Preliminary environmental impact assessment of a geothermal project in Meshkinshahr, NW-Iran

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Abstract

In this report, a preliminary environmental impact assessment is presented for a geothermal project on the western slopes of Mt. Sabalan, approximately 16 km SE of Meshkinshahr City, in the province of Ardabil in Northwest Iran. Various researchers have investigated this area's geothermal resources over the past few years for the possibility of using the geothermal energy to generate electricity. A preliminary review was carried out of the possible environmental effects of this proposed project as a precursor to an environmental impact assessment (EIA). In this study, an attempt has been made to identify the likely key impacts of geothermal exploration, drilling, and operation, and potential mitigation measures. The results of this study suggest that detailed studies be carried out on water supply for drilling; on how to properly dispose of effluent water; on the monitoring of gas emissions to the atmosphere during drilling and operation; and methods to reduce soil erosion. It is also recommended that a detailed assessment survey on the biology of the area be done, as well as the socio-economic effects of this project on the lives of residents of Meshkinshahr City and the nearby villages.

Keywords: *geothermal, environmental, renewable energy, Meshkinshahr, EIA.*

1 Introduction

The environmental aspects of geothermal development are receiving increased attention with the shift in attitudes towards the world's natural resources. Not only is there a greater awareness of the effect of geothermal development on the surrounding ecosystems and landscape, but also a greater effort is being made to use the resources in a sustainable manner. Geothermal power generation is often considered as a 'clean' alternative to fossil fuels or nuclear power plants but it is still necessary to survey its effects on the environment. Geothermal power generation results in the release of non-condensable gases, and fine solid particles into the atmosphere.

In recent years, attention has been focussed on the utilisation of geothermal energy as an alternative to hydropower, and fossil fuel power plants. The Ministry of Energy and Renewable Energy Organisation of Iran is considering the development of the Meshkinshahr geothermal field to construct the first geothermal power plant there. Before such a project is initiated, however, an environmental impact assessment is necessary. The Ardabil province has close to 1,200,000 inhabitants, including the 165,000 inhabitants of Meshkinshahr City. The Meshkinshahr area is located in a formerly farmed area in NW-Iran. In this report, probable environmental effects of a geothermal power plant project in the Meshkinshahr area are described, and some recommendations for mitigation of project effects in the geothermal field and the surrounding areas given (Armannsson and Kristmannsdottir, 1992).

2 Environmental impact of geothermal projects

Environmental impacts from geothermal development vary during the various phases of development. Geothermal development can be described as a three-part process:

1 Preliminary exploration, which has hardly any environmental effect.
2 Drilling. Each drill site is usually between 200 and 2,500 m^2 in area, and the soil in these areas is compacted and changed. There is also deposition of waste soil and drill mud. Construction of roads, well pads, and power plant sites result in cut and fill slopes that reshape the topography of the area, but the effect on the area's topography is not significant. Air pollution can result from gas emissions; smoke exhaust from generators, compressors and vehicles. During well testing, steam and spray can have an adverse effect on the local vegetation with trees and grass being scalded. Dust carried by wind blowing across exposed surfaces may also have a deleterious effect (Webster, 1995).
3 Production and utilization. Soil movement for the construction of pipelines, the power plant and other buildings may affect Land. During operation, subsidence and induced seismicity are the main possible effects

3 Existing environment of Meshkinshahr geothermal area

3.2 Meshkinshahr - brief history

The Meshkinshahr geothermal prospect lies in the Moil valley on the western slopes of Mt. Sabalan, approximately 16 km SE of Meshkinshahr City. Mt. Sabalan was previously explored for geothermal resources in 1974, with geological, geochemical, and geophysical surveys being undertaken (Foutohi, 1995). Renewed interest in the area resulted in further geophysical, geochemical and geological surveys being carried out in 1998. These studies have resulted in the identification of a number of prospects associated with Mt. Sabalan. The present study has been undertaken to find out what information is needed to establish baseline environmental conditions involving surveys of geology and land, weather conditions, noise conditions, ecology and socio-economic conditions.

3.3 Geology and land conditions

Mt. Sabalan is a large stratovolcano, consisting of an extensive central edifice built on a probable tectonic horst of underlying intrusive and effusive volcanic rocks. Enormous amounts of discharged magma caused the formation of a collapsed caldera about 12 km in diameter, and a depression of about 400 m. The lava flows in the Sabalan are mostly trachy andesite and dacite with alternating explosive phases. The schematic geological map (Figure 1) shows the volcanic formations from Eocene to Quaternary.

3.4 Geophysical surveys of Meshkinshahr

During the summer of 1998, a resistivity survey of the Mt. Sabalan geothermal area, in northwest Iran, was undertaken for SUNA (Renewable Energy Organisation of Iran). The primary objective of this survey was to carry out geothermal exploration of the Sabalan area to delineate any resistivity anomalies that may be associated with high-temperature geothermal resources. The subsurface resistivity structure was modelled to assess the size of the geothermal resources; to facilitate the choice of initial exploration of well sites; and to prepare conceptual models for the hydrology of the geothermal fluid reservoirs.

The planning of the resistivity survey called for a flexible approach for both method and site selection. The types of structures that the survey was designed to target included:

- Lateral resistivity boundaries - to assess resource extent;
- Vertical resistivity layers - to assist hydrological modelling and drillhole planning;
- Two-dimensional (or 3D) structure - to assist in locating fault zones, caldera and graben structures or intrusives.

The scope of the project involved a total of 212 resistivity stations in an area of about 860 km^2 on the slopes of Mt. Sabalan, near Meshkinshahr and Sareyn (Ardabil). Three complementary resistivity methods were chosen to achieve the desired accuracy and penetration depth range for practical drilling target purposes:

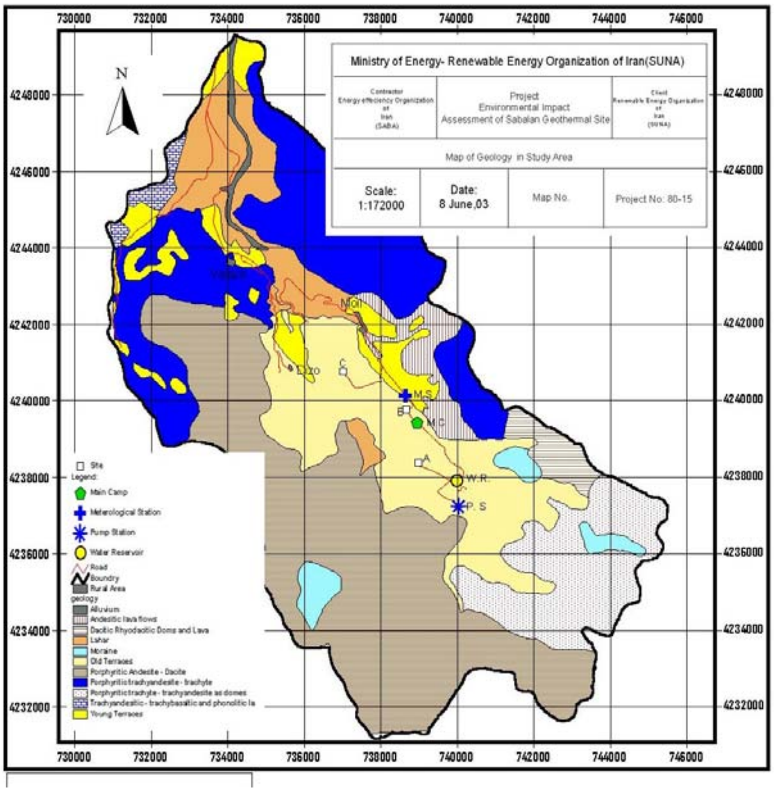

Figure 1: Schematic geological map of the Meshkinshahr area.

- DC (direct current, AB/2=25 m Schlumberger array),
- TEM (transient electromagnetic, 50 or 100 m central loop array), and
- MT (magneto-telluric, frequency range 8 kHz - 0.02 Hz).

Station locations were selected by the survey crew to fulfil the exploration objectives of the survey while taking into account considerations of terrain (to minimise topographic distortions in the data), and site accessibility. A resistivity map of the Meshkinshahr area is shown in Figure 2 (Bogie et al., 2000).

3.5 Hot springs

In the Meshkinshahr geothermal area, there are several hot springs with a temperature in the range of 25–85°C, originating in Mt. Sabalan. The springs in the Meshkinshahr prospect issue mainly from the gravels of the Dizu Formation. There are no springs reported downstream at lower elevations. The Gheynarge, Khosraw-su, Malek-su and Ilando springs produce neutral-Cl-SO_4 waters with up to 1,500 ppm Cl and 442 ppm SO_4, with significant concentrations of Mg (up to 24 ppm). They exhibit a simple dilution trend indicating mixing with varying amounts of shallow groundwater and a strong seasonal cyclic variation in flow rate but very little seasonal variation in temperature or chemistry, which is indicative of storage behaviour. Despite the elevated Cl concentration, isotopic ratios for the waters plot on the local meteoric water line.

