

Figure 2.16: Mahapelessa hot water springs

Mahapelessa is the only hot water spring located in the southern part of the country in Hambantota district. The location can be access from Sooriyawewa or Mirijjawila. The first well contains the original hot springs where the water is about 44°C. Few other surrounding wells (Figure 2.16) had been constructed from the original to feed water in lukewarm. In the vicinity of the Mahapelessa hot springs, there are two ancient rock cave hermitages coming down from time immemorial namely, Madunagala and Karambagala. In ancient times Arahants (highest stage of meditation of a Buddhist monk), had lived in those rock cave shelters had used this hot water. Now the place has developed by the local government and very famous among the travelers because it was one of the only few accessible hot water springs till 2009 due to the terrorist activities happened near the other locations.

b) Kivulegama (Jayanthi wewa)

Figure 2.17: Kivulegama hot spring

Kivulegama hot spring is a single hot well located in a privately owned land with lukewarm water. The spring is located along the Pallan oya Road near Jayanthi Wewa in Ampara District. This is the only private owned hot water spring in Sri Lanka also the lowest temperature can be recorded as 34 °C. According to the villager the spring is located near Jayanthi wewa in early stage and after the construction of reservoir now it has shifted to this new location.

To reach the well, take the Pallan oya Road which leads to Inginiyagala from the Wadinagala Junction on Siyambalanduwa Ampara road. Travel along this road approximately 1.9 km to the Pallanoya Bridge. Travel 850 meters passing the bridge to reach the Bund road to the left and the well can be found about 100m walk.

c) Kapurella

Kapurella hot spring is the warmest spring in the country with temperature recording of 65°C and located in the boundary of Thoppigala forest. Until the defeat of the LTTE terrorists in 2009, this area was continuously under threat from the terrorists group and access was restricted. Kapurella hot spring lies in a marshy area in the jungles of Kapurella. Access is through uninhabited forest through elephant country.

This site can be reached from Ampara from the Chenkaladi Padiyathalawa Road (A5), in 69 Junction take the right side turn towards Chenkaladi and travel about 6 km to Tampitiya junction then turn left. The spring can only be access by foot from Tampitiya wewa through forest by crossing Maha Oya. This is largest spring although 18 spring positioned together to form a large ponding area covered by grass and Cane.

Figure 2.18: Kapurella hot spring

d) Marangala (Wahawa)

Wahawa Hot Springs located in a rural village off Padiyathalawa and is the only pressure hot spring in Sri Lanka. The water rises about 3m from the ground level due to the inside pressure of the source. There are 18 springs scattered in the village and the paddy fields. Highest temperature can be recorded as 43°C. They are built in form of tanks and a tower type but it seems that only a few that are being used. Surface manifestation of thermal springs has been recorded from ancient times and even ruins of a spa dedicated to Buddhist monks seen in the vicinity of Wahawa springs. The spring is located about 14 km from the Padiyathalawa town.

Figure 2.19: Hot water artesian tube well in Wahawa

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e) Maha Oya

Maha Oya hot water springs was located 2 km from Maha Oya town travelling on the Maha Oya, Mahampitiya road. Seven springs with different can be found and the temperature of the hottest spring is around 54°C. The area was developed by the local authorities but was cut off for the general public till 2009. The source is very closer to the Maduru oya national park.

Figure 2.20: Maha oya hot water spring

f) Nelum wewa (Gal wewa)

Figure 2.21: Nelum wewa hot spring

The spring is located in Bora wewa village of Polonnaruwa district in north central province. Out of one of the hottest springs in Sri Lanka, Nelum wewa hot springs is the most recent discovery (Kumara & Dharmagunawardhane , 2014). Although these hot springs have been known to the villagers, the existence of the spring was made public in 2009. Temperature of the hottest spring is around 62℃.

This spring lies on the sand banks inside the Nelum wewa (Gal wewa) reservoir on the foothills of the famous Dimbulagala mountain range in the Mahaweli B Zone. This spring is also unique in the sense that it is inside a wewa (reservoir) and submerges during the October rains. Out of the seven springs 3 springs have been closed and 4 wells have been constructed out of the balance springs. The location can be access from Polonnaruwa Batticaloa road after passing Sevanapitiya and turn right to Nelum wewa 4 km from the main road. Access to the springs cannot be done by foot on the rainy season.

g) Muthugalwela (Gurukumbura)

Mutugalwela lies inside the Maduru Oya National Park on the boarders of the Maha Oya Padiyathalawa Mahiyangana Road. This rural village is populated by the Dambana aborigines but lies deep inside the jungles of Maduru Oya about 15 km away from Dambana.

According to aborigines, there has been two springs in the area of Mutugalwela which had been a guaranteed water supply to this rural village. One spring called kurutiyavinna has been gone under the waters of Kirawanagalkanda reservoir when it was built. The second spring has been inside the Maduru Oya National Park which is now not accessible to the villagers.

h) Kanniya

Kanniya hot water spring has now become a popular attraction for those who visit Trincomalee now that the LTTE Terrorists which controlled this area has been completely wiped out. There are 7 hot springs now converted to bathing wells. The temperature of each is slightly different from each other and highest recorded as 42°C. It is also believed the water from the wells have therapeutic healing powers and can cure many aliments.

According to the notice board put by the Pradeshiya Sabha at the wells, this well goes back to the times of King Ravana who ruled the country over 5000 years ago. However now it has been accepted that these wells belonged to a great Buddhist monastery which span vast area. Attack of king Elara of the North and East has destroyed the most of the Buddhist remains in these areas and only few has escaped the wrath of the Eelamists who have taken up to the task of erasing all signs of ancient Buddhist civilization in these areas for the last 30-40 years.

Figure 2.22: Kanniya hot water springs

i) Rankihiriya (Ulpotha)

The two springs at Gomarankadawala hot spring is also referred to as Rankihiriya Hot Springs, Ulpatha Hot Springs or Ulpotha Hot Springs. This hot water spring positioned closer to the Rangiri Ulpotha Buddhist Ruins lying in a picturesque landscape in the dry zone. Temperatures of the water in these wells are 42°C

3. RESEARCH METHODOLOGY

3.1 Identification of Potential Areas

Geothermal energy is one of the cleanest forms of energy which hasn't utilized for energy applications in Sri Lanka. The country hasn't located geologically favor conditions for geothermal energy development (near a plate boundary or within active volcanic terrain); the presence of hot water springs in the southern and eastern part of the country reflects the necessity of further exploration.

Sri Lanka has nine identified hot water springs with different temperatures and no direct steam emission can be observed through cracks or near the springs. In eight locations more than one spring can be found comparing with nine hot water springs. Though the hot water springs located only one part of the country the potential area identification was focused primarily based on the geology of the country. Seven hot water springs were located in Vijayan complex closer to the boundary of Highland and Vijayan complexes and the balanced two in Trincomalee district sorely belongs to Highland complex.

Identified thermal springs near the HC-VC boundary were in inspected and the absolute positions were collected using global position satellite device. Thermal springs in Trincomalee district were dropped down from the study due to their location in HC. Muthugalwela spring also not considered in this study because it is locating in Maduru Oya national park in deep forest and the access is difficult.

Six hot water springs in Southern and eastern region of the country were selected for chemical analysis. Water samples from Mahapelessa, Kivulegama, Kapurella, Marangala, Maha oya and Nelum wewa were collected from each hot water spring and tested for major anions, cations and some relevant elements. Testing of samples was done within 48 hours and temperatures of the springs (maximum temperature) were recorded using infrared thermometer. Depending on the major anion concentrations (Cl-SO_4- HCO_3) the formation of the water in the selected hot springs was predicted.

Magneto telluric survey data (5 traverses) for five springs excluding Kivulegama was analysed for resistivity depth to identify the underground resource distribution of the geothermal near the hot springs. Also cross traverse between Kapurella, Maha oya and Marangala was analysed for further.

Based on the results from the chemical analysis and the resistivity depth analysis of magnetotelluric (MT) survey data, potential areas for geothermal energy harnessing in southern and eastern region of the country were identified.

3.2 Energy Harnessing

For the estimation of the energy potential, reservoir temperatures and the capacities were calculated. Assessment of the temperatures of the geothermal reservoirs was based on the results from the chemical analysis. Mainly cation geothermometers used to determine the average reservoir temperatures.

MT resistivity depth sections were considered for the calculation of geothermal reservoir volumes. Due to the non-availability of three dimensional MT data, only the suitable cross sections for power generation have identified. Imaginary reservoir locations were identified for Kapurella, Maha oya and Marangala springs by observing the MT resistivity depth section the cross traverse.

Volumetric capacity generation was studied for the resources under the hot springs; hence maximum sustainable power generation capacities for 1 km^3 reservoir volume were calculated. Finally levelized electricity generation costs for each source were calculated.

3.3 Selection of Suitable Geothermal Energy Applications

Possible applications of the geothermal energy for both electricity generation and thermal applications were considered depending on their reservoir temperatures and the depth from the surface.

4. CASE STUDY: SOUTHRN AND EASTERN

4.1 Identification of Potential Areas

Geothermal energy is a new form of energy in the Sri Lankan country context. Because is very hard to find a proper estimation about the availability of the resource underground and calculated the economics of the exploration. That may be the root cause for the lack of development in this sector and few other barriers may also affect the development of this new source.

Although Sri Lanka is not located in a plate boundary or near an active volcanic region the interest about this resource usually lags. In generally most of the countries that using GE energy are located closer to plate boundaries and in some cases flows of steam can be visible from the faults or cracks. However Sri Lanka is fortunate to have nine identified hot water spring associated with a geological and tectonic boundary that covers more than 300 km stretch from Kinniya in Trincomalee district to Mahapelesa in Hambantota district in the country gives positive indication about the underground energy resource.

Geothermal springs are the natural springs that contain hot water. Hydro geothermal systems link the global lithosphere, hydrological and atmospheric cycles of the environment. Generally three important factors control the generation of hot springs, including heat sources, ground water and reservoir rocks. The major process of thermal water is to bring the heat from the interior to the surface through a permeable path or aquifer. The main heat sources are from magmas within the upper mantle that intrude to shallower levels from unstable areas such as active volcanic belts or fault zones and the natural conduction . Groundwater is the main source of water, which is principally derived from rain and cool water on the surface that percolates to the subsurface along voids, fractures, joints, or faults of rocks.

4.1.1 Geographical positioning of hot water springs

Identification of the absolute geological positioning of hot water springs is vital since they are the actual ground indications of geothermal resource. Nine hot springs are found within two totally different geological units of Sri Lanka. Seven of these hot springs or thermal springs are distributed along a narrow low land belt running from Hambantota to Trincomalee and occur within the boundary of two main geological units (HC and VC) and two are located on the HC. No any volcanic activities or steam flows on the ground of Sri Lanka. Hot water springs in Trincomalee district located on the HC. Hence the positions and the lithological unit of each hot spring listed in Table 4.1. Muthugalwela is located in the Maduru Oya national park therefore access is difficult; Kanniya and Rankihiriya are in the HC hence not considered in this study.

Mahapelessa is located in Hambantota district of Southern province. Kivulegama, Kapurella, Marangala, Maha Oya are located in Ampara district of Eastern province and Nelum Wewa is located in Polonnaruwa district of North Central province.

Table 4.1: Positions of hot water springs

No	**Hot spring**	**Lithological unit**	**Geographical position**	
			N	**E**
1	Mahapelessa	Vijayan complex	6°15'13.02"N	80°58'54.11"E
2	Kivulegama	Vijayan complex	7° 8'27.10"N	81°33'8.87"E
3	Kapurella	Vijayan complex	7°38'1.38"N	81°25'7.04"E
4	Marangala	Vijayan complex	7°21'41.95"N	81°18'32.73"E
5	Maha Oya	Vijayan complex	7°33'7.82"N	81°21'10.96"E
6	Nelum wewa	Vijayan complex	7°53'26.60"N	81°11'58.33"E
7	Muthugalwela	Vijayan complex	-	-
8	Kanniya	Highland Complex	-	-
9	Rankihiriya	Highland Complex	-	-

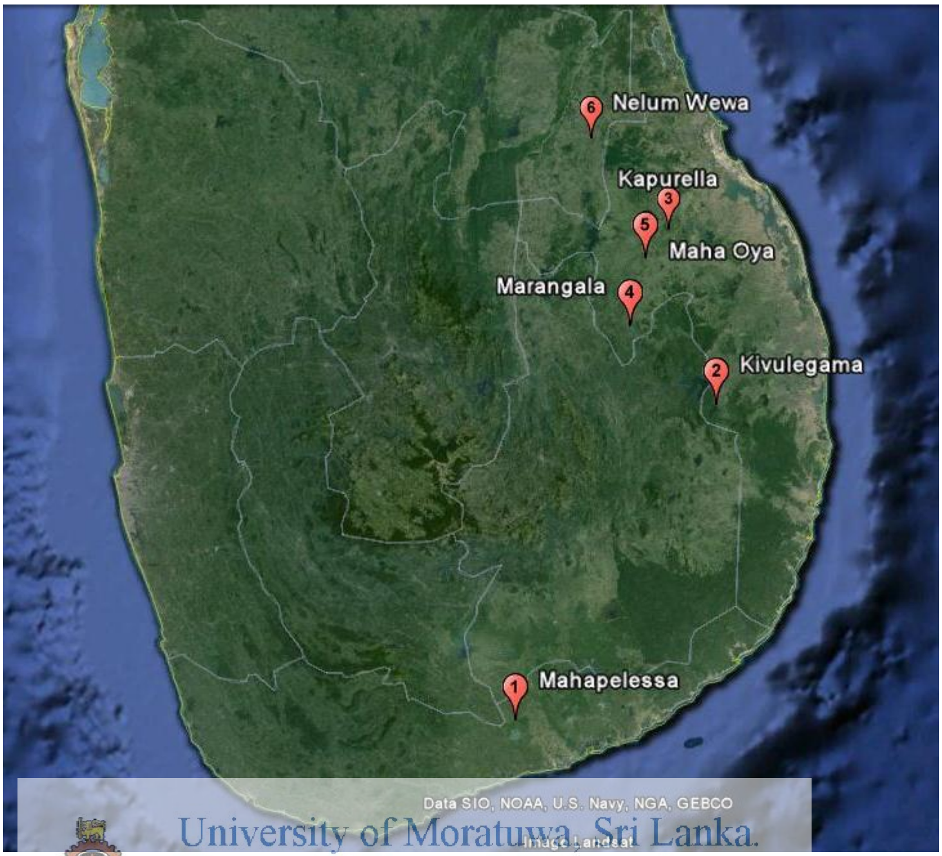

Figure 4.1: Global positioning of selected hot springs

4.1.2 Chemical analysis of water from the hot springs

Chemical analysis of geothermal water is the first step in a long process which eventually yields results that provide building blocks in the model of a geothermal system. The chemistry of geothermal fluid is an important factor in exploration, development and utilisation of geothermal resources. In the exploration phase geochemistry is used to evaluate the origin of the water, to estimate underground temperature, characterise the reservoir chemistry in respect to utilisation and to define environmental impact of the utilisation.

The input parameters for the geothermometers are the chemical analyses of the water samples of hot springs. It is imperative that this step is properly carried out because all subsequent steps depend on it. When collecting samples from hot springs it is desirable that the water be free flowing from the sample spot. If not, a sampling pump is needed. Usually there are several hidden dangers inherent in the collection of geothermal sample. The terrain may be treacherous and dangerous chemicals need to be handled. Thus there is an obvious need for well trained personnel with insight into possible errors and interferences to carry out this task. The most common mistakes made during sampling involve the use of improper containers, improper cleaning and lack of or improper treatment for the preservation of samples. However in Sri Lanka the risks of collection of water samples are less compared with volcanic regions.

All the six locations water is freely flowing from the hot spring and the water temperature also recorded. Main chemicals analysed in the selected hot springs were categorised in Table 4.2.

Table 4.2: Analysed chemicals in 6 springs

Cations	Anions	Volatiles	Other
Sodium (Na) Potassium (K) Calcium (Ca) Magnesium Iron(Fe)	Chloride (Cl) Sulphate (SO_4) Fluoride (F) Nitrate (NO_3) Phosphate (PO_4) Bi carbonate (HCO_3)	Hydrogen(pH) Carbonate (CO_3)	Conductivity Dissolved solids

Collected samples were sealed and send to the testing laboratory within 48 hours. Analysis was mainly focused on the three cations (Na, K and Mg) and three anions (Cl, SO_4, HCO_3). Chemical compositions from the chemical analysis demonstrated in Table 4.3.

Table 4.3: Chemical composition of geothermal water from 6 springs

Substance or Characteristic	**Mahapelessa**	**Kivulegama**	**Kapurella**	**Marangala**	**Maha Oya**	**Nelum wewa**
Temperature (C)	44	34	65	43	54	62
PH value	7.98	7.06	7.7	7.58	7.81	8.32
Conductivity (mS/m)	836.5	78.3	148	136.2	140.6	146.5
Total dissolved solids(mg/l)	4100	384	728	668	689	718
HCO_3^- (mg/l)	18.6	161.8	53.4	4.8	95.2	41.2
Cl^- (mg/l)	2592	50.05	295.32	50.05	80.08	245.26
SO_4^{2-} (mg/l)	124	120	134	126	112	128
Na^+ (mg/l)	1080.2	85.3	244.2	15.4	107.6	211.9
K^+ (mg/l)	23.1	4.6	5.8	10.3	15.1	10.7
Mg^{2+} (mg/l)	214.63	31.7	14.63	21.95	9.76	14.63
Ca^{2+} (mg/l)	176.7	48.19	20.08	40.16	140	24.1
F^- (mg/l)	6.08	7.08	8.4	8.8	7.6	6.8
NO_3^- (mg/l)	0.5	0.4	0.4	0.3	0.3	0.2
PO_4^- (mg/l)	0.14	0.38	0.42	0.23	0.25	0.37

Cl-SO_4-HCO_3 analysis of selected hot springs

A classification of the waters was carried out on the basis of relative contents of the three major anions Cl-SO_4- HCO_3 as indicated in Figure 4.2. Geothermal waters have been classified with respect to their anion and cation contents into alkali-chloride water, acid Sulphate water, acid Sulphate-chloride water and bicarbonate water (Armannsson , 2007). Cold groundwater often has lower chloride concentration than geothermal water (Giggenbach , 1988).

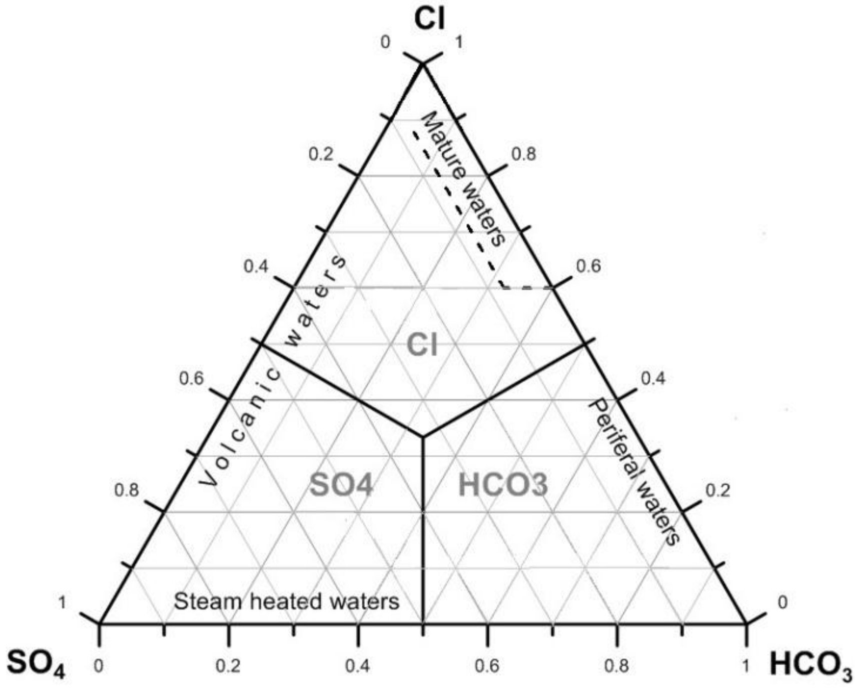

Figure 4.2: Cl-SO4-HCO3 triangular diagram

Source: (Giggenbach , 1991)

Table 4.4: Cl-SO_4-HCO_3 analysis of 6 hot water springs

Substance	**Mahapelessa**	**Kivulegama**	**Kapurella**	**Marangala**	**Maha Oya**	**Gal wewa**
HCO_3^- (ppm)	18.6	161.8	53.4	4.8	95.2	41.2
Cl^- (ppm)	2592	50.05	295.32	50.05	80.08	245.26
SO_4^{2-} (ppm)	124	120	134	126	112	128
Total anions (ppm)	2734.6	331.85	482.72	180.85	287.28	414.46
HCO_3^- %	0.68	48.76	11.06	2.65	33.14	9.94
Cl^- %	94.79	15.08	61.18	27.67	27.88	59.18
SO_4^{2-} %	4.53	36.16	27.76	69.67	38.99	30.88

Table 4.4 illustrates the total anion concentration and the percentages of selected anions in each hot water sample.

a) **Cl-SO_4-HCO_3 analysis of Mahapelessa hot spring**

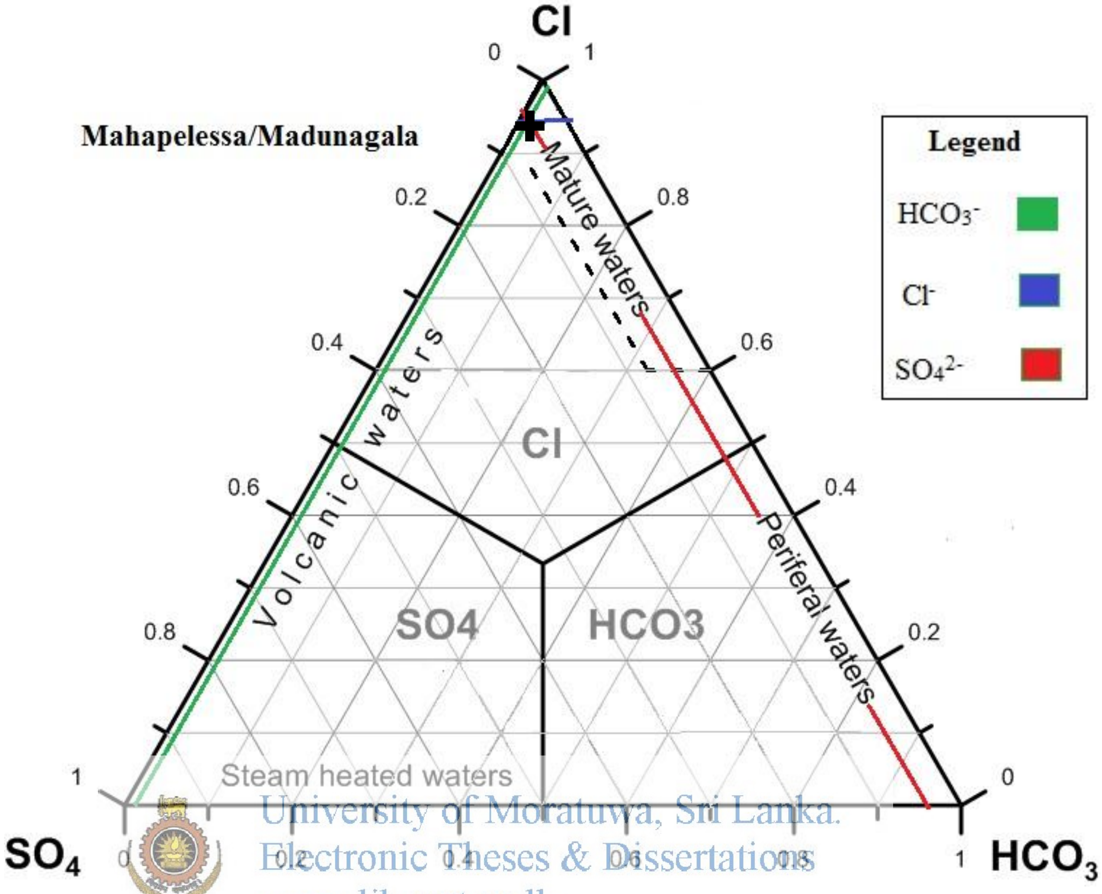

Figure 4.3: Cl-SO_4-HCO_3 triangular diagram of Mahapelessa

Mahapelessa hot water spring has the highest Chloride percentage compared with all six samples and it has the lowest concentrations of bicarbonate and Sulphate. Obviously the water can be predict as volcanic water (Giggenbach , 1988) may be as a result from the absorption of magmatic gases followed by close to isocheimal dissolution of rock contacted. The geothermal water may be mixed with sea water through the geological cracks because the location is the very closer to the sea (nearly 17 km from the sea) also can assume to reflect conditions within the deep primary neutralization zone. Acid spring or other high sulphide mineral assemblages of the host rock cannot be predicted by observing the sample.

b) Cl-SO_4-HCO_3 analysis of Kivulegama hot spring

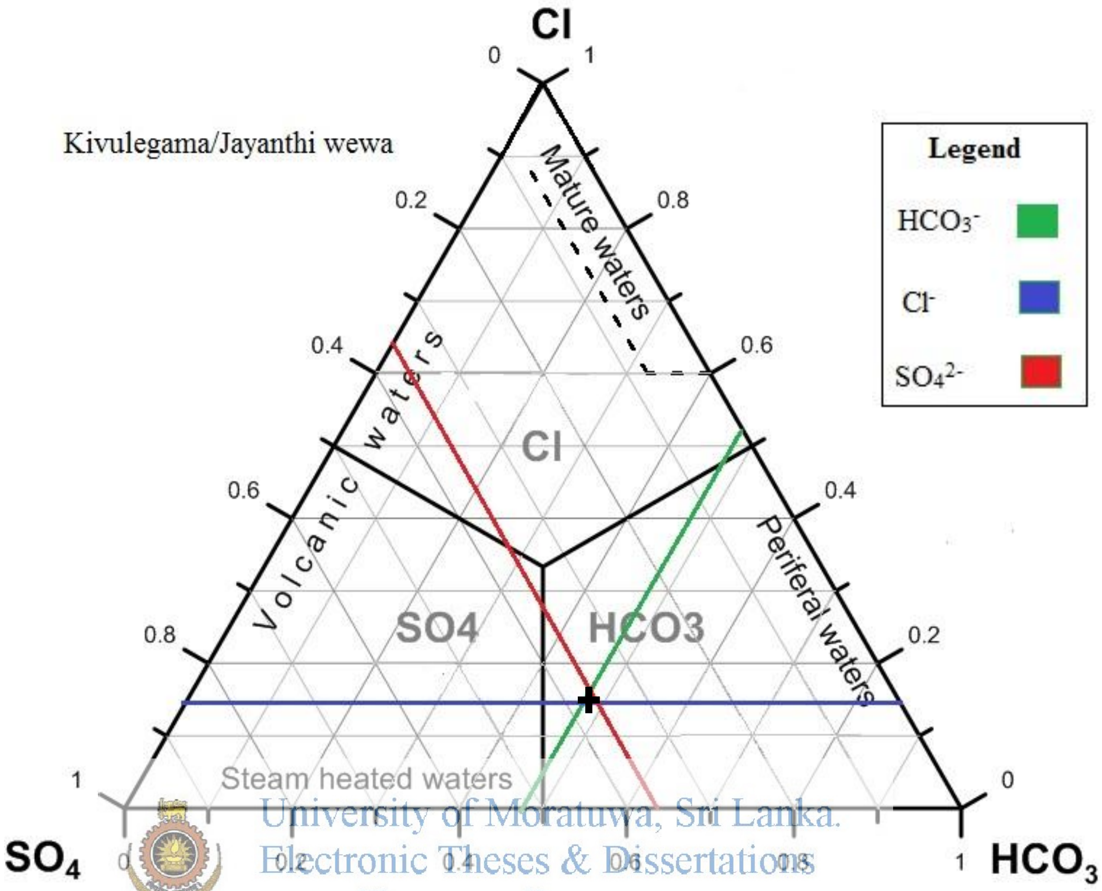

Figure 4.4: Cl-SO_4-HCO_3 triangular diagram of Kivulegama

Kivulegama hot water sample hasn’t reflected abnormal concentration of anions; also the water is within the drinking water standards of Sri Lanka except with the Fluoride; instead it has the lowest chloride concentration among other samples. The water can be assumed to be discharged from deep geothermal source. The water samples are in rich with bicarbonate and Sulphate but very small chloride percentage; although the location is nearly 33 km away from the sea. This is the highest bicarbonate sample compared with the other six samples and periferal waters with rich bicarbonate concentration are expected.