The Moil, Moil 2, Aghsu and Romy springs are acid (pH 4.28, 3.20, 3.53 and 2.76 respectively). The Moil 2 and Aghsu springs are typical acid-SO_4 waters and therefore have formed by condensation and oxidation of H_2S, implying boiling at greater depths. The Moil springs have beenslightly neutralised, and are therefore further from the source of H_2S than the Moil 2 springs. The Romy spring waters contain significant Cl (119 ppm). It is difficult to derive water of this temperature and chemistry by mixing other spring chemistries, and so it is possible that the Romy spring waters may represent a diluted but acid equivalent of the neutral Cl-SO_4 waters. The storage

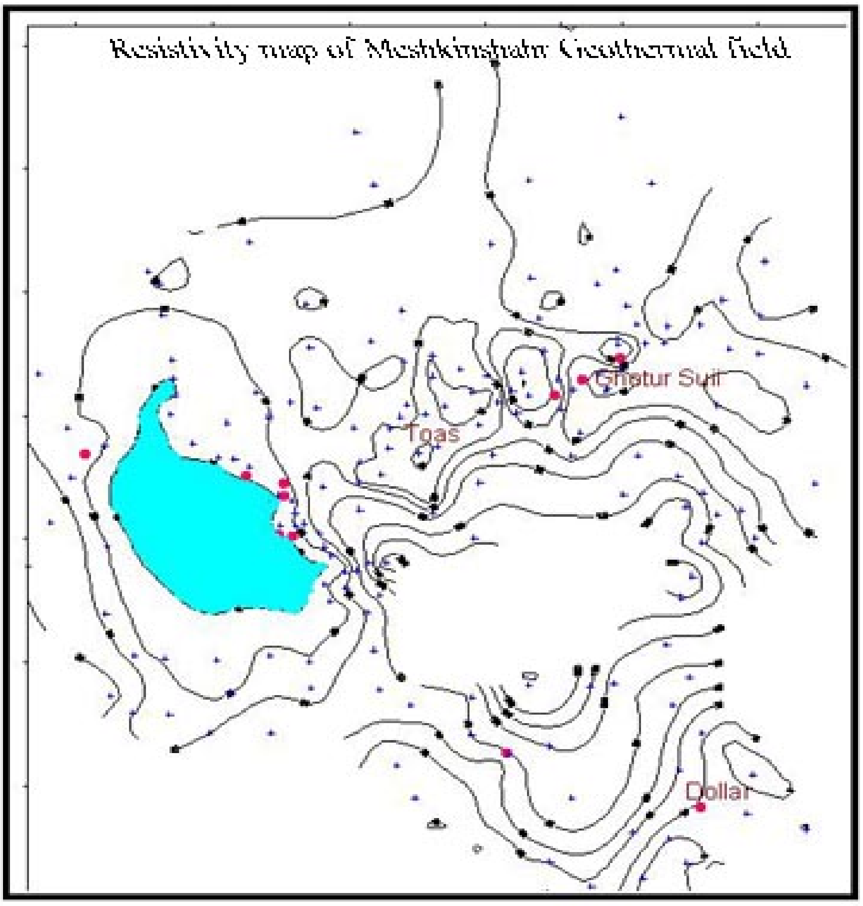

Figure 2: A resistivity map of Meshkinshshr area (Bogie et al. 2000).

behaviour of the springs is indicative of them being fed by very large perched groundwater aquifers, and to obtain a high Mg neutral Cl-SO_4 composition requires that magmatic volatiles have condensed and been neutralised within these aquifers. A degassing, shallow intrusive and possible heat source is therefore inferred which is consistent with a similar conclusion from the geology (Bogie et al., 2000).

3.6 Weather conditions

Measurement of weather conditions in this geothermal field started with the installation of the Moeil meteorological station at the site in April 2000. At this meteorological station, data is continuously collected for temperature, humidity, wind speed, wind direction, solar radiation and air effluent such as SOx, and NOx. Data is recorded automatically every half hour.

Precipitation in this area has been measured from April 2000 to the present at this meteorological station. Yearly precipitation is 196 mm. Maximum precipitation in December is about 39 mm and the minimum in June and July is zero. Temperature data for the Moeil meteorological station for 2002 are shown in Figure 3. The maximum temperature is recorded in July at about 31°C, and the minimum in January is about -19°C.

Humidity data for this area was collected in 2002 at the Moeil meteorological station. Maximum humidity is recorded in December, at about 78%; and the minimum is recorded for August, about 13%.

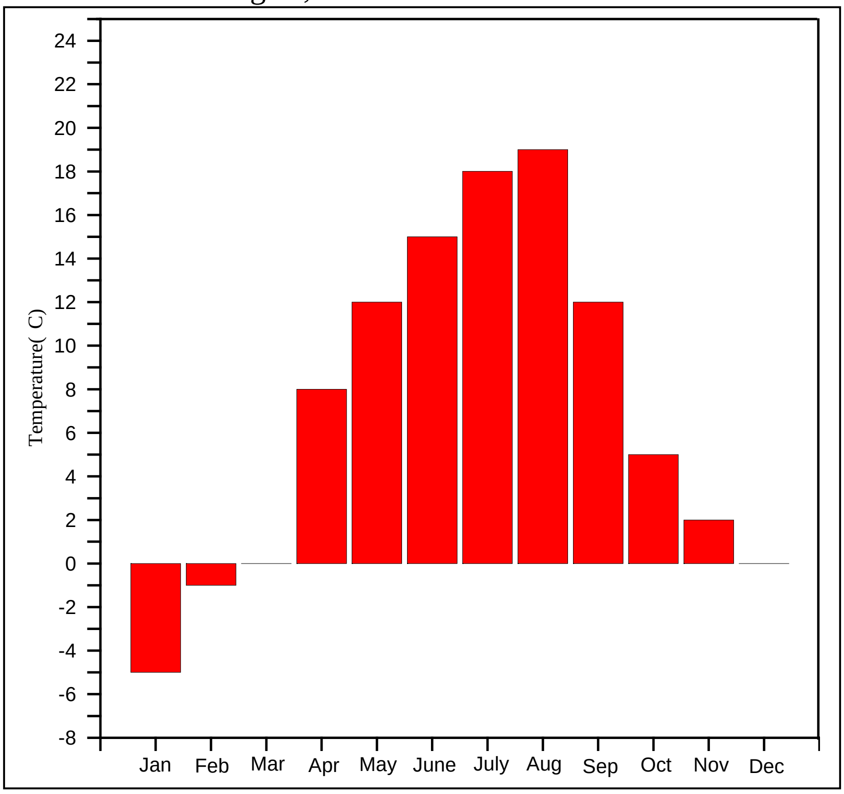

Figure 3. Temperature in Moeil Meteorological station for 2002.

April 2002, at 30 points to cover the whole area. The results show that the noise level in the whole area is less than average.

3.7 Air quality

Meshkinshahr geothermal field is an unexploited natural area without any industrial or other air polluting activities. Only some gases from geothermal manifestations escape to the atmosphere. The concentrations of H_2S are higher than of other gases in geothermal manifestations, and it seems necessary to monitor this in the area. H_2S concentrations have been monitored over the whole area, about 132 km^2, where most of the geothermal manifestations are located. The concentrations of gases in the north-western part of the area are greater than in the other parts, because most of the gases are released to the atmosphere from this area.

3.8 Wind patterns

Wind conditions were measured during the year 2002 at the Moeil meteorological station. Hourly wind direction and wind speeds have been used to make a wind rose plot, and it is seen that the most common wind directions are northeasterly and west/south-westerly. Figure 4 shows the yearly wind pattern at the Meshkinshahr area for 2002.

3.9 Noise conditions

Most geothermal developments are in remote areas where the natural level of noise is low and a slight change in noise level is detectable. The Meshkinshahr area is without any industrial activities; thus there is no noise pollution there at present. The base noise level was measured in April 2002, at 30 points to cover the whole area. The results show that the noise level in the whole area is less than average.

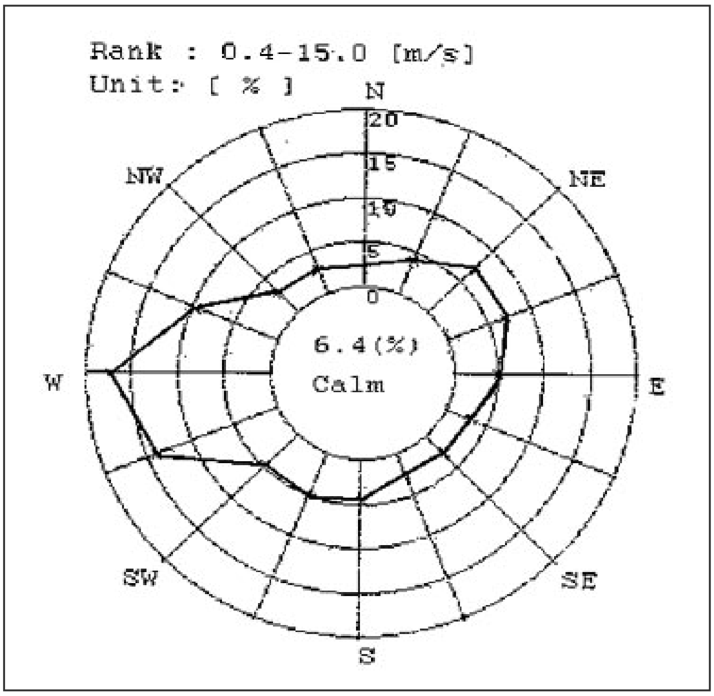

Figure 4: The yearly wind pattern at the Meshkinshahr area in 2002.

3.10 Social and economic conditions

The region of Meshkinshahr in northwestern Iran has a population of approximately 165,000. Its principal town, Meshkinshahr, has 65,000 inhabitants. The main industries are community service such as teaching, health care, banking, trading, farming, fish farming and ranching. Industrial activities include slaughtering, meat processing, cannery and wood industry. For several decades, this region has suffered a brain drain because there have been few jobs for highly educated people. The percentage of highly educated people in the Meshkinshahr region is very much lower than the national average. For many years, the local government of Meshkinshahr has been trying to improve the economy of this area by creating some permanent and provisional jobs. In the last few years though, there were very low amounts of precipitation in the whole of Iran, and also in the Meshkinshahr area, causing most of the farmers to have economic problems. The government has been trying to install some industrial manufacturing to help the people. Most of the sectors that have been developed are tourism-related activities, but others that are in line include food production (fish and farm produce), mining of minerals, the utilisation of high-temperature geothermal fields, the direct use of geothermal energy (swimming pool, fish farming), and construction of a dam for electricity production and irrigation. In recent years, attention has been focussed on the utilization of the high-temperature geothermal field to produce 100 MW of electricity in Meshkinshahr.

3.11 Vegetation

In the spring of 2002, with the aid of plant biologists, a vegetation map of the study area was made (Figure 5) which shows the entire area is covered by vegetation. The density of coverage is 15% at high elevations (above 3,200 m); 45% coverage from 2,400 m to 3,200 m; and 30% coverage for elevations below 2,400 m. The recorded permanent flora of Meshkinshahr consists of 369 species.