c) Cl-SO_4-HCO_3 analysis of Kapurella hot spring

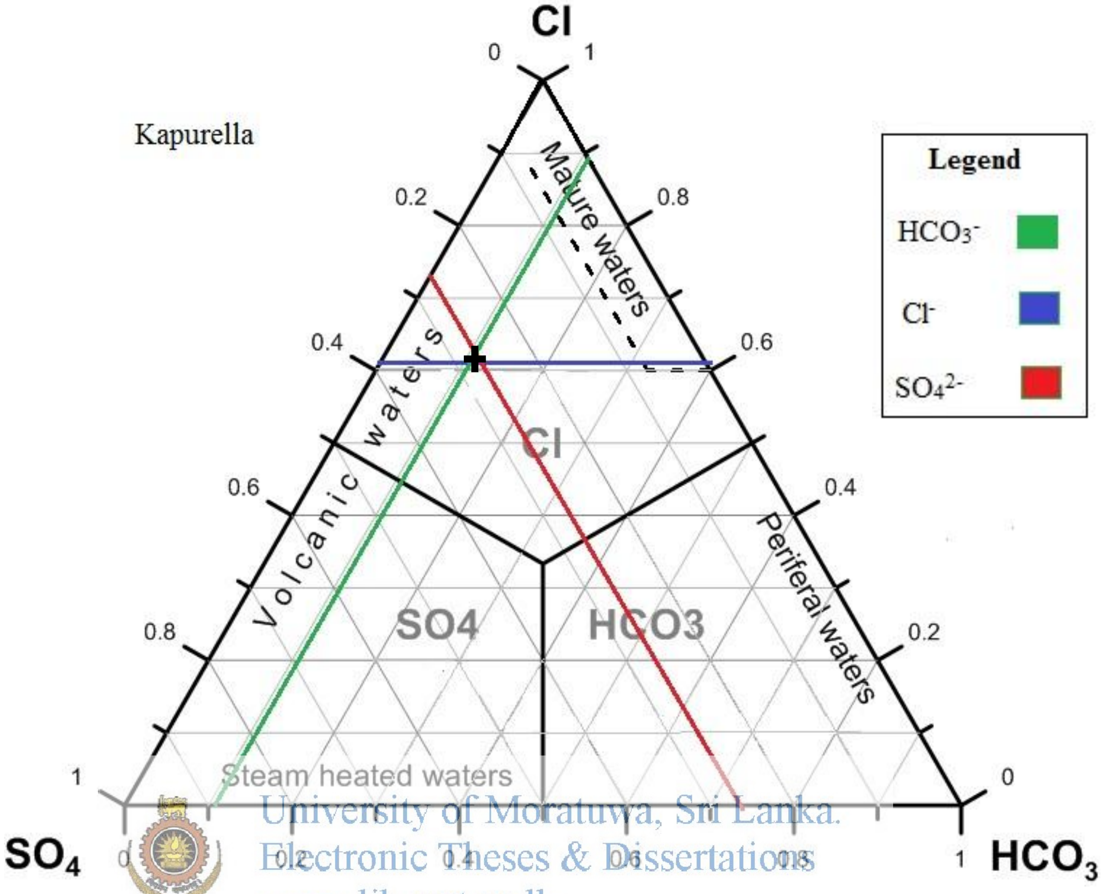

Figure 4.5: Cl-SO_4-HCO_3 triangular diagram of Kapurella

Kapurella is also has second highest chloride concentration compared with the other samples. It is also can be assumed as volcanic waters but mixed with neutral chloride water with highly acid chloride sulfate waters. Mature NaCl waters of neutral pH, which are rich in Cl and plot near the Cl vertex. This water type, also known as alkali-chloride or neutral chloride is typical of the deep geothermal fluid found in most high temperature systems. Chloride is used as a tracer in geothermal investigations because it is a conservative ion in geothermal fluids, as it does not take part in reactions with rocks after it has dissolved. Chloride does not precipitate after it has dissolved; it does not return to the rock so its concentration is independent of the mineral equilibrium that controls the concentration of the rock-forming constituents (Dolgorjav , 2009).

d) **Cl-SO_4-HCO_3 analysis of Marangala hot spring**

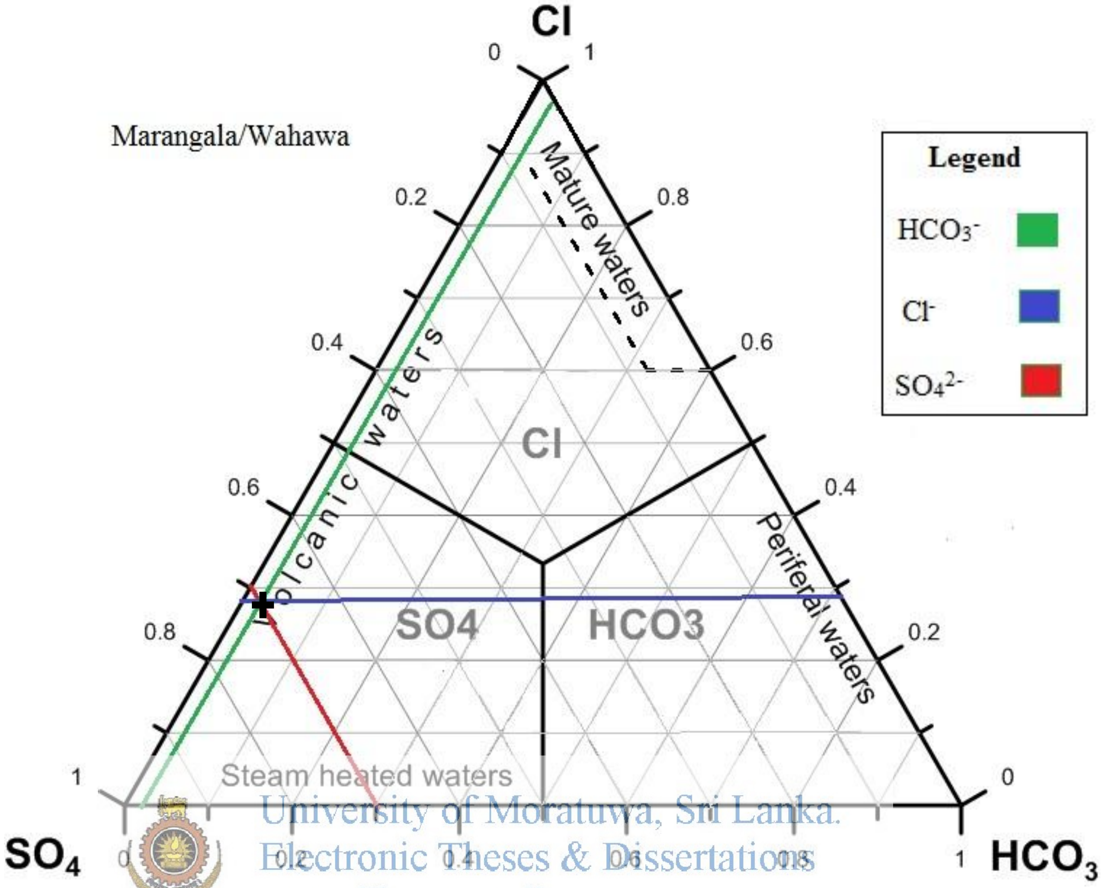

Figure 4.6: Cl-SO_4-HCO_3 triangular diagram of Marangala

Marangala hot water sample has the highest Sulphate concentration also can be assumed as a mixture of volcanic and steam heated waters. Volcanic and steam heated waters are generated through the absorption of either high temperature hydrochloric (HCl) bearing volcanic gases or lower-temperature H_2S bearing geothermal vapours into the groundwater (Dolgorjav, O, 2009). The sample is in the Sulphate region so the source may also be an acid spring. The origin of Sulphate is not clear but may be due to buried rocks of a marine sediment origin in the region or other high sulphide mineral assemblages of the host rock.

e) Cl-SO_4-HCO_3 analysis of Maha Oya hot spring

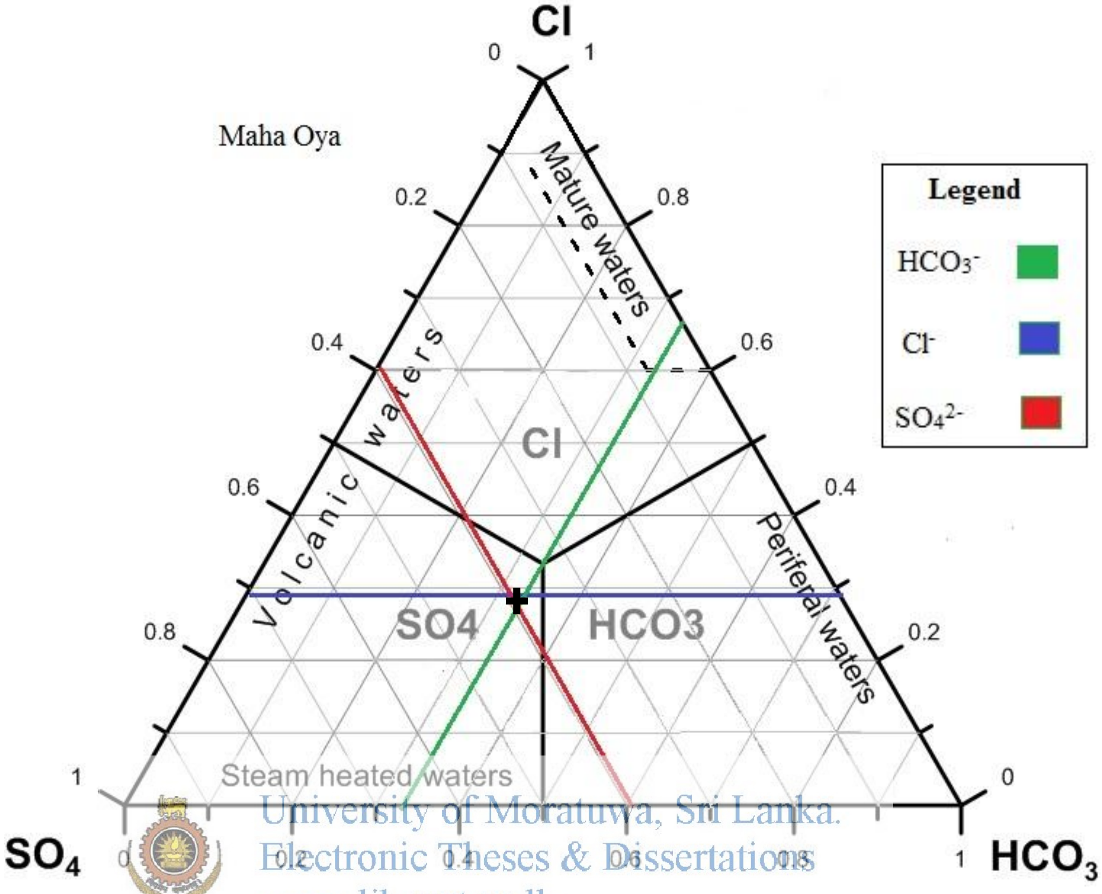

Figure 4.7: Cl-SO_4-HCO_3 triangular diagram of Maha Oya

In Maha Oya sample has almost balanced chloride, Sulphate and bicarbonate. However it is biased to the Sulphate region. Steam heated water can be expected from this sample. The location is about 41 km from the sea and no any sign of mixing sea water with the geothermal water sources.

f) **Cl-SO_4-HCO_3 analysis of Nelum wewa hot spring**

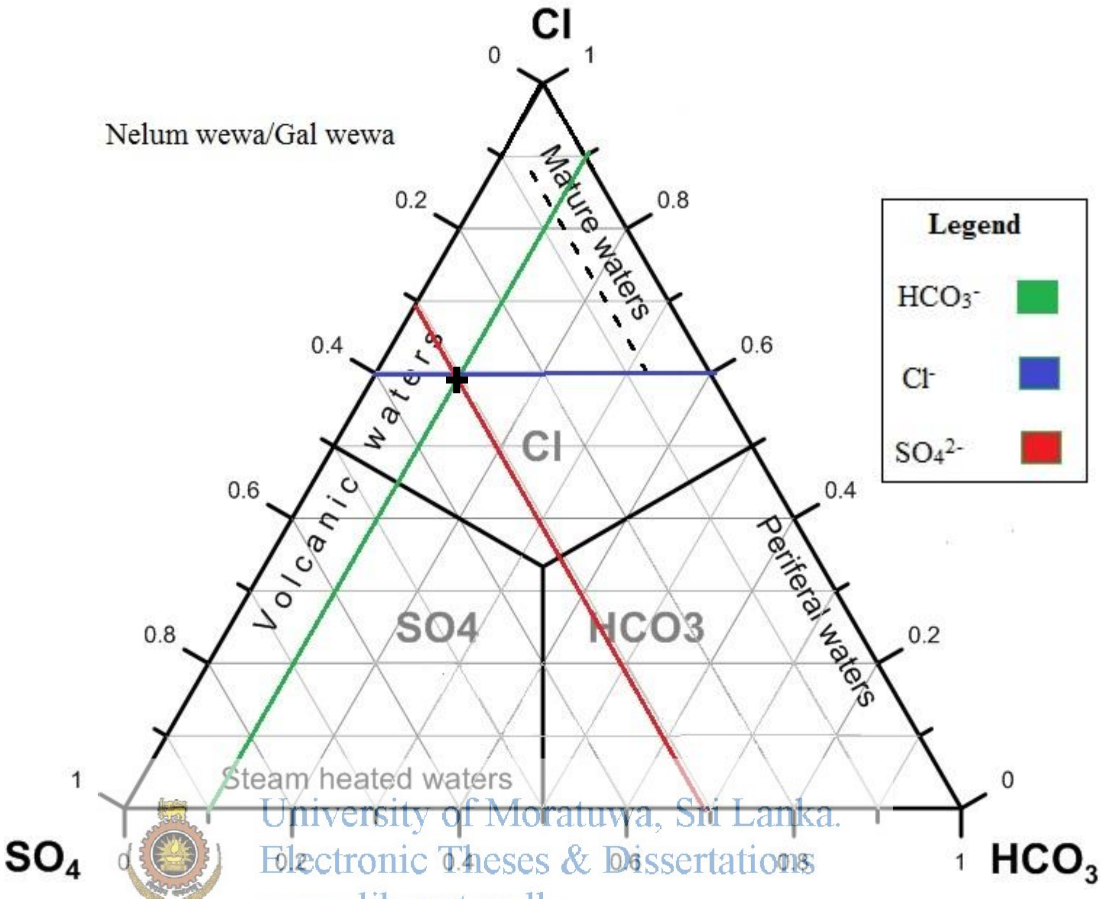

Figure 4.8: Cl-SO_4-HCO_3 triangular diagram of Nelum wewa

Nelum wewa hot water sample is in rich with chloride and considerable percentage of Sulphate can be observed. The water is from the volcanic generated at depth but considerably diluted during their rise to the surface. This water type, also known as alkali-chloride or neutral-chloride is typical of the deep geothermal fluid found in most high temperature systems.