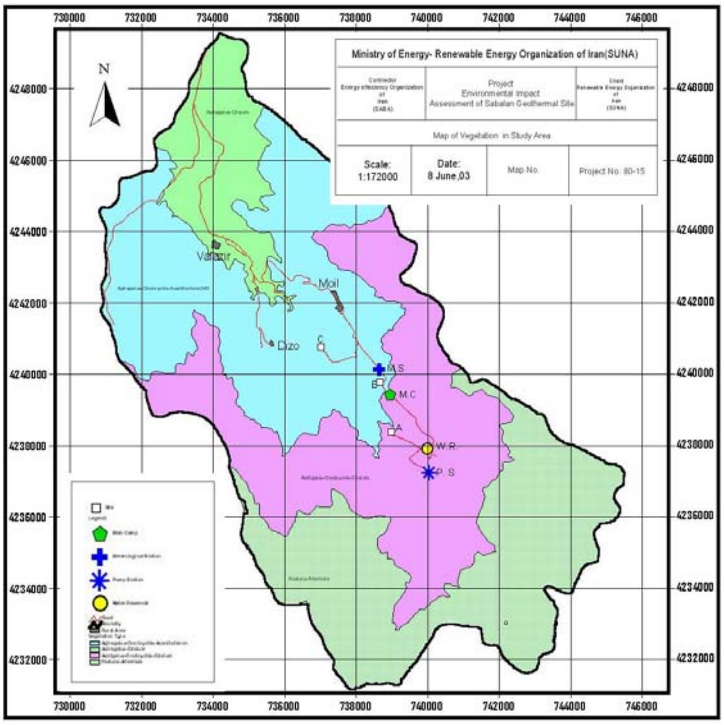

Figure 5: Vegetation map of the project area.

Most of the resident activity in the Meshkinshahr area is sheep farming, and protection of vegetation is very important for the local government.

3.12 Fauna

The Meshkinshahr area is a mountainous area, and the fauna is rich. Sheep farming in summer time is the most important activity of the residents, but they leave the area in wintertime because this area gets very cold. Due to this movement, the number and types of species in winter and summertime are quite different. The permanent fauna of the Meshkinshahr area has been recorded as consisting of 250 species. Some species like Phasianus, Mergus albelus, Aaudial chrysaetos and sturnus vulgaris are overabundant.

3.13 Tourism

In a general report on tourism in Iran that was published by the Ministry of Society and Culture, it was recommended that geothermal areas be given high priority in the development of tourism, especially in the Ardabil province due to Mt. Sabalan. Also in the Meshkinshahr area, many hot springs with different temperatures are found, and very nice landscape in all seasons. Opening up the area by way of new roads would change conditions drastically, and might bring in a greatly increased number of tourists and also change the most common route for climbing the Sabalan peak, because when the road to the Meshkinshahr geothermal field is finished, this will be the shortest way to the Sabalan peak.

4 Environmental impact assessment

Baseline environmental conditions have been estimated, with suggested further analysis, to determine the impacts of a geothermal project for all relevant phases of development, and to propose mitigating measures to reduce environmental impacts.

The objective of an environmental impact assessment is to determine the potential environmental, social and health effects of a proposed development project. An EIA attempts to assess the physical, biological and socio-economic effects of the proposed project in a form that permits logical and rational decisions to be made. Attempts can be made to reduce or mitigate any potential adverse impacts through the identification of possible alternative sites and/or processes.

4.1 Geology and land

During exploration, there is no significant impact on geology and land, only in geophysical exploration such as the drilling of shallow wells to obtain a geothermal gradient map, during which there are some effects on land and soil from disposal.

During drilling, 10 km of road construction and preparation of 3 drill sites can cause unstable earth conditions and changes in geological substructure. During well testing, care should be taken not to discharge the wastewater directly to steep areas, but sumps should be made to contain this waste water, as failure to do this can cause serious gullying.

Each drill site in Iran is on average about 20,000 m^2 in land area. In this project, 3 wells are drilled during the first phase. About 60,000 m^2 of land in this area, mainly used for sheep farming, will be affected during drilling and many years after that. The soil in these areas will become compacted and changed, and close to the drill site there will be some deposition of waste soils. The construction of a 10 km access road, camping facilities, storage areas, buildings, pipelines, powerhouse and worker's quarters will affect about 860,000 m^2 of land.

During operation, subsidence and induced seismicity are the main possible effects on the land around the power plant and the surrounding areas. A monitoring program for subsidence in this area is recommended. The base level of the geothermal field was recorded in summer 2001.

4.2 Effects on air

Gas emission to the air would take place during all phases of the proposed project. During the construction and decommissioning phases, dust would result from surface disturbances and vehicle travel on unpaved roads. Non-condensable gases, including hydrogen sulphide (H_2S) and carbon dioxide (CO_2), will be released from the geothermal fluid during well drilling and testing, and during power plant operations. Oxides of nitrogen, carbon monoxide, and oxides of sulphur emitted from internal combustion engines will be released during all phases of the project. A summary of the effects on air during such a project follows:

- Small quantities of critical air pollutants will be released from mobile construction equipment and other vehicles, but this impact will be below the level of significance.
- Large quantities of critical air pollutants, in particular oxides of nitrogen (NO_x), will be released from drilling rig engines during well drilling operations, but this impact will not be significant if wells are drilled one by one, and only one active drill rig is operated at any one time.
- Hydrogen sulphide will be released during well flow testing from well pads, and it is necessary to control the concentration of H_2S in the atmosphere and keep it below levels specified in international standards.
- Hydrogen sulphide will be released to the atmosphere during power plant operation. H_2S concentrations measured in steam samples from the area are not dangerously high.
- The project will release "greenhouse gases" which will contribute to global warming. These gases consist mainly of carbon dioxide (CO_2) and some methane (CH_4). But a prediction of the amount of carbon dioxide released to the atmosphere per kilowatt of electricity shows it to be approximately 20 times smaller than the amount of "greenhouse gases" released from a fossil-fuel power plant for an equivalent amount of electricity.
- The main residential area in the Meshkinshahr geothermal field is in the eastern part, and the wind pattern is mainly from west to east. According to wind direction, , the power plant should be installed in the southern part of the field to minimize the effects from air pollutants.

4.3 Effects on water

The wells, which will be drilled in this area for high-temperature geothermal fluid will be deep and may require up to 50 l/s of water for periods of several months, depending on the number of wells to be drilled. The amount of water used as drilling fluid is enormous and should be discharged with utmost care into well-designed sumps, or possibly re-injected as this can affect the quality of the groundwater in the area.

Hydrological studies show that the groundwater flow in the study area is from southeast to northwest, and these waters finally discharge into the Khyav River. Drinking water for Meshkinshahr City, and agricultural water for more than 20,000 residents in the northern part of Meshkinshahr comes from the Khyav River, so it is necessary to survey the effects of the geothermal effluent on the river.

Spent geothermal fluid from the power plant will be injected into an injection well that is located behind the exploration wells. The concentration of dissolved solids and gases in geothermal water and steam are greater than in shallow ground water. Therefore, it is necessary to monitor the effect of geothermal fluid on surface water and shallow groundwater after the installation of a power plant.

4.4 Noise effects

In the Meshkinshahr geothermal field, there will not be serious noise impacts during geothermal project activities such as drilling, well testing and operation. Only during well testing will there be some temporary noise, which will affect wildlife in the vicinity of the drill rig. Workers on-site will need to wear appropriate hearing protection as a necessary safety precaution. The greatest noise effects during power plant operation are from the cooling tower, transformer, and turbine-generator building. When power plant operation starts, noise mufflers must be used to keep the environmental noise level below the 65 dB limit set by the U.S. Geological Survey (Kestin et al., 1980). With a reduced level of noise, workers, tourists and wildlife will not be seriously affected.

4.5 Flora

The vegetation will be destroyed during drill site preparation with the construction of buildings, pipelines, transmission lines, and roads, but this effect is not significant because the drill site can be re-vegetated with the same species after drilling and well testing are completed. During operation, a monitoring programme including the monitoring of pollutant gases such as H_2S in the atmosphere should be carried out, and if the concentrations of these gases become higher than limits set by standards, measures must be taken to reduce their amounts in the atmosphere.

Sheep are in this area and graze extensively on the surrounding vegetation. During drilling and well testing, care should be taken to avoid damage to vegetation when disposing of drilling effluents and operational wastewaters to avoid damage to vegetation that might be consumed by sheep. A detailed study should also include the potential effect of changes in the thermal area, such as increased steam flow due to exploration, to changes in the distribution of the thermally adapted plants, and to whether some of the species could be rendered extinct.

4.6 Fauna

During exploration for geothermal energy in this area, damage to animals is unlikely. During construction of roads, preparation of drill sites and drilling, the effect of noise from the drill rig and well testing will cause most of the animals to move from the vicinity of the drill rig. The most significant effect of geothermal power plant operation on the environment is air pollution. The sensibility threshold of animals to the smell of gas is the same as for humans. A detailed study on the identification of all animals, and a survey of the probable effects of long-term geothermal operation on animals is required. The stocks of some species like Phasianus, Mergus albelus, Aaudial chrysaetos and sturnus vulgaris may collapse and have to be watched carefully.

5 Conclusions and recommendations

- Hydrological studies show that the groundwater flow in the study area is from southeast to northwest, and these waters are finally discharged into the Khyav River. Drinking water for Meshkinshahr City and agricultural water for more than 20,000 residents in the northern part of Meshkinshahr comes from the Khyav River, so it is necessary to survey the effects of geothermal effluent on the river.
- The extreme permeability of the lava formations suggests that it should not be difficult to dispose of effluent water. As there is always a danger of over-exploitation of the fluid, the best solution economically and environmentally is re-injection.
- The greatest damage to the vegetation of the area has up to now been due to sheep grazing, and limiting this activity would improve

the flora of the area. A careful recording of rare plants, especially those that normally only grow near hot springs should be undertaken.

- Building of a power plant in this area would increase access by way of new roads. Thus, increased tourism would be expected and might even call for some tourism-related services in the area. Due to the dense populations of some species like Phasianus, Mergus albelus, Aaudial chrysaetos and sturnus vulgaris, have to be watched carefully as their stocks may collapse. The greatest noise effects during power plant operation are from the cooling tower, transformer, and turbine-generator building. When power plant operation starts, noise mufflers must be used to keep the environmental noise level below 65 dB.
- Hydrogen sulphide will be released to the atmosphere during power plant operation. H_2S concentrations in steam samples from the area are not dangerously high.

6 References

Armannsson. H, and Kristmannsdottir. H. (1992). Geothermal Environmental Impact, *Geothermics*, Vol. 21, No. 5/6, pp. 869-880.

Fotouhi, M. (1995). Geothermal Development in Sabalan, Iran, *World Geothermal Congress 1995*, Florence, Italy, pp. 191-196.

Bogie, I., Cartwright, A.J., Khosrawi, K., Talebi, B., and Sahabi, F. (2000). The Meshkinshahr geothermal prospect, Iran. *Proceedings World Geothermal Congress 2000*, Kyushu - Tohoku, Japan, pp. 997-1002.