4.1.3 Magnetotellurics survey of hot water springs

Introduction to the magnetotelluric scan

Magnetotellurics (MT) is an electromagnetic geophysical scanning method for reasoning the earth's subsurface electrical conductivity from measurements of natural geomagnetic and geo electric field variation at the Earth's surface. Investigation depth ranges from 300m below ground by recording higher frequencies down to 10,000m or deeper with long-period soundings (Volpia , et al., 2003). The sensitivity of electrical conductivity to the presence of small quantities of interconnected fluids makes the electric (DC) and electromagnetic (EM) methods particularly applicable to geothermal areas, especially where a water dominated reservoir is heated by a hot, partially molten or dry magmatic body. Both the water reservoirs and the magmatic body produce conductive anomalies that can be defined by EM methods. Of all the EM methods, MT seems to be the most appropriate since the investigation depth of MT can easily reach several km (Volpia , et al., 2003). Wide-band (100–0.001 Hz) MT data can also explore the earth structures in conductive environments. The acquired date from the MT survey should be filter to remove unwanted signals and analysis should be done. Finally modeling using specially designed software to have an interpretation about subsurface geological structures.

Preliminary MT survey of thermal springs in Sri Lanka

A magnetotelluric survey was conducted by Hobbs B.A. and the team to map the lateral variation of resistivity with depth along 9 km profiles across seven known hot springs of Sri Lanka for locating thermal waters within deep faults or hot dry rock that would help geothermal energy development. This is the first and only MT test which has been done in Sri Lanka and the test is done for 7 traverse covering Mahapelessa, Kapurella, Maha Oya, Wahawa (Padiyathalwaa), Nelum wewa, Kanniya and Rankihiriya hot water springs. Sri Lanka scientist from Institute of Fundamental Studies (IFS), Geological Survey and Mines Bureau (GSMB), National Water Supply and Drainage Board (NWSDB), University of Uva Wellassa had joined to the study.

Sri Lankan counterparts of the project visited all the hot spring sites nominated for study and selected a number of potential sites where MT might be possible. During the campaign, at the start of each traverse these potential sites were revisited and a final selection was made. MT site preparation comprised laying out telluric lines along magnetic north and east directions, burying and connecting electrodes, digging trenches around 0.5 m deep in magnetic north and east directions, placing, leveling, burying and connecting magnetic coils, measuring telluric line lenGEhs and recording serial numbers of the magnetic coils. No vertical magnetic field measurements were made. The MT acquisition group recorded GPS locations for each MT station. The group had six coils and hence three sets of MT equipment. At any one time there were usually two sets in operation with one set in transit to a new site. Before MT recordings began, transient electromagnetic (TEM) measurements were made (this is to remove the noises around the electrodes by external sources), where possible, with a transmitter loop size of 100 m by 100 m. An average of two MT stations per day was achieved throughout the survey, even with long moves between traverses (Hobbs , et al., 2013).

Along profiles crossing each spring site, MT stations were established approximately every 1 km while traverse lines were about 7 – 9 km long. All together 87 MT stations were measured and Mahapelessa MT traverse was extended to 27 km to the HC-VC boundary. Two dimensional (2D) MT inversion data from 5 hot water springs (excluding Kanniya and Rankihiriya) done by Hobbs and the team was used to predict the underground geothermal resource and for the assessment of the potential sites.

a) MT survey in Mahapelessa (MP)

According to the MT test done by Hobbs and the team; MT traverse from south west (SW) to north east (NE) was selected crossing the location of the Mahapelessa hot spring from Angunakolapelessa to Suriyawewa., and the geologic cross-section approximately coincident with the MT traverse is presented in Figure 4.9: Geology and the selected MT traverse in MP, the resistivity depth model under the MT traverse is shown in Figure 4.10 and this indicates relatively lower resistivity region to the SW under MT stations 109 to 105. There is no evidence of any very low resistivity regions closer to the surface that could be associated with a significant amount of hot water saturated rock or hot dry rock to economic depths. This resistivity cross section does not show convincing evidence for expected geothermal reservoirs. The Udawalawe river fault (yellow in Figure 4.9) is seen as a low resistivity region between MT stations 109-108.

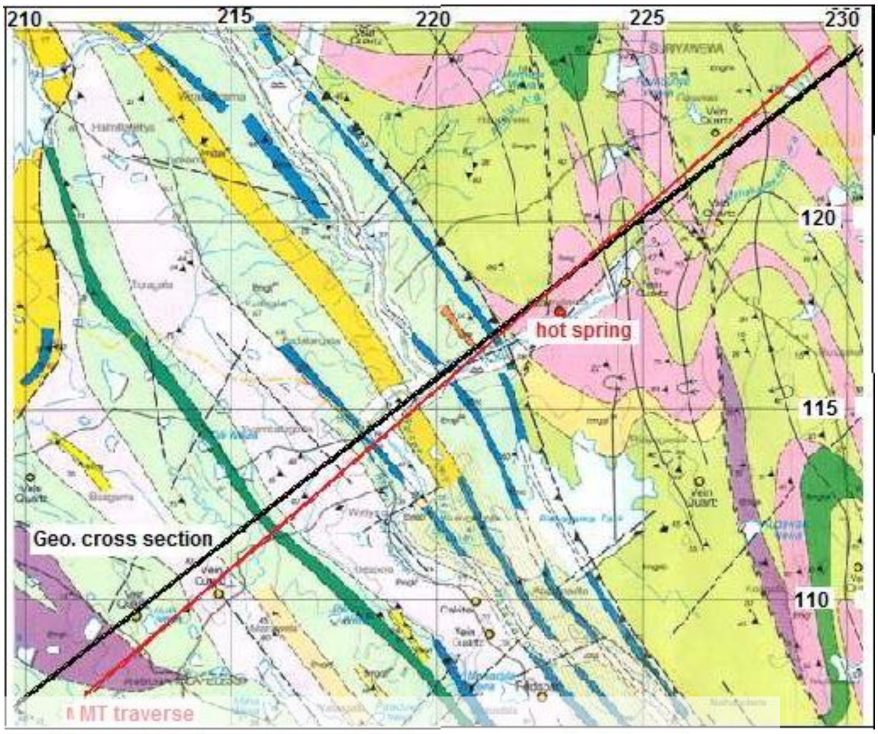

Figure 4.9: Geology and the selected MT traverse in MP

Source: (Hobbs , et al., 2013)

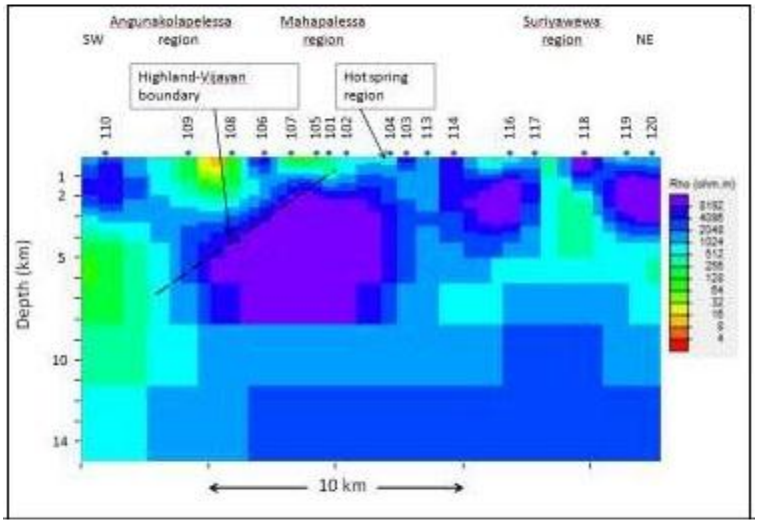

Figure 4.10: MP resistivity depth section after 2D inversion

Source: (Hobbs , et al., 2013)

The origin of the Mahapelessa hot spring cannot be discerned here, it could assume in different ways, waters of the Walawe river fault in higher elevations running a few kilometers deep to be heated by the normal geothermal gradient and then rising upward by artesian action along fine fractures or fissures of the Gonawiddagala Ambalantota shear zone or may be due to the deeper geothermal reservoir beyond the MT penetration.

Selected MT traverses for Kapurella, Maha Oya and Marangala

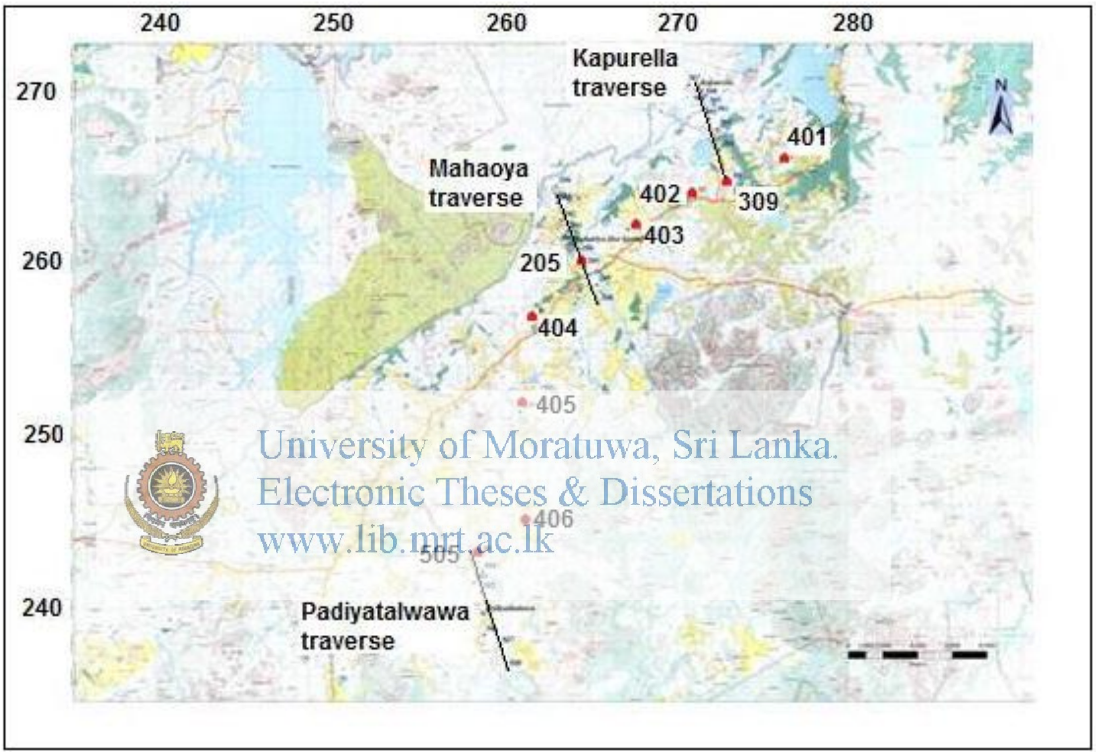

Figure 4.11: Selected MT traverses for KP, MO, and MA

Source: (Hobbs , et al., 2013)

Three MT traverse paths were tracked by Hobbs B.A. and the team covering the exact positions of the hot water springs (Figure 4.11). All the three paths were nearly parallel to each other in south east to North West. Other than the initially planned traverse they have taken a cross profile covering these three springs (MT station 401 to 406) and noted high deviation from linearity. Cross traverse shows a low resistive region at a depth of 12 km in the adjacent of MT site 403, where the geothermal temperature can be estimated to be 350 °C.

b) MT survey in Kapurella (KP)

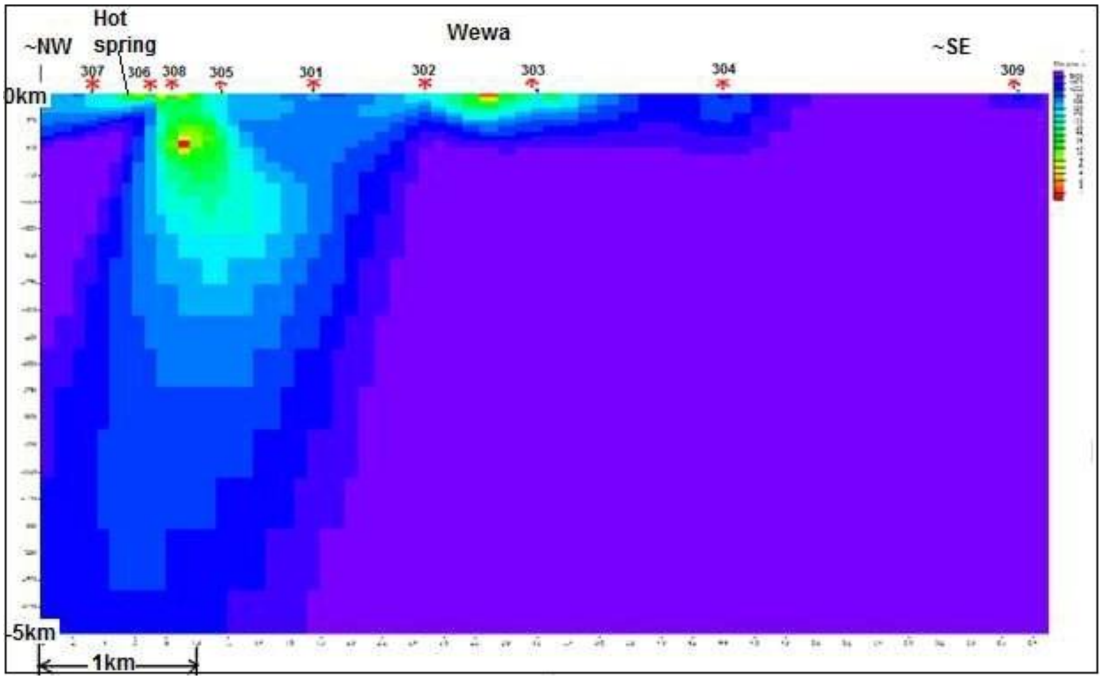

Figure 4.12: KP resistivity depth section for 5 km after 2D inversion

Source: (Hobbs , et al., 2013)

Refereeing KP resistivity model (Figure 4.12), a very low resistive region is found at a depth of 500 m below the hot spring region (MT sites 306, 308, and 305). Rocks elsewhere in this 5 km region is extremely resistive. The low resistivity can be identified with hot water accumulation with in fissured rock. Kapurella thermal spring is the hottest known spring, with a surface temperature of 65℃ .Considering the outside temperature around the spring area it can be predicted that the water to be originating at least at a depth of 1 km if no heat losses and near surface mixing with surface waters are considered. Geothermal water accumulated at this shallow depth is to be considered as an intermediate accumulation that should be fed from a deeper source region. According to the superior MT depth penetration of KP (Figure 4.13) results a low resistivity area from the 8km depth (Nimalsiri , et al., 2015) and continue further downstream. So it can be expected that high temperature geothermal deeper source is feeding the intermediate accumulation of Kapurella.

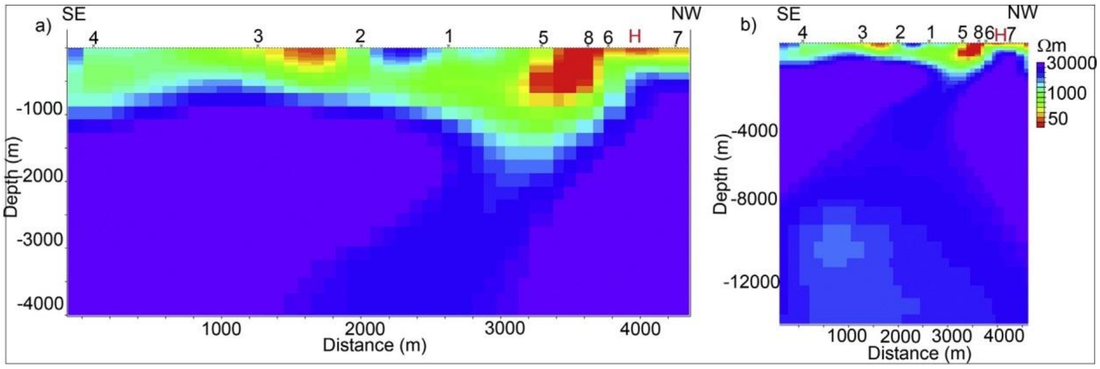

Figure 4.13: KP resistivity depth section 2D inversion for 14 km

Source: (Nimalsiri , et al., 2015)

c) MT survey in Marangala (MA)

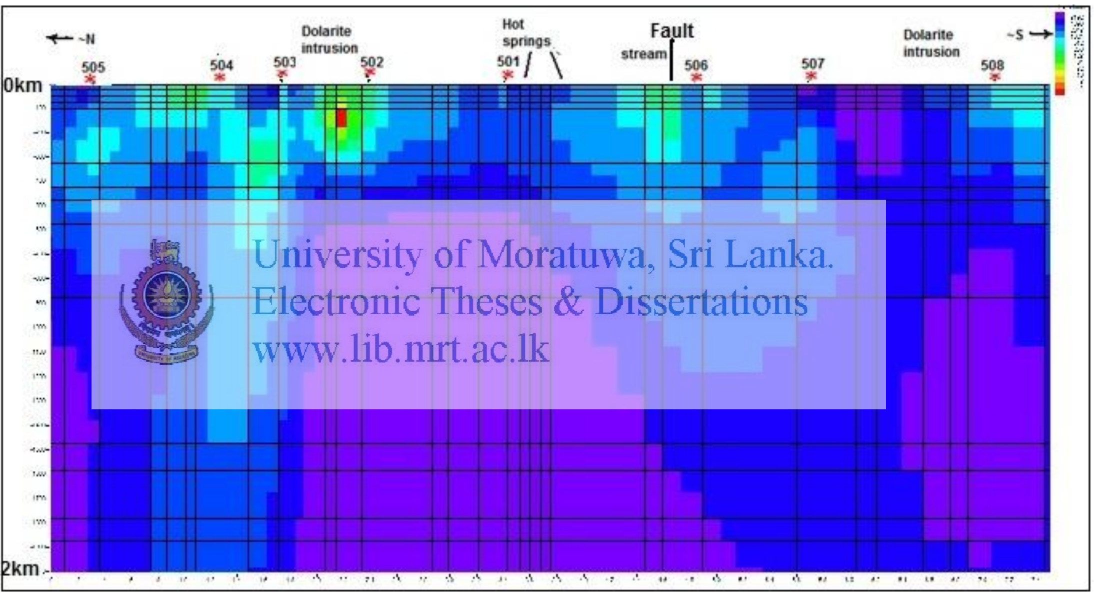

Figure 4.14: MA resistivity depth section 2D inversion for 2 km

Source: (Hobbs , et al., 2013)

On the north end of the traverse, there is a large conducting region through a highly resistive layer. Between MT station 503 and 502 very low resistivity than the other low resistive areas. The resistivity here is most likely influenced by the dolerite intrusion that is observed on the surface. Such broad sized low resistivity regions were not observed at the other MT traverses. Refereeing MT to a deeper penetration in Figure 4.15, the low resistivity area is furthermore increasing by area and resistivity from 502 to 505 MT stations.

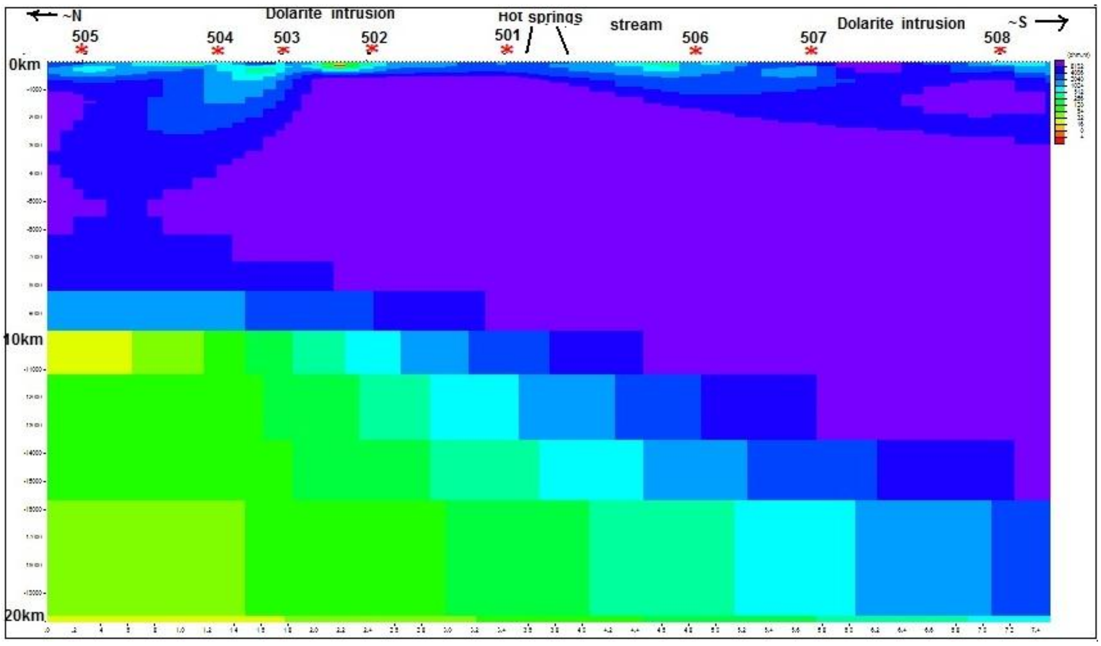

Figure 4.15: MA resistivity depth section 2D inversion for 20 km

Source: (Hobbs , et al., 2013)

d) MT survey in Maha Oya (MO)

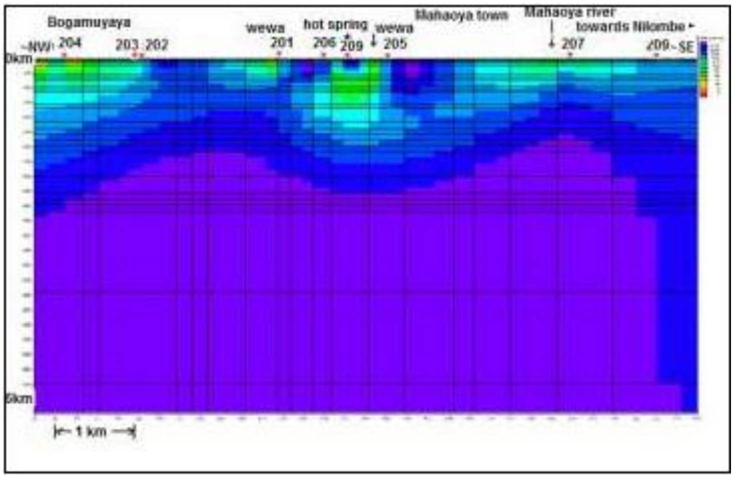

Figure 4.16: MO resistivity depth section 2D inversion for 6 km

Source: (Hobbs , et al., 2013)

Maha Oya 2D resistivity model to a depth of 6 km is presented in Figure 4.16. There is no evidence of very low resistivity that could be holding water or hot dry rock. To the contrary, the model infers that the basement is highly compact and free of any fluid filled fractures. The moderately low conducting region near the surface at the spring (under MT station 209) may be a combined effect of the nearby cold water storage and the hot spring.

e) MT survey in Nelum wewa (NW)

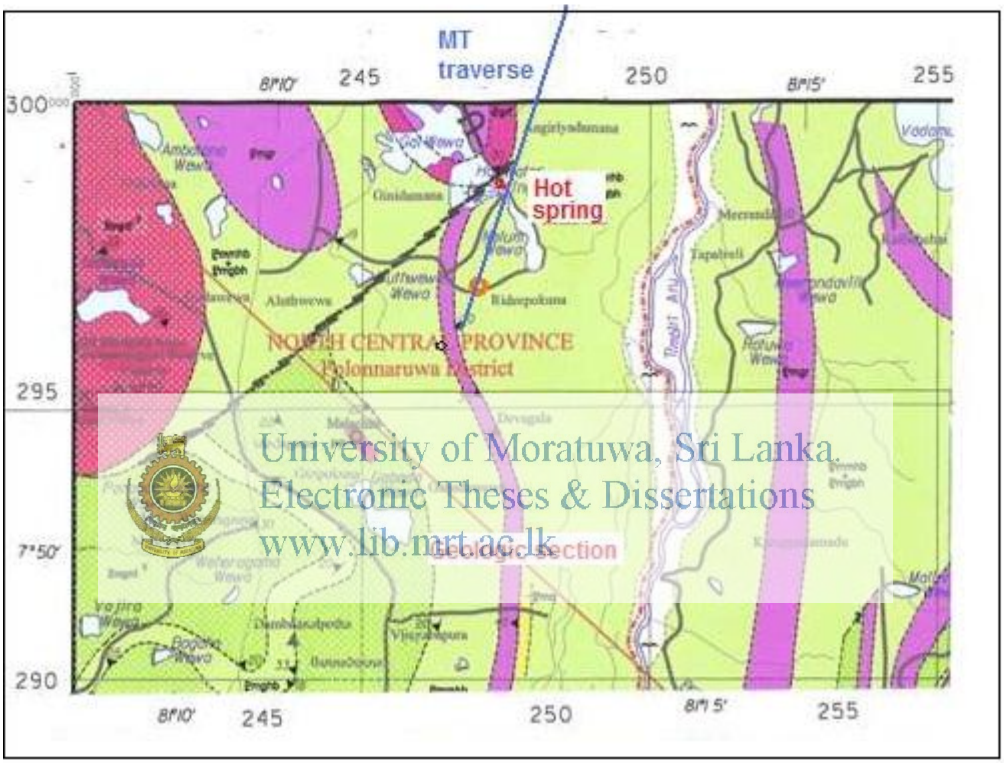

Figure 4.17: Selected MT traverse for NW

Source: (Hobbs , et al., 2013)

MT survey was conducted Hobbs B.A. and the team for Nelum wewa hot spring along the traverse (north east to south west) in Figure 4.17. The 2D inversion of the accepted MT stations was presented in Figure 4.18 . The inverted depth is 10 km and greater depth could not be achieved due to lack of long period data. An inclined low resistivity region within the high resistivity can be identified with the fault shear zone crossing the MT profile at the hot spring. As there is no very low resistivity path observed within the relatively low resistance region, thermal water must rise through narrow fissures within this fault zone. It is likely there is a deeper low resistivity reservoir of high temperature beyond the present MT traverse feeding this hot spring.