Webster, J.G. (1995). Chemical impacts of geothermal development. In: Brown, K.L. (convenor), *Environmental aspects of geothermal development*. World Geothermal Congress 1995, IGA pre-congress course, Pisa, Italy, May 1995, 79-95.

Kestin, J., DiPippo, R., Khalifa, H.E., and Ryley, J., (editors) (1980). *Sourcebook on the production of electricity from geothermal energy*. U.S. Dept. of Energy, Washington, D.C., 997 pp.

Aspects of the quality - Environmental management system and cleaner production

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Abstract

Management is a significant factor in any business activity. It may be enhanced by the application of various management systems. These will help to obtain, organize, administrate, evaluate and control particulars: information, quality, environmental protection, health and safety and various resources (human, finance etc). Environmental management should embrace recent changes in the area of environmental protection, and be tailored to recent regulations in this field – entirely legal and economic, as well as take into use management systems that meet the requirements of the contemporary model for economic development. These changes are aimed at abandoning the conventional approach of environmental protection and replace it with sustainable development. The keys and the aims of Cleaner Productions are at present being implemented in various companies as a non-formalised environmental management system. This concept is suggested here as a proper model for practice where geothermal energy is used. Formalized environmental management system is also discussed. By showing the features and the power of CP this paper is a signal oriented to involve the awareness of top management of diverse Romanian companies.

***Keywords**: environmental management, management system, cleaner production, sustainable development*

1 Introduction

The effects of modern development forced us to think ‘integrated’. Sustainable development principles require that environment management policies and practices are not good by themselves but sould also integrate with all other environmental objectives, and with social and economic development objectives.

Environmental management comprising both the latest improvements in the sphere of environmental protection and implemented management systems should meet the requirements of the new model for economic development. This can be attained leaving the conventional approach to environmental protection using instead its sustainable development (Adamczyk, J., 2001). Shortly, we will recall what Sustainable Development means. It consists of continuous economic growth whilst at same time keeping the integrity of the triad: economy-society-environment. Sustainable Development is significant mainly at macroeconomic level (e.g. national or regional). This paper deals with enterprises as a Sustainable Development addressee. To implement Sustainable Development at a company level, it is necessary to understand the enterprise as a system and to integrate it as a unit whilst also developing environmental management.

Wind, geothermal water, solar energy etc. are some of the alternative energetic sources of energy, and at the same time considered to be renewable, economical and ecologic – and can imply the concept “sustainable”. But unfortunately still only exploited to a small degree in Romania (Mihai, A., 2003).

The following chart (Figure 1) shows the direct use of geothermal energy in Romania (Popovski, K. et al., 2000).

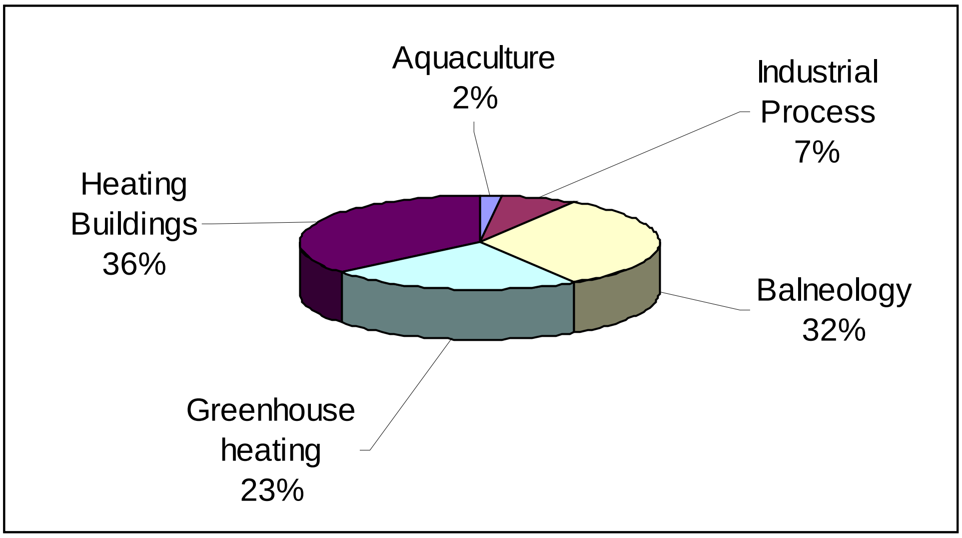

Figure 1: Direct use of geothermal energy in Romania.

Sustainable Development promotes protective strategies dealing with pollution prevention, aiming to maintain environmental quality (Riccio, V. A., 2001) and to diminish unrestrained use of resources (in particular the non-renewable resources). As a result this strategy is a balance with a broad-spectrum linking economic growth and the use of natural resources. It provides a new approach to a long-term development, as well as taking into account the environmental requirements, in contrast to a restrictive view of economic growth at any price.

Within this framework Cleaner Production (CP) assigns the same goals and settles on the measures indispensable for sustainable development. It shows the importance of reducing raw materials, energy consumption, and production of waste and pollution emissions (Adamczyk, J., 2001). The possibility is quite wide and cleaner production has been acclaimed to be one of those topics today that accommodates a significant spectrum of disciplines pull out from engineering, designing, sociologists, economists, politicians, and the civil society.

The conclusions of the Earth Summit have been incorporated in Agenda 21 at Rio de Janeiro, and imposed upon us to think ‘integrated’. That is part and parcel of the concept of sustainable development (SD).

The principles of sustainable development involve activating environmental management policies and practices. These are not sound by themselves but only if integrate with all other environmental objectives, and with social and economic development objectives. Those objectives were realized, and followed by development of strategies to make effective the objective of sustainable development.

The United Nations Environmental Programme (UNEP) adopted the concept of “Cleaner Production” (CP), while in industry it was modifed as Eco-efficiency. As defined, Cleaner Production constitutes the continuous application of an integrated preventive environmental strategy to processes, products, and services seeking to increase efficiency and reduce risks to humans and the environment.

When applied in a restricted manner, focusing on the processes in the existing establishments and facilities, CP is similar to other strategies such as pollution prevention, waste minimization, or cleaner technologies. They all contribute to emphasise elimination or reduction of waste and pollution at source. The validation of the outcome of processes in: the reduction of inputs, reduction of waste disposal costs and in a better product quality, bringing benefits (good image, as well as financial) to the company.

CP as one of the strategies for planning environmentally sustainable development has realised the development and growing importance of other strategies as part and parcel of itself, for instance:

- Focus on product design and development based on the life-cycle analysis (LCA);
- Focus on safer production (management of hazardous materials);
- Recognition of the role of management systems in introducing environmentally-sound technological change (EMS);
- Focus on creating an environment conducive to CP rather than interventions at the enterprise level.

The sphere of the Cleaner Production concept found a good niche in economic development. CP is considered as a means to achieve supplementary dialogue between policy-makers and industry. This movement is comprehensive across global boundaries in addressing global environmental issues. The CP concepts have significant implications in areas such as climate change and global warming because of its links to efficiency improvement in energy utilization.

In many countries conscientious companies have discovered that some benefits are obtainable through "going green". This can be achieved by enhancing the efficiency in production, by new efforts in adapting ecological, and finally improving company image.

Nowadays it is very common for the people in charge to see the advantages of following "green" goals. Actually, the companies must understand the competitive advantage to adopt more than minimum conformity with regulations. If we analyse the issues that influence companies to improve their environmental performance and adopt the environmental strategies we observe that these differ by level as: product, firm or even sector.

Notice the following groups of issues that are interrelated:

1) Official policies and regulations;
2) Financial matters;
3) Performance and competitiveness related issues;
4) Company's code of conduct;
5) Company's image in the community (social accountability).

Business activity can be established using various **management systems**. These will help to obtain, organise, administrate, evaluate and control particulars: information, quality, environmental protection, health and safety, various resources (human, finance etc.) (Riccio, V. A., 2001).

Operating within such concepts can be considered as an incentive to apply high quality management. Such procedures are also highly recommend for the Romanian geothermal sector! Because the geothermal sector is linked to the concept sustainable development and simultaneously to environment protection, we consider this type of energy resource a chance to develop a non-formalized system that is in fact Cleaner Production. Its benefits are very suitable to Romanian`s organisational culture.

2 Environmental management systems

Geothermal energy has been increasingly utilized in the last three decades all over the world and there was an increasing interest in exploiting this resource in various ways (direct use, electricity generation etc.)

It is clear that environmental concepts have changed from the early conventional and dogmatic meaning related to purifying the ecological sphere without regard to economic development, management topics, technological change, social needs and political arguments. There is no doubt that the new atmosphere surrounding environmental issues today is toward management, and organisation system.

The management systems can be carried out either autonomously or as an integrated management system that encompasses all the problems linked to the management of an organisation, whatever the type.

We can identify the management systems as:

- Formalised systems, based on some reference points as standards (standardised systems) or on laws; or
- Non-formalised systems (Adamczyk, J., 2001).

The former are management systems based on the standards series as ISO 9000, 14000 or 18000, and the latter point to Cleaner Production or TQM (www.iso14000.com).

Mostly used in Europe are two formalised environmental management systems (EMS):

- EMS based on BS 7750:1992 – Environmental Management and Audit Scheme-EMAS;
- EMS based on the ISO 14000 series.

The first one (EMAS), was approved by the Council of the European Union in 1993 (Council Regulation No. 1836/93). As other standards it is a deliberate scheme for industry. To join in Environmental Management and Audit Scheme a company must review its own environmental performance on a regular basis, which means to develop an environmental management system.

The goals of EMAS are:

- To initiate cleaner technologies;
- To reduce, avoid and remove all emissions prior to leaving the process;
- To diminish the use of natural resources.
- This system presumes that companies are fully responsible for their environmental impact. Consequently the company's main responsibilities include:
- To assume a favourable direction to have an environmental policy that will promote continuous improvements in its environmental performance;
- To develop an action plan of environmental area.
- To acquire efficient training programme to enhance employees' environmental awareness;
- To do Eco-audits;
- To put together available, relevant information to the community;
- This management system – EMAS, is approachable mainly to the companies that operate in industrial sectors. The method can, however, be adopted into other economic sectors such as distribution or public services.

The standards regarding EMAS were published in the years 1996-97. (ISO 14000), but a valuable experience had been gained by setting up earlier environmental management standards (BS 7750 and EMAS) and the quality management standard (ISO 9000).