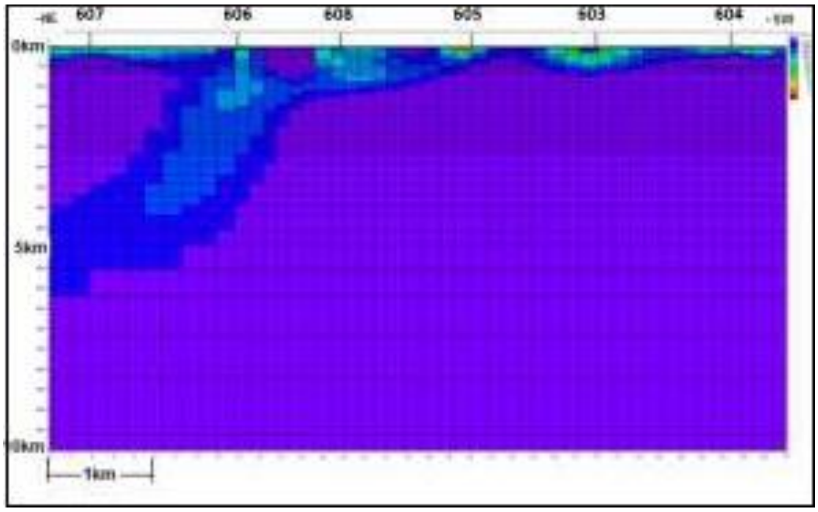

Figure 4.18: NW resistivity depth section after 2D inversion for 10 km

Source: (Hobbs , et al., 2013)

4.1.4 Assessment of potential sites

Assessment of the potential areas for geothermal energy harnessing in Southern and Eastern part of the country has been done based on three observations. The geological positioning of the hot water springs, chemical analysis of the water samples collected from the springs and the MT survey data around the springs. Sri Lanka is not located in a plate boundary or near an active volcano the initial identification about the potential areas cannot be made by observing the plate tectonics. So the available locations of hot water springs were used as the observation areas. Results from the chemical analysis and the MT survey have been assessed to identify the potential sites in Southern and eastern areas.

Assessment based on chemical analysis

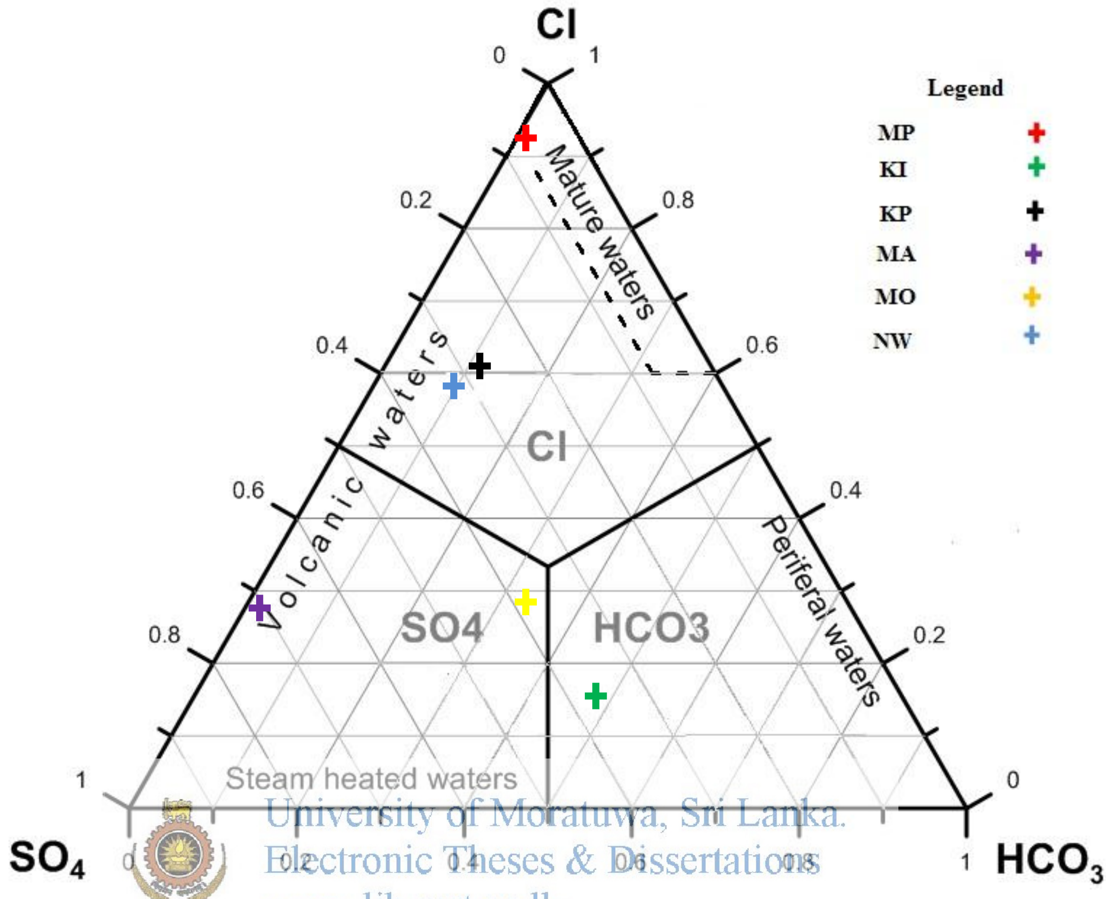

Figure 4.19: Summary of Cl-SO4-HCO3 analysis for 6 springs

According to the analysis of anions of the selected hot water springs, four samples have representing the characteristics of volcanic and steam heated waters. Volcanic and steam heated waters are generated through the absorption of either high temperature hydro chloric bearing volcanic gases or lower temperature H_2S bearing geothermal vapors into the groundwater. Spring water from Marangala and Maha oya has this characteristic. Kapurella and Nelum wewa are in rich with chloride. This water type, also known as alkali-chloride or neutral-chloride, is typical of the deep geothermal fluid found in most high temperature systems.

Mahapelessa has very high chloride concentration but not due to the deep geothermal fluid. The reason for very high chloride concentration may as a result of sea water mixing with the spring water because this spring is located very closer to the sea and the area has lot of geological fine fractures. The origin of the Mahapelessa hot spring cannot be differentiated here, it could well be waters of the Walawe river fault in higher elevations running a few kilometers deep to be heated by the normal geothermal gradient and then rising upward by artesian action along fine fractures or fissures of the Gonawiddagala Ambalantota shear zone.

Kivulegama spring water is also not associated with deep geothermal reservoir according to its chemical concentration. Water percolating through the geological fractures of HC will getting warmer due to the natural geothermal gradient; may then rising upward by artesian action in the spring. The high fluoride concentration due to the mixing of heated water with the cold springs (Usually normal spring water in this area has high fluoride).

So according to the chemical analysis of the selected hot water springs; Kapurella, Nelum wewa, Maha oya and Marangala respectively representing the characteristics of deep reservoir geothermal water giving an indication of the underground potential availability for energy harnessing.

Assessment based on MT survey

MT survey data can be used to determine the underground structures near the MT traverses. MT data for five sites from the six selected sites were considered to assess the underground geothermal reservoir capacity. MT survey has not been done for Kivulegama spring but that is not vital to do MT near the spring due to its very low temperature (lowest among the six samples) and typical anion concentration.

According to the MT resistivity depth data analysis of Mahapelessa in Hambantota district does not reflect subsurface geothermal reservoir to the depth of 16km. Only small areas of low resistivity near the spring but there is no evidence of any very low-resistivity regions that could be associated with a significant amount of hot water saturated rock or hot dry rock. So according to the available MT data Mahapelessa does not reflect positive indication for geothermal energy harnessing.

Kapurella, Marangala and Nelum wewa MT data illustrated low resistive areas of smaller cross sections closer to the existing thermal springs. KP and MA have low resistivity areas less than 500m depth. Superior penetration of MT data reveals there is no very low resistivity path observed within the relatively low resistance region, thermal water must rise through narrow fissures within this fault zones. It is likely there is a deeper low resistivity reservoir of high temperature beyond the present MT traverses feeding this hot springs. So according to the MT data KP, MA, and NW can be identified as very high potential sites for geothermal energy harnessing.

Maha oya MT data for 6km penetration does not reveal any sign of an underground geothermal reservoir or hot dry rock by observing the resistivity depth 2D inversion. By observing the Marangala-Maha oya-Kapurella (MMK) cross traverse resistivity model (Figure 4.20), there are two low resistivity bands on either side of MT station 205. The one to the NE is towards the 12 km deep low resistivity below station 403, the other on the SW trends deeper and directed towards the deeper north end of Marangala traverse (MT station 505) where there is a dolerite dyke(Hobbs *et al.*, 2013). MT station 205 is very closer to the Maha Oya hot spring. Hence when comparing the cross profile with individual profiles (Figure 4.20), it is most likely that Maha Oya hot spring is fed mostly from the low resistivity region below station 403 and, to an extent, from Marangala.

So according to the MT resistivity depth analysis it can be clearly assess that Maha oya, Kapurella and Marangala hot water springs are associated with high temperature deep geothermal reservoirs; may be interconnected in the deep. So Maha oya is also can be considered as a potential area for geothermal energy harnessing.

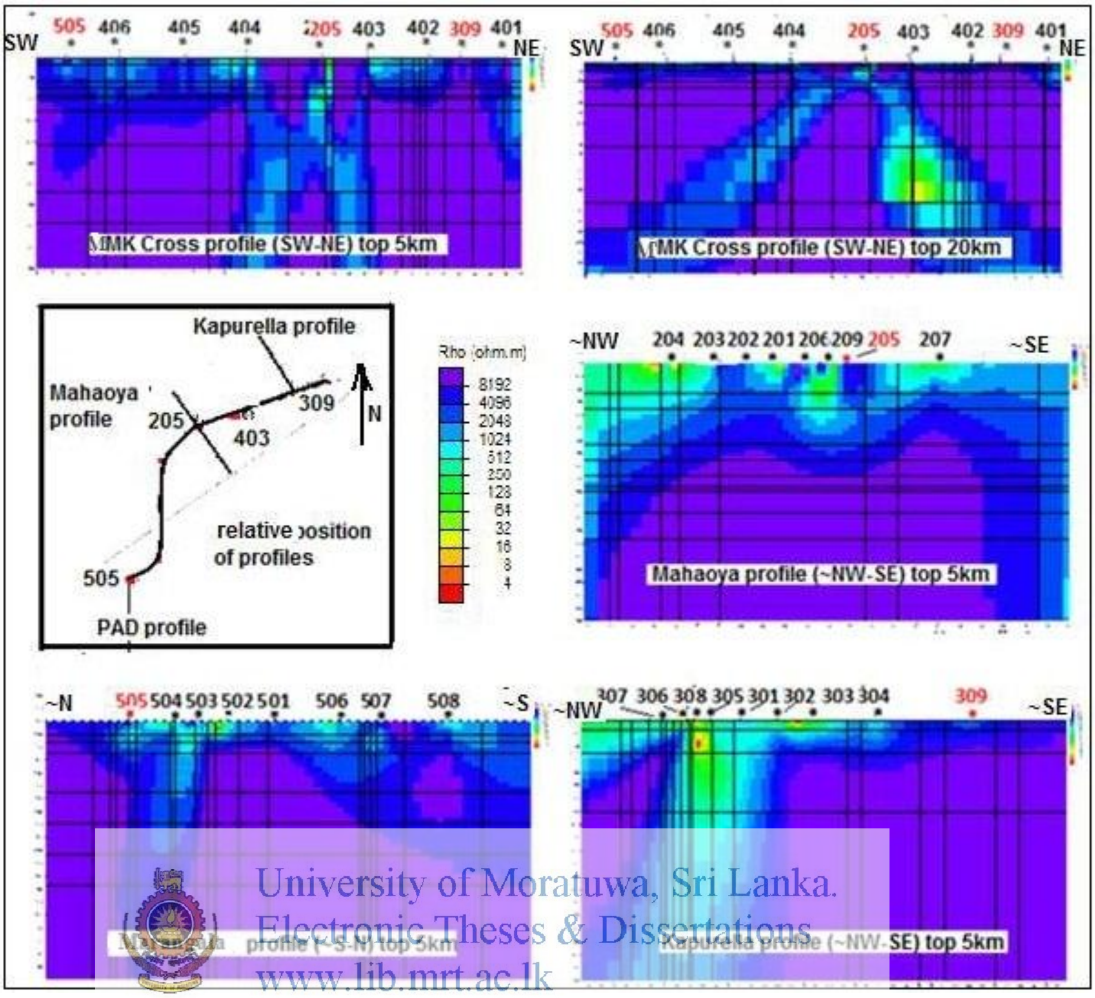

Figure 4.20: MT resistivity depth section for KP-MO-MA cross traverse

Source: (Hobbs , et al., 2013)

4.2 Energy harnessing

Energy harnessing from the identified geothermal resources near the locations of hot water springs in southern and eastern region of Sri Lanka has been done on the assessment of the temperatures, reservoir capacities and the volumetric generating capacities.

4.2.1 Assessment of the temperatures of the reservoirs

The application of chemical geothermometers is one of the most important methods for the exploration and development of geothermal resources. It is useful for predicting subsurface or reservoir temperatures and obtaining valuable information about what is happening in the reservoir during exploitation. Cooling of the water in the up flow zones of a geothermal system may occur by conduction, boiling or mixing with cold water (Dolgorjav , 2009). The basic assumption is that a temperature dependent equilibrium is attained between the fluid and the minerals in the reservoir. The temperatures in geothermal reservoirs are generally not homogeneous, but variable, both horizontally and vertically, so geothermometers are useful for revealing the temperature of the water body (aquifers) feeding drill holes. Temperatures encountered in a deep drill hole may be higher than those indicated by chemical geothermometers, particularly if the waters investigated are fed by shallow aquifers (Arnorsson , et al., 1983). The silica (quartz and chalcedony), Na-K and Na-K-Ca geothermometers are the most important. These geothermometers are all based on the assumption that specific temperature dependent mineral solution equilibrium is attained in the geothermal reservoir. Assessment of the temperatures was done by using cation geothermometers of the selected samples.

Temperature assessment by cation geothermometers

Cation geothermometers are widely used to calculate subsurface temperatures of waters collected from hot springs and wells. There are many different geothermometers as shown in Table 4.5, and it is rare that they all give similar results, especially when applied to thermal fluids (Giggenbach , 1988).

Assessment of the reservoir temperatures by the concentrations of Na, K and Ca (Table 4.3) using different equations illustrated in Table 4.6.

Table 4.5: Temperature equations in °C for cation geothermometers

Geothermometer	Equation	Range (°C)	Source
Na-K	$\frac{933}{0.993 + \log\frac{Na}{K}} - 273.15$	25-250	(Arnorsson , et al., 1983)
Na-K	$\frac{856}{0.857 + \log\frac{Na}{K}} - 273.15$	100-275	(Truesdell , 1976)
Na-K	$\frac{1217}{1.438 + \log\frac{Na}{K}} - 273.15$		(Fournier , 1979)
Na-K	$\frac{1390}{1.750 + \log\frac{Na}{K}} - 273.15$		(Giggenbach , 1988)
Na-K-Ca	$\frac{1647}{\log\left(\frac{Na}{K}\right) + \beta\left[\log\left(\frac{\sqrt{Ca}}{Na}\right) + 2.06\right] + 2.47} - 273.15$ $\beta = \frac{4}{3}\ for\ t < 100°C;\ \beta = \frac{1}{3}\ for\ t > 100°C$ or for $\frac{\sqrt{Ca}}{Na} < 0$		(Fournier & Truesdell, 1973)

.

Table 4.6: Temperatures of the reservoirs based on different equations

Temperatures in (°C) by methods	**Mahapelessa**	**Kivulegama**	**Kapurella**	**Marangala**	**Maha Oya**	**Gal wewa**
Fournier and Truesdell	119.94	132.35	118.79	241.08	173.2	148.28
Truesdell , 1976	65.61	129.64	71.83	556.56	227.48	124.3
Fournier, 1979	118.43	176.56	124.26	481.49	258.1	171.86
Giggenbach ,1988	133.3	187.39	138.79	449.05	260.88	183.07

Depend on the calculations based on cation geothermometers; assessment of the average temperatures of the geothermal resource near the locations of existing hot water springs can be made. Results were presented in Table 4.7. Truesdell 1976 temperature estimation for MP, KP and MA were not within the range of the calculation hence not considered in calculating averages.

Table 4.7: Summary of the temperature assessment

Hot spring	Maximum temperature (°C)	Average temperature (°C)
Mahapelessa	133.30	123.89
Kivulegama	187.39	156.49
Kapurella	138.79	127.28
Marangala	556.56	390.54
Maha Oya	260.88	229.92
Gal wewa	183.07	156.88

4.2.2 Calculation of reservoir capacities

Reservoir capacity assessment is essential to predict the geothermal resource und their distribution patterns. For a detailed calculations of the reservoir capacities, 3 dimensional (3D) MT survey need to be carried out along the paths of the identified potential areas. In this study the capacity calculation is based on 2D MT survey data of limited MT stations and traverses. So it is very hard to predict about the actual dimensions of the geothermal reservoirs only the cross sectional areas can be calculated using the available resistivity depth 2D inversions of hot water springs.

Considering the MT data from KP, MO, MA traverses and MMK cross traverse, an imaginary reservoirs can be assumed (Figure 4.21) to be under KP and MA hot water spring locations and another reservoir between MO and KP (near MT station 403). There is a tendency of connection between MO and KP reservoirs to form a large geothermal source which feeding energy for all three hot springs.

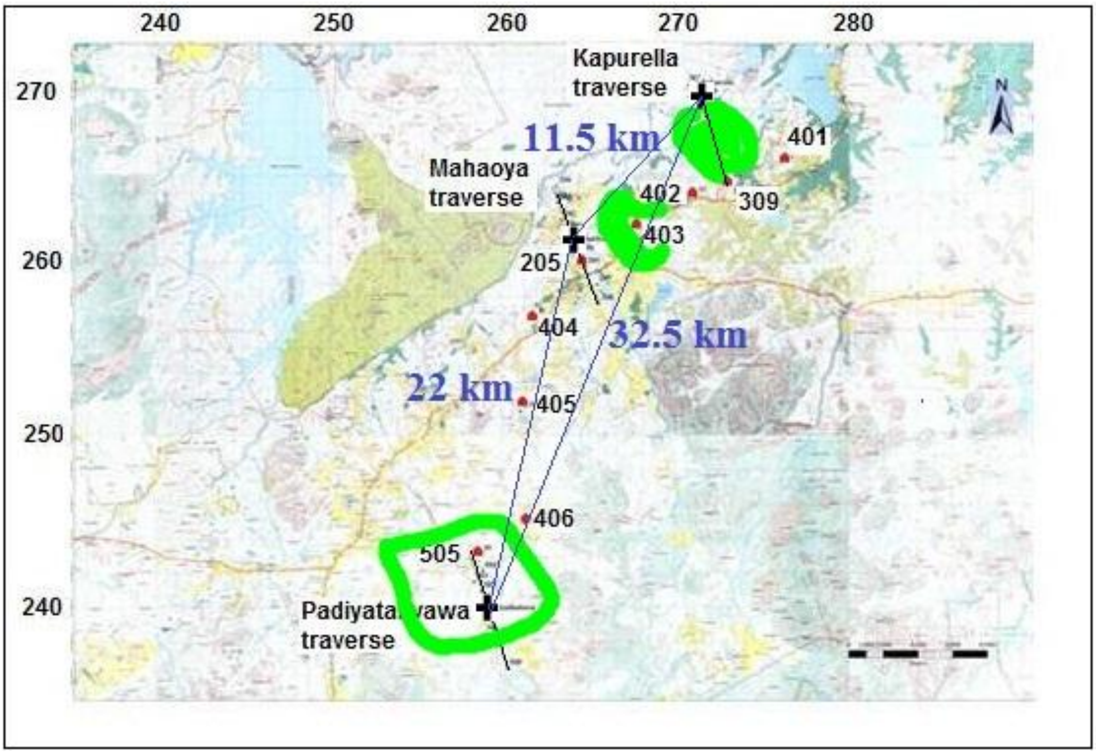

Figure 4.21: Imaginary reservoirs under KP, MO and MA

So the calculated cross sections of the probable geothermal reservoirs according to the 2D MT survey traverses can be listed as Table 4.8.

Table 4.8: Calculated reservoir cross sections along the MT traverses

Hot spring	Reservoir cross section from the MT resistivity depth analysis along the selected traverses (km^2)	
	Shallow (<5km)	Deep (>5km)
Mahapelessa	13.23	14.21
Kivulegama	MT data not available	
Kapurella	3.48	15.67
Marangala	0.17	41.24
Maha Oya	0.67	Not detected
Gal wewa	Not detected	Not detected

4.2.3 Energy potential

This study is more based on theoretical calculations and assumptions so that most of the field data was based on geochemical calculations, coupled with geological and geophysical observations and limited MT traverse profiles. Production history and well data were not available in Sri Lanka. In order to estimate a green field generating capacity without actual reservoir data on the down, there are three main methods available. These methods are volumetric modeling, lumped parameter modeling and distributed parameter modeling. Volumetric modeling was used to coarsely estimate the generating capacity of the potential in southern and eastern areas mainly near the existing hot springs.

Volumetric generating capacity assessment is based on a volumetric calculation of the heat in place for each area of interest, with reasonable assumptions made about the percentage of that heat that can be expected to be recovered at the surface and the efficiency of converting that heat to electrical energy. The heat in place calculation takes into account only a volume of rock and water that is reasonably likely to contain adequate permeability and temperature for the generation of electricity using contemporary technology. Hot rock that is deeper than likely to be economically drillable in a commercial project is not considered. For more detailed and accurate estimations of the heat from the rock by commercial production of geothermal fluid must be drilled and tested.

Maximum sustainable generating power plant capacity (E) is given by equation 4.1 (GeothermEx, Inc, 2005).

$$\mathbf{E} = \frac{\mathbf{V C_V (T - T_0) R}}{\mathbf{FL}} \quad (4.1)$$

V= Volume of the reservoir

C_V= Volumetric specific heat of the reservoir

T= Average temperature of the reservoir

T_0= Reinjection temperature (Usually the average annual ambient temperature)

R=Overall recovery efficiency (The fraction of thermal energy in the reservoir that is converted in to electrical energy at the power plant)

F=Power plant capacity factor (Average value for commercial GE power plants is 0.95)

L= Power plant life (usually 30 years)

Overall recovery efficiency can be determined by equation 4.2 (GeothermEx, Inc, 2005).

$$\mathbf{R} = \frac{\mathbf{Wre}}{\mathbf{C_f(T-T_0)}} \quad (4.2)$$

r = Recovery factor (The fraction of thermal energy in place that is recoverable as thermal energy at the surface, usually 1-10%)

C_f = Specific heat of reservoir fluids

W= Maximum available thermodynamic work from the produced fluid

e = Utilisation factor to account for mechanical and other losses in a real power cycle (usually 45%)

Volumetric specific heat of the reservoir (C_V) is given by equation 4.3(GeothermEx, Inc, 2005)

$$\mathbf{C_V = \rho_r C_r(1-\varphi) + \rho_f C_f \varphi} \quad (4.3)$$

ρ_r = Density of rock matrix (Considered as 2750 kg/m^3)

C_r = Specific heat of rock matrix (Considered as 900 J/kg°C)

ρ_f = Density of reservoir fluid (Considered as 926 kg/m^3)

C_f = Specific heat of reservoir fluid (Considered as 4185 J/kg°C)

Φ = Reservoir porosity (Considered as 7%)

W can be derived from the First and the Second laws of Thermodynamics as equation 4.4 and equation 4.5

$$\mathbf{dW} = \mathbf{dq}\left(\mathbf{1} - \frac{\mathbf{T_0}}{\mathbf{T}}\right) \text{ (4.4)}$$

$$\mathbf{dq} = \mathbf{C_f dT} \text{(4.5)}$$

Considering equations 4.4 and 4.5;

$$\boldsymbol{W = C_f[T - T_0 \ln T]_{T_0}^{T}} \text{ (4.6)}$$

So by equation 4.3;

$C_V = 2.573$ MJ/m^3°C

$T_0 = 35$ °C

By considering the average temperatures; maximum sustainable generating power plant capacity (E) for the unit volume of geothermal reservoir (1km^3) under the surface of selected hot springs in southern and eastern region of the country can be calculated as Table 4.9.

Table 4.9: Sustainable power plant capacities for 1 km^3 reservoir volume

Hot spring	**W (J/kg)**	**R**	**E (MW/km^3)**
Mahapelessa	187,153.20	0.02	5.76
Kivulegama	287,467.65	0.03	8.85
Kapurella	196,234.65	0.02	6.04
Marangala	1,132,544.70	0.03	34.86
Maha Oya	539,865.00	0.03	16.62
Nelum wewa	290,690.10	0.03	8.95

4.2.4 Levelized power cost

Levelized cost of geothermal power ($\bar{C}$) can be determined by calculating capital power component of levelized cost ($\bar{C}_{CAP}$), O & M component of levelized cost ($\bar{C}_{O\&M}$) and levelized cost for drilling make up wells ($\bar{C}_{MW}$) over the plant life. Table

4.10 illustrates the development scenarios for the GE resources near the selected hot springs.

Table 4.10: Analysed development scenarios in Southern and Eastern

Hot spring	Plant capacity (MW)	Unit capital cost (C_d) LKR/kW	O & M cost (C_o) LKR/kWh	No of initial production wells	Initial harmonic decline rate (Di)	t_c
Mahapelessa	5.76	336,730	2.69	2	0.52	17
Kivulegama	8.85	333,625	2.67	3	0.99	14
Kapurella	6.04	336,448	2.69	2	0.56	16
Marangala	34.86	308,579	2.51	8	6.33	6
Maha Oya	16.62	325,939	2.62	4	2.39	8
Nelum wewa	8.95	333,526	2.67	3	1.00	14

Table 4.11 represents the levelized cost for electricity generation near selected hot springs considering 1 cubic kilometer reservoir. t_c is calculated by considering the plant capacity and t_d is considered as 20 years(usually purchase of electricity to the national grid under standardized power purchasing agreements for the period of 20 years). Plant factor of 90% of a typical GE plant was considered in the calculations. Inflation and interest rates were considered 6% and 10% respectively. Variable part of the O & M was considered as 20% from the total O & M cost.

Table 4.11: Levelized power cost in Southern and Eastern

Hot spring	D(t_d)	D(t_c)	$\overline{C}_{CAP}$ (LKR/ kWh)	$\overline{C}_{O\&M}$ (LKR/ kWh)	$\overline{C}_{MW}$ (LKR/ kWh)	$\overline{C}$ (LKR/ kWh)
Mahapelessa	0.0456	0.0519	2.3409	2.8586	0.5231	5.12
Kivulegama	0.0476	0.0663	2.3243	2.8438	1.4612	6.03
Kapurella	0.0459	0.0559	2.3397	2.8577	0.7886	5.38
Marangala	0.0496	0.1638	2.1543	2.6715	5.7877	10.1
Maha Oya	0.0490	0.1214	2.2740	2.7940	3.8976	8.38
Nelum wewa	0.0476	0.0674	2.3237	2.8432	1.5253	6.09

Initial harmonic decline rate for a 50MW power plant considered as 10 % (usually it is taken as 5% in typical power plants). Power plant life was assumes as 30 years.

4.3 Selection of Suitable Geothermal Energy Applications

The reservoir temperature of Sri Lanka is calculated here to be in the 100-160°C range for 4 springs and more than 200 °C for Marangala and Maha Oya. According to the MT resistivity depth analysis it represents that the reservoir is beyond the economical depth for electricity generation but according to the chemical analysis it is not. So the available data is not sufficient for predict the financial viability of electricity generation under normal tariff structure (Unless a special tariff provides for the developers to enter in to geothermal electricity generation as individual power produces). Hence raw heat could be utilized for other suitable applications. The Lindal diagram (Figure 2.12) indicates the temperature range of geothermal fluids suitable for various applications. Possible applications for geothermal energy in Sri Lanka based on the Lindal diagram are the following.