ISO 14000 is a set of standards that deals with activities for environmental protection and pollution prevention. The most important standards of environmental management system, are based on the previous ISO 14000 series, namely:

- ISO 14001 – Environmental management systems. Specification and application guidelines. ISO 14001:1996 establish basis for procedures of environmental management system.
- ISO 14004 – Environmental management systems. General principles, systems and supporting techniques.

As a result these standards have been developed to be:

- Used by companies of any size and type;
- Adoptable for a range of geographic, cultural and social conditions.

Environmental Management System (EMS) is defined as:

"An element of a general management system that involves organisation chart, planning, responsibilities, codes of practice, procedures, processes and necessary means for developing, implementing, managing, reviewing and maintaining of environmental policy"(Beltramo, R. and Pandolfi, E., 2001).

For instance a management system promotes a continuous improvement in environmental performance by repeating the following activities in an iterative manner:

- To design and implement an environmental policy (environmental planning);
- To achieve the environmental objectives;
- To validate and to prevent (measurements and assessment of effects);
- To scan (permanent evaluation and control);
- To review management activity (continuous improvement of a system).

The experience shows clearly that the system requires on-going improvement in compliance with environmental performance, thus leading to improvement in an environmental management system.

Implementation of environmental management system by a company is valueable for their positive and truthful environmental approach, as well as for local communities. This is the reason why we strive to develop this approach in Romanian enterprises.

3 Non-formalised environmental management system

The Industry and Environment Programme Activity Centre at the United Nations Environmental Programme (UNEP) published the *Cleaner Production Programme* in Paris 1989. Cleaner Production is in fact a preventive environmental strategy based on this program.

UNEP defines Cleaner Production as: "The continuous application of integrated preventive environmental strategy to processes, products and services, to increase efficiency of production and services and reduce risks to humans and the environment".

The key of CP is to promote preventive strategy as opposed to traditional waste reduction approach. Accordingly, it involves progressive pollution prevention for manufacturing processes, as well as products to reduce environmental impacts during production and throughout the entire life cycle of the product. We stress the strategy of reduction of waste and emissions before they leave the process.

Cleaner Production facilitates the implementation of sustainable development at company level. It can also be understood as a non-formalised environmental management system. Its aims are:

- Improving of environmental quality of manufacturing processes and products;
- Employing cleaner technologies (energy and materials saving);
- Accessibility to training programmes for employees.
- Cutting off toxic raw materials and products;
- Carrying out technical solutions of high reliability;
- Encouraging efficiency by reducing the generation of waste;
- Implementing closed material cycles all through the life cycle (design, production, distribution, use and re-use of by-products);
- Supporting environmental products and technologies;
- Proximate recycling facilities for industrial waste;
- Decreasing all emissions and waste to the environment.

Cleaner Production can be included in integrated management systems (www.iso14000.com). The CP certification procedure involves a four-step procedure:

1. Application for Company's Cleaner Production Certificate (after completing the second level training on CP), along with required documentation.
2. Verification of application at the Cleaner Production Centre.
3. Evaluation of applications by the Qualification Committee.
4. Awarding to the company the Company's Cleaner Production Certificate.

This procedure is open to all companies operating in the industrial and service sectors that are prepared to implement the CP strategy as an environmental non-formalised management system. So far, in Romania there is no company reported having been awarded the Company's Cleaner Production Certificate.

The companies granted the Company's Cleaner Production Certificate are subject to on-site audit on a two years basis to check the proper function of their environmental management system based on Cleaner Production.

The case for more use of geothermal energy is a matter of energy liberalization policy, as well as ecological issues.

According to UE Romania must assume a new "Energy Policy", in fact this is already being prepared to be adopted within a few months, and this will take into consideration the geothermal potential. Accordingly, Romania expects a "boom" in this sector in the future. On this premise we try to draw attention to the application of the CP as a non-formalized management system, which in our opinion has a great potential for success.

At this stage Romania has a certain experience in the geothermal sector, but not as extensive as is its potential deserves, although it is a fact that geothermal energy is the most utilised of the renewable resource of Romania.

On the other hand, in the last two years numerous ecological accidents have been reported in Romania. These emphasise the responsibility of the companies to reflect and decide on how to avoid repetition of such accidents. It allows the communities, as well as the companies to achieve not only considerable environmental benefits but also large profits.

Generally, the programmes recommended for adoption are non-formalised environmental management systems.

An initiative must be taken to set up a Romanian Cleaner Production Centre based on an Agreement on Cleaner Production and Sustainable Development for Industry. The Romanian of Engineering Associations (AGIR) and the Technology Agency and the Romanian Centre for Environment (Testing and Certification) must be made aware of the Company's Cleaner Production Certificates. The companies that implemented Cleaner Production as an environmental management system can benefit in financial terms (Adamczyk, J., 2001).

We must take into consideration environmental performance driven access to favourable financial funding.

4 Conclusion

Cleaner Production is a strategy for shielding of the environment. It can be used as a non-formalised environmental management system on a company level. It is in our opinion highly appropriate for Romanian environment.

The benefits of the implementation of this system are the following:

- To the environment by reducing environmental impacts;
- To the company by additional savings and reduced operating costs.

Similar to the formalised environmental system, Cleaner Production involves the improvement of company's environmental performance. Experience indicates that companies involved in the Cleaner Production programmes achieved decreased waste and emissions; lesser utilization of raw materials and consumption of energy in addition to reduced in production costs and environmental fees. All these are achieved by continuous improvement through implementing the CP projects.

The costs related to operating a Cleaner Production project are paid back within a short time (months or years – depending on the project).

Many companies in European countries are developing corporate environmental strategies to reduce negative impacts on the ecosystem. This involves adopting environmental objectives' statements, conducting audits and monitoring performances. But we are not to forget that the ecosystem is unique for us. All of us, individuals and communities, small enterprises and multinational companies are responsible for preserving it for future generations.

5 References

Adamczyk, J. (2001). The Environmental Management of Enterprises in the Principles of Sustainable Development Realisation. In: Commodity Science in Global Quality Perspective. *Products - Technology, Quality and Environment, 2nd-8th September 2001, Maribor, Slovenia.*

Beltramo, R., Pandolfi, E. (2001). Environmental Certification of the Municipality of Cesana: A Cost/Benefit Analysis. In: Commodity Science in Global Quality Perspective. *Products - Technology, Quality and Environment", 2nd-8th September 2001, Maribor, Slovenia;*

Mihai, A. (2003). *In căutarea energiei de langa noi,* Revista "Banii noştrii", no. 23, 26 iunie 2003, pp.13-14, Bucureşti.

Popocski, K., Seibt, P., Cohut, I. (2000). *Geothermal energy in Europe. State - of - the – art and necessary actions and measures to accelerate the development.* International Summer School on Direct Application of Geothermal Energy, Publication No 19/2000, Skopje.

Riccio, V. A. (2001). OHSAS 18001: Occupational Health and Safety Management Systems Standard. In: Commodity Science in Global Quality Perspective. *Products - Technology, Quality and Environment, 2nd - 8th September 2001, Maribor, Slovenia;*

www.iso14000.com

Geothermal energy production and its environmental impact in Hungary

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Abstract

The utilization of geothermal energy has a long tradition in Hungary. When the present economic recession in the country ends in the near future, geothermal energy will surely play an increasing role in the energy supply. The paper shortly reviews the history of geothermal power use and discusses the present state of geothermal energy production in the country. Present power statistics as well as future plans are detailed.

Keywords: *steam outburst, direct utilization, balneology, reinjection.*

1 Introduction

Natural conditions in Hungary are very favorable for geothermal energy production and utilization. The anomalously high terrestrial heat flow (~0.09 W/m^2), the high geothermal gradient (~0.05 °C/m), and the vast expanses of deep aquifers form an important low-enthalpy geothermal resource.

Surface manifestations have been known since ancient times: thermal springs of Budapest had been used in the Roman Empire and also later in the medieval Hungarian Kingdom. The artificial exploration of thermal waters began with the activities of V. Zsigmondy, the legendary drilling engineer, who in 1877 drilled Europe's deepest well (971 m) in Budapest. Between the two World Wars, while prospecting for oil, huge thermal water reservoirs were discovered. Based on data of this exploration, Boldizsár (1944, 1956) recognized the high heat flux and geothermal gradient in the Pannonian Basin Figure 1. (at the end of the paper). He also constructed the world's first regional heat flow map of Hungary, (Boldizsar, 1958).

During the 50's and 60's hundreds of geothermal wells were drilled, mainly for agricultural utilization. The peak of geothermal activity was at the late 70's: a total of 525 geothermal wells were registered, the best 30 of them had a production temperature of more than 90^{o}C. Total thermal power capacity of these wells was 1,540 MW, but utilization was seasonal and the efficiency was rather low.

Today the utilization of geothermal energy has decreased substantially while the technical level and the efficiency of utilization has increased.

2 Geological background

The Pannonian basin is encircled by the Carpathian Mountains. The Earth's crust here is relatively thin (~25 km) due to sub-crustal erosion. The thinned crust had sunk isostatically and tertiary sediments mostly fill the basin thus formed. Pannonian sediments are multilayered, composed of sandy, shaly, and silty beds. Lower Pannonian sediments are mostly impermeable; the upper Pannonian and Quaternary formations contain vast porous, permeable sand and sandstone beds. The latter formed the upper Pannonian aquifer, which is the most important thermal water resource in Hungary.

The individual sandy layers have various thicknesses between 1 and 30 m. Their horizontal extension is not too large, but the sand lenses are interconnected forming a hydraulically unified system. This upper Pannonian aquifer has an area of 40,000 km^2, an average thickness of 200-300 m, a bulk porosity of 20-30%, and a permeability of 500-1,500 mD. The hot water reservoir has an almost uniform hydrostatic pressure distribution; local recharge or discharge can slightly modify this pattern.

Carbonate rocks of Triassic age having a secondary porosity is another type of geothermal reservoirs. These can be fractured or karstified rock masses with continuous recharge and important convection. About 20% of the Hungarian geothermal wells produce from such carbonate rock formations (Bobok, et al., 1984).

The existence of high enthalpy reservoirs was proved by a dramatic outburst of steam from the well Fábiánsebestyén in the Southeast of Hungary in 1985.

From an exploratory borehole over-pressured steam had blown out at a pressure of 360 bars and a temperature of 170°C. The mass flow rate was approximately 80 kg/s. The reservoir is a fractured dolomite formation at the depth of 3,700 m. The duration of the blowout was 47 days, and the wellhead pressure as well as the flow rate remained constant. The well was finally killed and the borehole cemented. At the present, feasibility studies are going on to determine the dimensions and the geothermal potential of the reservoir. Existence of other deep, high-enthalpy reservoirs in the Southeastern part of Hungary seems to be possible.