4.3.1 Electrical applications

Based on the calculations (Table 4.9) of sustainable power plant capacities for selected 6 hot water springs; it is obvious that underground potential is available. Marangala, Maha Oya, Nelum wewa and Kapurella areas are more suitable for the exploration of electricity generation using geothermal due to the lack of population density(land acquisition for power generation in not an issue) and the availability of water sources nearby to feed in to the hot dry rocks(or hot geothermal fluid). Therefore few 10MW scale power plants can be constructed in Ampara district, licensed under non-conventional RE development.

4.3.2 Thermal applications

At present, most hot spring areas are already being used as bathing and tourist attraction places in Sri Lanka. Hot springs with lower subsurface temperatures could be developed as public bathing places and saunas. Since all the hot springs are located in the eastern part of the country, and some of them are close to the sea, there is a greater possibility for developing some hot spring locations into tourist attractions

Direct use applications tap geothermal resources to provide thermal energy. Those types of projects are feasible throughout a larger section of the applications because they use more widespread, low temperature resources (generally from 20°C to 150°C). Direct use applications commonly support agricultural and industrial activities but are also an efficient means of heating and cooling of buildings.

Space conditioning

In Sri Lanka, the total installed capacity of electricity generation is nearly 3368 MW and the maximum daily demand is approximately 2146 MW. Electricity consumption on a normal day is 32 GWh. This value can increase up to 42 GWh on hot days (Sri Lanka Sustainable Energy Authority, 2013) and decrease on rainy days. The difference, 10 GWh, between the upper margin and the lower margin would probably be used for air conditioning and water supply. These geothermal resources could be used for air conditioning in villages and towns within 10-20 km distance from the geothermal site. The technology is based on well-known absorption chillers and requires the building of a district cooling pipe system.

Agriculture

The major application of geothermal energy in agriculture is the heating of greenhouses in order to control the climate, mainly temperature and relative humidity. The temperature of the water supplied to the greenhouse depends on the heating demand and ranges from 40-100°C. The water is distributed in steel pipes which could be placed under the soil, on the soil or on benches, between rows of plants or suspended in the greenhouse space.

In order to produce fast maturing and high quality plants, certain growing conditions must be maintained as close as possible to the optimum. These include nutrients and climatic conditions such as temperature and humidity. Eastern region of Sri Lanka has large quantity of farming lands. Hence the geothermal energy can be used in plant nurseries and large scale greenhouse plantations.

Hot water supply

Another electricity consuming activity is the heating of water. At present, a main hot water supply network is not available in Sri Lanka. If geothermal hot water from the reservoirs could be supplied to nearby consumers, it would reduce the cost of fossil fuels and would be another income source for the National Water Supply and Drainage Board of Sri Lanka.

Industrial and commercial uses

Drying or dehydration of agricultural products is one of the major industrial applications of geothermal energy. Dairy processing is yet another application of geothermal energy where fresh milk from the farmers can be pasteurized using hot geothermal water. Geothermal resources also are used in mineral extraction, timber drying and textile industries.

Sri Lanka is a tropical country in South Asia. All the geothermal resources are available closer to the sea. Drying of stock fish is carried out normally by sunshine on the shore. During drying, yields can be infected by insects. Geothermal heat could be utilized in a controlled and continuous manner to protect hygiene and prevent the wastage of food. It would also supply continuous production independent of weather conditions.

4.4 Discussion

The study was carried out to assess the potential areas for geothermal power generation in Sri Lanka mainly in southern and eastern part of the country. For this study analyzing the chemicals and magnetotelluric scanning were considered as the main research activities. Magnetotelluric scan equipment’s are generally very expensive and at present limited number of countries have the testing equipment’s. Also MT testing is very complex when analysing the data to get resistivity depth sections. Thus available MT testing data for five locations and a traverse were considered as the test data for predicting about the reservoir cross sections. But it was not possible to calculate reservoir volumes using existing 2D MT data. There is a high probability of occurrence of low depth resource beyond the available MT traverse which was not counted in this study.

Testing of the geothermal water for chemicals was done for the selected sources. Depending on the chemical concentrations of the water samples the characteristics of the sources were predicted. Testing of the geothermal waters for isotopes characterization may improve the accuracy of the predictions because it reflects whether the geothermal water is mixed with the ground water and the percentages of mixing (Chandrajith, et al., 2013). Due to the non-availability of isotope testing in Sri Lanka the study was narrowed down only to chemical analysis.

Based on the assessment of the geothermal potential for energy generation in Sri Lanka; it was identified that the resource is available near the existing hot water springs and some intermediate locations. Volumetric capacity assessment for a 1 km^3 reservoir volume represents positive sign and economical levelized power cost of generation.

The main drawbacks for the exploration of the resource are the lack of funding for the researches and the expertise knowledge. Developers lag to invest their money for explorations, because no any acceptable basic resource assessment data for geothermal are available in Sri Lanka. Many scientists during past few decades worked on the geothermal resource estimation based on geology, ground water temperatures, volcanic studies, geochemistry, resistivity surveys, and seismic data analysis. However most of these studies are based on theories. Recent magnetotelluric resistivity depth analysis studies near the hot springs revealed actual cross sections with positive signs of resource. For the continuation of the studies for further explorations, three dimensional magnetotelluric tests should be done in the identified feasible areas. Also the scan should be followed by a test drilling which needs more investments. At present most of the studies were in a bottleneck due to lack of adequate investment finances.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Geochemical analysis is one of the available accurate testing methods to estimate the temperature of the underground resource. MT testing is also considered as very accurate to obtain resistivity depth sections of locations. According to the chemical analysis of the water from selected hot water springs, samples from Kapurella, Nelum wewa, Maha Oya have representing the characteristics of volcanic water and Marangala steam heated waters. Kapurella and Nelum wewa are in rich with chloride. Mahapelessa has very high chloride concentration but not due to the deep geothermal fluid. The reason for very high chloride concentration may as a result of sea water mixing with the spring water because this spring is located very closer to the sea and the area has lot of geological fine fractures. Kivulegama spring water is also not associated with deep geothermal reservoir according to its chemical concentration. Water percolating through the geological cracks of HC will getting wormer due to the natural geothermal gradient; may then rising upward by artesian action in the spring. The high fluoride concentration due to the mixing of heated water with the cold springs (Usually normal spring water in this area has high fluoride).

So according to the chemical analysis of the selected hot water springs; Kapurella, Nelum wewa, Maha oya and Marangala respectively representing the characteristics of deep reservoir geothermal water giving an indication of the underground potential availability for energy harnessing.

The 2D MT resistivity depth analysis covering MP, KP, MP, MA and NW reveals low resistivity areas near the hot springs of Kapurella, Marangala and near Maha Oya. Further penetration of MT reveals the sign of large reservoir under MA and KP about 10~20 km deep. And the intermediate reservoir between MO and KP may feed the MO spring. It is likely there is a deeper low resistivity reservoir of high temperature beyond the present MT traverses feeding MP, MO, and MA hot springs.

Average temperatures of the geothermal reservoirs are around 120-160°C for MP, KI, KP and NW and for Marangala, Maha oya 390 and 230°C respectively.

Calculation of the reservoir cross sections along the MT traverses represents considerable sizes of reservoirs can be exist beyond the present MT traverses. The existing MT traverse data can only be used to determine the cross sections of few low resistivity areas in MP, KP and MA.

Maximum sustainable generating capacity for a unit volume of reservoir represents availability of economic potential beyond the usual depths of conventional geothermal power plants. Hence MO, MA, KP and NW sites were suitable for further exploration of geothermal energy. Levelized electricity generation cost for MP, KI, KP and NW is around 6 rupees and for MA, MO it is about 10 rupees.

5.2 Recommendation

To develop this approach further, the calculated characteristics of the geothermal waters should be cross check with the actual ground profiles. Existing locations of the hot springs were used as initial testing locations for MT. But new hot spring locations also can be available around. Night time infrared photography using a flight or drone may be useful to detect all the hot water accumulations in the country. It was recommended to continue the chemical analysis for isotopes.

Based on the data from the chemical analysis and 2D MT survey represents that volcanic water sources may present and source regions for thermal waters could exist at locations laterally off the present MT profiles and may even shallower, worthy of geothermal exploitation at present times. Though the upward passages of thermal waters were not resolved with the present MT site separations, it is possible that thermal waters from within the relatively low resistive bands extending to the surface from the deeper low resistive regions may have fluid connectivity that aids extraction at relatively shallower depths. In order to economically tap the geothermal heat the shallow reservoirs should be identified. For future exploration, 2D cross MT survey which covering KP, MO, MA and NW or sophisticated 3D MT surveys are strongly recommended.

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APPENDICES

Table 1: Relevant geothermal field characteristics in the world in 2005

Country	Field	Drilled area (km^2)	Type	Depth (m)	Temperature (°C)	Production wells	Reinjection wells	Running capacity (MW)
China	Yangbajain	4	Water	200	140-160	14	6	15
Costa Rica	Miravalles	30-35	Water	1000-2000	240	32	20	163
El Salvador	Ahuachapán	4-Mar	Water/Steam	600-1500	230-240	19	5	63
El Salvador	Berlín	3-Feb	Water	2000-2500	300	9	15	56
France	Guadeloupe	4	Water	300-1100	250	6		15
Guatemala	Zunil I	4	Water	1500-2300	300	6	2	24
Guatemala	Zunil II	10-Aug	Water/Steam	800-1200	240	2		5
Guatemala	Amatitlán	9-Jun	Water/Steam	1000-2000	300	4		5
Iceland	Krafla	6-May	Water	1000-2000	190-210	21	1	60
Iceland	Nesjavellir	8-Jun	Water	1000-2000	300-320	18		90
Iceland	Svartsengi	8-Jun	Water	1000-2000	240	11	1	46

Country	Field	Drilled area (km^2)	Type	Depth (m)	Temperature (°C)	Production wells	Reinjection wells	Running capacity (MW)
Indonesia	Kamojang	15-20	Steam	1500	245	29		140
Indonesia	Salak	20-25	Water	1000-2000	240-310	30	15	361
Indonesia	Darajat		Steam	2000	245	17		135
Indonesia	Dieng		Water		280-330	25		60
Indonesia	Wayang Windu		Water		250-270	18		110
Indonesia	Lahendong		Water		260-330	15		20
Italy	Larderello	250	Steam	1000-4000	150-270 and 350	180	23	473
Italy	Travale Radicondoli	50	Steam	1000-4000	190-250 and 350	22	0	147
Italy	Bagnore	5	Water	1000-3000	200-330	7	4	19
Italy	Piancastagnaio	25	Water	1000-3000	200-300	19	11	60
Japan	Ogiri	8	Water	1000-2000	260	19		30
Japan	Otake Hatchoubaru	10-Aug	Water	1000-2500				122
Japan	Takigami		Water					25

Country	Field	Drilled area (km^2)	Type	Depth (m)	Temperature (°C)	Production wells	Reinjection wells	Running capacity (MW)
Japan	Yanauzu Nishiyama		Water					65
Japan	Onikobe		Water					12
Japan	Uenotai	10-Sep	Water	1000-2000	300-320	9	7	29
Japan	Kakkonda		Water		230-260 350-360			80
Japan	Matsukawa	4	Water		260	17		24
Japan	Sumikawa		Water			15		50
Japan	Mori	6	Water	500-1500 2000-2500	230-250	10	9	50
Kenya	Olkaria E	5	Water	500-2000		26	0	45
Kenya	Olkaria W	12	Water					70
Kenya	Olkaria NE	9	Water	1800-2700		9		12
Mexico	Cerro Prieto	150-200	Water	2 800	300-340	149	9	720
Mexico	Los Azufres	35	Water	1600-2000-3000	150-200 280-300	29	6	188
Mexico	Los Humeros		Water			17	2	35

Country	**Field**	**Drilled area (km^2)**	**Type**	**Depth (m)**	**Temperature (°C)**	**Production wells**	**Reinjection wells**	**Running capacity (MW)**
Mexico	Las Tres Virgenes	30	Water	2100	280			10
New Zealand	Wairakei	15	Water/Steam		160-260			220
New Zealand	Ohaaki	8-May	Water		230-280			104
New Zealand	Rotokawa	25	Water	2000-2500	270-330			31
New Zealand	Kawerau		Water		240-300			15
New Zealand	Ngawha		Water	600-2800	220-240	2	2	10
New Zealand	Mokai		Water		270-320			55
Nicaragua	Momotombo	4	Water	300-800 800-1700 1700-3000	180-200 200-240 240-300	12	4	35
Nicaragua	San Jacinto-Tizate		Water	1500-2500	260-280	3	2	10 By 2005
Papua New Guinea	Lihir	5-Mar	Water/Steam	300-1000	250-300	3		6
Philippines	Tiwi	13	Water	900-2800	320	43	16	232

Country	**Field**	**Drilled area (km^2)**	**Type**	**Depth (m)**	**Temperature (°C)**	**Production wells**	**Reinjection wells**	**Running capacity (MW)**
Philippines	MakBan	7	Water	900-3400	345	72	21	402
Philippines	BacMan	10	Water	1300-3000	240-320	22	8	150
Philippines	Tongonang	53	Water	1500-3000	250-300	81	33	723
Philippines	Palinpinon	48	Water	2500-3000	250-300	36	13	192
Philippines	Mt. Apo	21	Water	750-3000	230-310	17	6	108
Russia	Pahuzhetka		Water		200	7		11
Russia	Mutnovsky	15-Dec	Water/Steam	700-2500	240-300	17	4	62
Turkey	Kizildere		Water		240			17
USA	The Geyser	100	Steam	600-3000				888
USA	COSO	20	Water	500-3500	200-330	90	20	270
USA	East Mesa	24	Water	1500-2500	150-190		41	107
USA	Heber	5	Water	1200-1800	160-180	21	23	65
USA	Salton Sea	16	Water					350
USA	Casa Diablo		Water	200	160			27
USA	Brady		Water					26

Country	Field	Drilled area (km^2)	Type	Depth (m)	Temperature (°C)	Production wells	Reinjection wells	Running capacity (MW)
USA	Beowave		Water					16
USA	Dixie Valley		Water					68
USA	Steamboat		Water					36
USA	Puna		Water	2 000	160			27
USA	Roosevelt		Water					20