3 Production and utilization

Most Hungarian geothermal wells produce hot water from the upper Pannonian reservoir system. A smaller part of them taps the deep karstic aquifer. Up to the present a total of 643 wells have been drilled that produce thermal water warmer than 40°C. Out of this number, 36 wells are abandoned and 103 are temporarily closed.

A typical geothermal well in Hungary might have a depth between 1,000 and 2,100 m. The well completion is typical. A 13 3/8 in (349 mm) conductor casing is set at a depth of 50 m, in a 17 ½ in (444.5 mm) hole. It is followed by a surface casing of 9 5/8 in (244.5 mm) at 500-1,800 m in a 12 ¼ in (311.1 mm) hole.

Finally a 7 in (177.8 mm) liner runs in a 8 ½ in (215.9 mm) hole to a depth of 1,000-2,100 m with its top at 30-50 m above the shoe of the surface casing. Each string is cemented in such a manner that the casing-hole annulus is totally filled.

Typical mass flow rates of the upper Pannonian wells can range between 20 and 30 kg/s. The production temperatures vary regionally as shown in Table 1 (at the end of the paper). Undoubtedly, the best area is in the Southeast of Hungary near the cities Szeged, Szentes and Hódmezővásárhely (Figure 1).

Most Hungarian geothermal wells operate without any artificial production method. Reservoirs are driven by both compaction and dissolved gas. Submersible pumps are installed in only a few wells, in which the reservoir pressure has been depleted substantially.

Balneology use was the earliest way to utilize thermal waters. Worldknown spas are in Budapest, Bük, Hajdúszoboszló, Harkány, Hévíz, Sárvár, Zalakaros and many other places. Altogether 214 thermal wells and 120 natural springs produce water for sport and therapeutically purposes (Ottlik, 1988).

Agricultural use is the most important branch of geothermal energy utilization in Hungary. Greenhouses of more than 500,000 m^2, plastic tunnels and soil heating is supplied with the heat of thermal water. Technical level of these geothermal heating systems can be very different. There are well-designed systems and ones with sophisticated controll, where a dozen of geothermal wells supply a cascade of sub-systems: greenhouses, plastic tunnels and soil heating are connected in series (e.g. Szentes). In other cases a single well provides thermal water directly to greenhouses, and the discharged, still relatively hot water causes a low efficiency and environmental problems sometimes.

Animal husbandries are heated by thermal water in more than 50 cases at chicken, turkey, calf and pig farms. Low-temperature released waters supply fishponds near Szentes and Győr. The estimated thermal power applied in the field of agricultural utilization is about 120 MW.

District and space heating by geothermal energy was started near balneology centers. The first examples are some apartment houses and the Budapest Zoo in between the two World Wars. In the late 50's district heating projects were started in Southeast Hungary e.g. Szeged, Szentes, Makó, Hódmezővásárhely. At the present, 9,000 flats in nine cities are heated by thermal water; the estimated total thermal power is more than 38.7 MW. Simultaneously, thermal water is used as domestic water in the same district. The thermal power of the domestic water supply is about 12 MW.

It is a little known fact that since 1969, thermal water is used in the secondary oil production technology in the Algyő oilfield. Presently 7,000 m^3/s of hot water is reinjected to the oil reservoir for oil displacement. The utilized geothermal power during this secondary oil recovery technology is 15 MW.

Another application is that gathering pipes are heated by thermal water in the heavy oil-producing oilfield Sávoly in the Southwest of Hungary.

There is an unusual utilization of geothermal energy in the oilfield Nagylengyel. An artificial gas cap is formed above the depleted part of the oil reservoir. Natural gas with a high content of CO_2 (~81%) is produced, transported and reinjected to develop a gas cap in the formation. The technology operates without compressors; compressor power is replaced by the thermal lift between the production and reinjection wells. The higher the extracted geothermal heat from the produced gas, the stronger the thermal lift and the higher the gas mass flow rate, while the extracted heat is utilized, too. In this case the fluid carrying the geothermal energy is the CO_2 gas.

Some important data of Hungarian geothermal wells are summarized in Table 1. Wells are grouped on the basis of utilization and the ranges of wellhead temperature. In order to estimate the total thermal capacities some practical approximations had to be made, as the flow rates of individual wells were not always measured. They were obtained from well completion measurements at different times thus their compatibility is questionable.

The estimated thermal capacity of any well was obtained from:

$$\mathbf{P} = \dot{\mathbf{m}}\mathbf{c}\left(\mathbf{T}_{\mathbf{wh}} - \mathbf{T}_{\mathbf{s}}\right) \tag{1}$$

Where $\dot{m}$ is the mass flow rate, c is the heat capacity of the water, T_{wh} is the wellhead temperature, T_s the yearly average temperature at the surface of 10,5°C.

These values are summarized for several temperature ranges and types of utilization. Averages are obtained by dividing the total amount by the number of wells.

The total available thermal capacity of Hungarian geothermal wells was found to be approximately 1,201 MW. Since the utilized temperature difference is substantially lower than (T_{wh}-T_s), the effectively utilized thermal capacity can be estimated at a level of 325 MW only. This gives an assumed load factor of 27%.

4 Environmental impact of geothermal energy production

Any geothermal activity needs to deal with the significant impacts on the surrounding physical, biological and socio-economic environment. The major concerns are: reservoir pressure decrease, pollution of fresh groundwater and the waterways on the surface thermal effects, emission of dissolved gases, ground subsidence and noise.

Hungarian geothermal reservoirs may be sedimentary, sandy or karstified limestone aquifers. Reservoir pressure decreasing occurs mainly in the sandstone aquifers. Some fields have been exploited more than seventy years, thus the piesometric head of the reservoir has subsided almost 70 m in the Hajdúszoboszló field, the production can be sustained by artificial lifting methods only. The supply of the carbonate aquifers in Western Hungary seems to be unexhausted.

The freshwater aquifers are located above the geothermal reservoirs. Thus the drilling operations can be hazardous. During normal drilling situations downhole drilling fluids are usually the greatest potential threat to the environment. In the case of oil-based mud the cuttings also present a problem. There is a variety of chemicals that are toxic e.g. chromates. During the well completion operations acid jobs can be hazardous.

Nevertheless a blowout can be the greatest environmental hazard while drilling. The most serious blowout of a geothermal well occurred in Fabiánsebestyén, Eastern Hungary in 1985. The mass flow rate was 80 kg/s having an extreme high salinity and the small creek Kórógy lost all kinds of life. The noise level during the outburst reached the 125 dB.

The salinity of the Hungarian geothermal brines is comparable to that of seawater. The water of the upper Pannonian aquifer contains mainly sodium or calcium carbonate; the brine in the lower Pannonian formations contains mainly sodium chloride. The environmental impact of the released thermal waters can be serious. The wells of Bükkszék spa produce more than 1 m^3/min of very saline water; its solved solids are 24.000 mg/l. This means that 14.000 t/year are polluting the small Tarna River.

Thermal waters contain dissolved gases, mainly methane, nitrogen, carbon dioxide and hydrogen sulphide. Methane is separated from the water and utilized in auxiliary equipment. The H_2S is more harmful because of its acid, corrosive nature. This may lead to perforation of the casing and damaging of the cement sheet as well. Fortunately H_2S is present only in a few Hungarian geothermal wells (e.g. Mezőkövesd).

Most problems of environmental pollution can be avoided by means of reinjection of the heat-depleted thermal water to the aquifer. The reinjection is very useful for some other reasons too. The pressure support of the reservoir can be provided, the enthalpy of the rock matrix becomes exploitable and the surface ground subsidence can also be avoided.

Reinjection is a routine technology in the petroleum industry. It is relatively simple to inject hydraulically into karstic carbonate aquifers, but short-circuiting the injected fluid to the production wells introduces a serious risk. It is a more complex procedure into a sandstone reservoir as the necessary injection pressure can substantially increase within a relatively short time. The permeability is decreased because of formation damage. It can occur because of clay swelling, pore space blocking by fine particles or precipitation of dissolved solids due to the mixing of injected water and the formation water or due to temperature changes. There are many efforts ongoing to solve these problems: theoretical analyses, numerical simulation, in the laboratory and by in-situ experiments. Successful industrial experiments were carried out in the city

Hódmezővárhely. The most important experiences are: a suitable choice of place and depth of the injection well, correctly designed and completed well, good hydraulic performance, very slow transient performance processes (pressure, temperature, flow rate).

Some Hungarian thermal water contains toxic materials: arsenic, beryllium, chromium, organic materials (pesticides) and pathogenic organisms, bacteria. If released to the natural waterways, toxic materials and the relative warm wastewaters harm the wildlife of these waters.

5 Future Developments

The Hungarian economy is starting to develop after some years of stagnation. There is no question that geothermal energy will continue to be an important resource base of this process. Environmental advantages of geothermal energy seem to be especially important, because CO_2 emissions in Hungary must be decreased by 4 million metric tons per year (Kyoto Protocol?).

Since 1995, three important projects have been started.

Feasibility studies are in the making to determine the conditions of electric power generation in the Southeast of Hungary, at the Békés basin. This is the site where high enthalpy geopressurized water has been found in Fábiánsebestyén and Nagyszénás. There seem to be serious technical problems due to the high pressure (360 bars at the wellhead) and the strongly saline water.

Two small-scale electric power generation plants are being planned using the organic Rankine cycle with 100^{o}C water in the Southern and Southwestern parts of the country. These projects aim at a complex utilization: the small modular prefabricated power plant may be the attractive element of the system. Direct heat utilization for district heating and greenhouses can make the project economically viable.

Acknowledgments

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6 References

Bobok, E., Navratil, L. and Takacs, G. (1984). Present Status of Geothermal Resource Assessment in Hungary. *Geothermal Resources Council*. Trans. Vol. 8, pp. 403-7.

Bobok, E., Jobbik, A. and Takács, G. (1998). Present stauts of geothermal energy utilization in Hungary. *Bulletins of Geothermal Resources Council*. Vol. 22, pp. 211-214.

Bobok, E., Tóth, A. (2000). Temperature Distribution in a Double Function Production Reinjection Geothermal Well. *Geothermal Resources Council*. Trans. Vol. 24, pp. 555-559.

Boldizsár, T. (1944). Geothermal Conditions of Pecsbanyatelep Coalmines (in Hungarian). *BKKL* Vol. 19-20, pp. 280-87.

Boldizsar, T. (1956). Terrestial Heat Flow in Hungary. *Geophisica Pura e Applicata*. Milano, Italy, Vol. 34, pp. 66-70.

Boldizsar, T. (1958). New Terrestial Heat Flow Values from Hungary. *Geophisica Pura e Applicata*. Milano, Italy, Vol. 39, pp. 120-5.

Ottlik, P. (1988). Geothermal Experience in Hungary. *Geothermics*. Vol. 17, pp. 531-35.

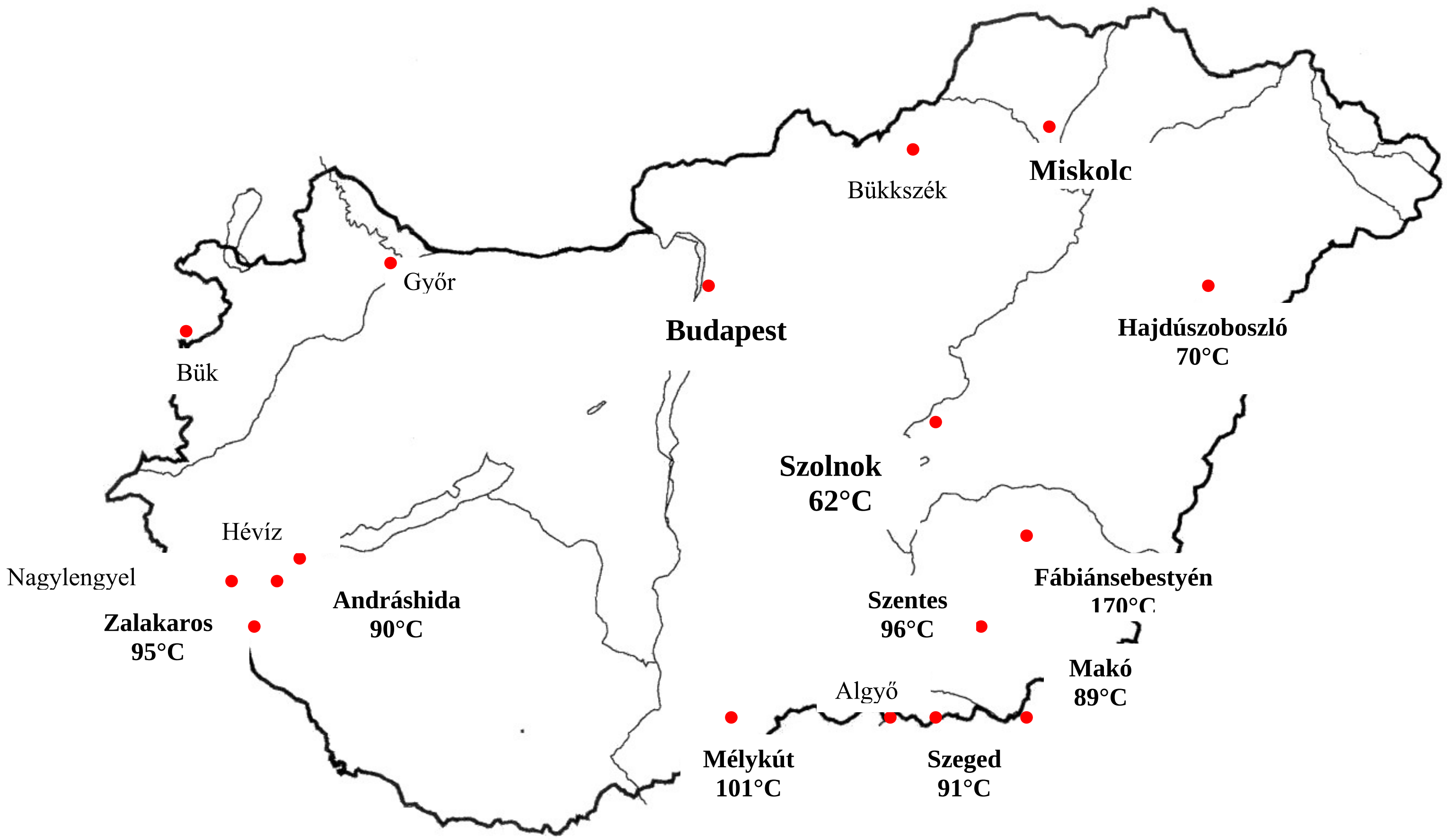

Figure 1:Wellhead temperature regions of Hungarian Upper Pannonian water wells.

Table 1: Hungarian geothermal well data.

Utilization		Temperature Range						
		40-50°C	50-60°C	60-70°C	70-80°C	80-90°C	90-100°C	>100°C
Number of Wells	Agricultural	14	14	15	18	28	20	1
	Industrial	13	14	14	4	3	1	0
	District Heating	2	2	1	3	1	5	1
	Multi Purpose	17	12	28	14	1	0	0
	Balneological	89	39	29	8	3	4	0
Total Mass Flow Rate, kg/s		659	665	955	841	696	811	62
Mass Flow Rate per Well, kg/s		14.32	15.83	16.47	21.56	21.09	23.85	31.00
Total Thermal Capacity, MW		95.19	125.90	219.92	228.88	215.65	292.03	23.62
Thermal Capacity per Well, MW		2.07	2.99	4.87	4.87	6.53	8.59	11.81

Practical methods of minimizing or mitigating environmental effects from integrated geothermal developments; recent examples from New Zealand

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Abstract

Monitoring of the environmental effects of geothermal resource utilisation in New Zealand has confirmed the benefits of appropriate management in terms of production and reinjection strategies. Such strategies can minimise, reverse or mitigate the effects on surface thermal activity. This applies to direct use of low enthalpy resources as well as integrated use of high enthalpy resources. At Rotokawa, a strategy of deep production and total shallow reinjection for an integrated steam turbine/binary power plant has resulted in a gradual enhancement of several chloride springs, with no significant detrimental effects. At Wairakei, less than 50% of the waste hot water is reinjected, but several users are able to take advantage of the separated hot water in a way that mitigates for the historic loss of geysers at Wairakei Valley. These include tourist facilities based on a geothermally-heated prawn farm, and hot stream restoration with an artificial geyser/silica terrace that was developed by local Maori. At Mokai, several years of production history from a binary/steam turbine, with shallow reinjection of brine and steam condensate, has not caused any significant environment effects on surface thermal features. At Rotorua, management of extraction and reinjection from numerous domestic bores has achieved a significant recovery in hot spring and geyser activity. Users of many other hot spring areas in New Zealand are also managed by application of regulatory control through policies and plans under the Resource Management Act. These plans are presently undergoing a process of industry-wide review and improvement, by addressing changes in the philosophy of environmental management.

Keywords: *New Zealand, environmental, Rotokawa, Wairakei, Rotorua, Mokai.*

1 Introduction

New Zealand, like Iceland, is a country that has pioneered the sustainable use of its indigenous geothermal resources, reducing the need to burn hydrocarbons, and thereby reducing CO_2 emissions. With declining natural gas reserves, N.Z. energy planners are increasingly looking to fill the gap in future energy supplies by increased geothermal utilisation, as a renewable energy source, rather than using coal. A key factor in achieving this goal is the management of environmental effects, through appropriate regulation. More practical methods of minimizing or mitigating such effects are needed, along with more integrated or “cascaded” uses, and examples of more-efficient and economic direct geothermal energy use, to encourage greater uptake of geothermal technology. Examples of such methods from recent geothermal developments in New Zealand (summarised in Thain and Dunstall, 2000) are given in this paper, together with a discussion of appropriate and practical geothermal system management policies.

2 Rotokawa

An integrated steam turbine and binary power plant at Rotokawa, with an installed capacity of about 25 MWe has been operating successfully since July 1997, utilizing 2 production and 3 reinjection wells. Confidence in the resource performance led to an increase in December 2002 of 5 MWe, and plans for a second stage (nominally 30 MWe) are well advanced. A strategy of deep production (1500-2500 m) and shallow injection (300-600 m) was adopted for the first stage based on limited vertical connection between these aquifers. Over 5 years, 20 Mtonnes has been produced. Full reinjection is practised, including steam condensate, but excluding non-condensable gases. Gravity and pressure monitoring has shown that the injection aquifer (originally 2-phase) has been re-saturating within a few hundred meters of the injection wells, and pressures have risen by a few bars. Production wells have shown no significant changes in enthalpy or output, although RK9 was shut down after problems in 2002-3 associated with casing damage. Deep pressures have declined by at least 12 bars.

Environmental monitoring, established under conditions associated with the original resource consent, has included gases (H_2S, Hg), groundwater, and surface thermal features. Over the 5 years, there have been no significant changes in gas emissions or ground water levels. Groundwater chemical monitoring has shown a gradual rise in chloride concentration of up to 5% per year. Average chloride flux, through surface discharges into the Parariki Stream, has also increased by about 8% per year, but remains within the wide range of natural fluctuations (+/-50%) caused by rainfall on Lake Rotokawa, the source of the stream. In December 2001, a new high-chloride discharging spring (“Ed’s spring”) appeared from an area of near-boiling hot pools about 300m southeast of the power station. This feature now has occasional periods of vigorous boiling and eruption, discharges about 2 l/s, deposits sinter, and is evolving an associated thermophilic ecosystem. Although its chemistry is distinctly different from that of the reinjected fluid, precluding the possibility of a direct fluid connection, the small pressure rise that stimulated its activity is probably related to increased pressures in the underlying injection aquifer. It is therefore considered an indirect effect of development, and an enhancement to the thermal feature environment at Rotokawa.

3 Mokai

At Mokai, a nominal 57 MWe integrated power plant (steam turbine and binary), began commercial operation in February 2000. Full reinjection (excluding gases) is also practised here, with production from 4 deep wells and injection into 2 shallow wells. Changes in the reservoir pressures have generally been as expected, and there has been no indication of premature reinjection returns or unexpected chemical changes. Improvements in direct use include a large glasshouse-heating project currently under construction.

A comprehensive environmental monitoring programme covering springs, streams, and groundwater, has shown no significant post-production changes to water chemistry due to abstraction or injection of fluids at Mokai. Temperatures and water levels in groundwater monitor bores have also shown no changes that could be attributed to reservoir pressure drawdown or reinjection returns. Monitored ecosystems, consisting of rare thermal ferns and aquatic invertebrates associated with hot spring discharges, have not been affected. A small increase in thermal activity was observed in March 2000 associated with a line of existing thermal craters near the reinjection area. These craters contain steam-heated mud pools. The increase in steam activity was local, and did not directly include reinjected chloride fluid, but may have been related to a local pressure increase in the underlying aquifer. A nearby hot spring used for bathing was not affected. Within a year, the expanded area of steam-heated ground was populated by thermally tolerant plants such as club mosses, leading to an overall enhancement of the local thermal ecosystem. The only adverse effect was the cost of re-fencing the thermal area to keep out stock.

4 Wairakei

Wairakei Power Station has been producing about 160 MWe for 45 years. Contact Energy is presently applying for renewal of Resource Consents to maintain full production for a further 25 years. In recent years, changes have included the purchase by Contact of the nearby 55 MWe Poihipi Road Power Station. This generates, from steam wells, a load-following output averaging 24 MWe (limited by Consents since 1997, to avoid interference). Historically, all the separated liquid at Wairakei was discharged into the Waikato River, but since 1997, 30-50% (about 13MT/yr) has been reinjected. This has caused a small (2 bar) pressure rise in the production area, and future plans are to reinject more fluid outside the resistivity boundary of the field to avoid premature cooling. A 15 MWe binary plant proposal to extract more energy from 130^{o}C reinjection fluids is currently undergoing detailed commercial consideration. Small quantities of steam are provided to Wairakei businesses for direct heating purposes. These include the Geotherm Exports orchid glasshouse at Poihipi, the Wairakei Resort Hotel (7.45 kT/yr), and Century Resources /IGNS offices. Increased direct use of waste hot water for tourist facilities has also been achieved at the nearby Prawn Farm (0.71 MT/yr) and the Wairakei Terraces (1.46 MT/yr), where new artificial silica terraces, a geyser, and alum pools have been constructed. The adjacent Te Kiri O Hinekai thermal stream, with its historic “Honeymoon Pool”, has been re-established by diverting hot water from the main Wairakei drain. In conjunction with a Maori ‘living village’ and animal park, this is now a popular tourist facility. “Craters of the Moon” (Karapiti) is another very popular Wairakei Tourist Park facility, freely accessible to the public and maintained by the Department of Conservation. This steam-heated thermal area expanded dramatically during the early days of Wairakei pressure drawdown, when boiling created more upwardly-mobile steam. The heat output increased 10 fold, from 40 MW in 1952, and then settled to a relatively stable 200 MW. Ongoing intermittent hydrothermal eruptions (about 1/yr) are an exciting reminder of the natural transience of these steam-heated features. All these environmental and amenity benefits are considered to partially mitigate for historic adverse effects, such as the loss of geysers at Wairakei Geyser Valley and Spa Park (Taupo), when reservoir pressures initially declined in the 1960s. Other environmental effects at Wairakei have included gradual subsidence (broad bowls up to 15m deep beneath the Wairakei Stream, and 3m at Spa Hotel, Taupo), and local drainage of groundwater aquifers in the Eastern Borefield (1980s) and Alum Lakes area (since 1997). These effects have been due to a steady decline (by over 60%) in the shallow steam zone pressures, which has caused drainage of some overlying compressible mudstones, and induced down-flows of groundwater through local fractures. The main consequences have included remedial adjustments to fixed structures such as pipelines, drains and transmission lines to accommodate strain accumulation, and some cooling and dilution of deep production fluids by down-flowing acidic groundwater.

5 Rotorua

Records of thermal feature changes at Rotorua go back more than 150 years. They have demonstrated a high degree of natural variability in geyser and hot spring discharges (Scott and Cody, 2000). Exploitation of the thermal aquifer beneath the city started in the 1920s but greatly expanded between 1967 and 1986. Natural surface activity declined noticeably from the 1970s, and despite the previous evidence for natural variability, this decline was attributed to pressure drawdown from excessive fluid extraction. To counteract this, the government implemented in 1987 a control program that included closures of many wells (within 1.5 km of the centre of Whakarewarewa thermal area), and punitive royalty charges with provisions to encourage reinjection. These measures have been very successful in reversing the decline. Aquifer water levels have risen by 2-3 m, and many thermal features have been rejuvenated. Spring discharge flows have increased, and geysers have resumed stronger or longer duration eruptions. The pressure rise has also stimulated some recent hydrothermal eruptions in Kuirau Park, including a dormant vent that had previously been buried and built upon.

6 Regulatory control through geothermal plans

The environmental management of geothermal resources in New Zealand is administered by Regional Councils under the Resource Management Act. The Councils have formulated geothermal policies and plans, and, in the case of Waikato Region, these are presently under review. The definition and use of terms in these documents can be a source of debate and confusion. Examples, in connection with thermal features, are: “significant”, “sinter deposition”, “protection/preservation”, “natural/artificial”, “interference”, and “reversible /recoverable”. In connection with resource use, issues such as “renewable/sustainable utilisation” and “adverse/beneficial effects” also cause concern. The following comments on these issues are intended to provide useful and practical guidance for managing such environmental concerns.

6.1 Significant or sinter depositing features

It is usually accepted that there will be *some* risk of losses of individual features in systems identified for development. The purpose of ranking surface geothermal features in a region is to identify, for protection, geothermal systems exhibiting “outstanding” features that could be seriously affected by resource utilisation, and to ensure that a representative range of features is protected. However, it is inappropriate to apply the term “significant” to *all* identified natural geothermal features. Some thermal areas are many square kilometres in size, containing dispersed weak steam vents and large portions of non-thermal ground. Application of rules to such features could place undue constraints on the owners of these properties.

The term “sinter depositing” can also be used inappropriately with regard to a means of classifying or ranking thermal features. It apparently provides a means of visually identifying springs that could be susceptible to deep reservoir pressure drawdown associated with fluid extraction. Highly mineralised hot springs and geysers, feeding from deep reservoir fluids, often do deposit large quantities of silica sinter. However, the term “sinter” covers a wide range of deposits that form in springs (e.g. amorphous silica, travertine, calcite) and these are not all diagnostic of a direct plumbing connection between the spring and a high temperature geothermal reservoir. Sinters can also form from acidic steam-heated groundwater, which is not directly connected to deep reservoir liquid. Indeed, deep pressure drawdown is likely to enhance such features through additional upward steam flow. Therefore, the term “sinter depositing” should not be used to rank features for protection on the basis of resilience or rarity, because the term is simply not a useful discriminator and hot spring “sinters”, in the broadest definition of the term, are relatively common.

6.2 Protection/preservation

Management plans are sometimes premised by an underlying simplistic assumption that protection of natural geothermal features from change is, a) achievable, and b) guaranteed by excluding large-scale resource utilisation. However, observations show that nearly all geothermal features vary naturally (cyclically, randomly or intermittently) over timescales that can range from minutes to decades. It is not possible to guarantee their *preservation* in terms of maintaining a constant discharge temperature, flowrate or heatflow. Furthermore, recent experience (e.g. at Rotokawa and Mokai) has demonstrated that large-scale resource development does not necessarily result in loss of surface geothermal features. Indeed, with innovative resource management strategies (e.g. shallow injection, when appropriate) discharge from thermal features of many types can often be enhanced rather than reduced. The principal aim of geothermal management plans and policies should be to encourage efficient integrated use, while protecting the *diversity* of thermal features in the region (rather than specific individual features). This can be achieved (as proposed in the Waikato Region) by designating several geothermal systems to remain undeveloped (except for tourism facilities), as a kind of environmental insurance policy. However, properly managed development of all other geothermal resources for sustainable energy utilisation should be facilitated, with reasonable conditions imposed, in a balanced manner. Conditions should encourage enhancement of *any* type of surface thermal feature, by way of mitigation for unavoidable and adverse changes to other thermal features. This replicates the sort of variation behaviour that occurs naturally. Geysers and fumaroles, for example, are both naturally transient features. So newly created steam vents compensate for the loss of chloride springs, or vice-versa.

An issue commonly faced by direct users of low enthalpy resources is the “buffer zone” distance from significant thermal features, and other users, that a new user should respect in order to avoid interference effects. A distance of 20 m is considered reasonable in New Zealand for relatively small amounts of fluid extraction and injection (<1 kg/s). There should also be some regulatory incentive for the use of down-hole heat exchangers or ground-source heat pumps, rather than direct fluid extraction, because of the relative benefit to the environment, in that pressure interference is no longer an issue.

6.3 Natural/artificial

A common misperception regarding geothermal features is to regard them in ‘black-and-white’ terms as being either natural or artificial. This can lead to a pedantic application of rules designed to preserve natural features and discourage artificial features. In fact, there is a continuum of natural to human influences on thermal features (that is, many ‘shades-of- grey’). At one end of the spectrum, for example, the artificial geyser and silica terrace at Wairakei Terraces, which uses water from the reinjection pipeline, is indisputably *man-made.* The Lady Knox “geyser” at Waiotapu is *artificial,* in the sense of being stimulated daily by soap to erupt through a hidden pipe (installed in 1906), but has a very natural appearance and is highly valued. The “Healy 2 Bore” at Tokaanu is another example of a geysering spring, sinter-cone and terraces, with an associated highly valued ecosystem, that has evolved over 50 years from an abandoned bore. Although it was initially created by *human activity,* it now appears totally natural. The “Craters of the Moon” thermal area at Wairakei has always existed as a natural feature, but the intensity of thermal activity increased dramatically in response to Wairakei pressure drawdown, so it has been *indirectly affected* by human activity. The same could be said of existing geysers and discharging hot springs at Orakei-Korako that are *indirectly* supported by raised groundwater levels in response to the artificial filling of Lake Ohakuri in 1961. Several hydrothermal eruptions at Kuirau Park, Rotorua, were stimulated by pressure recovery related to the bore closure programme. These examples illustrate the point that rules need to be made flexible enough to cater for a wide spectrum of scenarios when considering the desirability of human influences on geothermal features.

6.4 Reversible/recoverable development effects

Many of the past assumptions of the likely effects from *new*, large-scale geothermal energy developments are outdated. The modern philosophy is to develop new fields in stages, big enough to create measurable effects on the resource, but not big enough to create large irreversible effects on surface thermal features or resource sustainability. Stages are typically about 5 years in duration, and up to 2 times the previous level of utilisation. Monitoring, and predictions based on regularly updated reservoir models, provides confidence of the probable effects (out to about 50 years) for each stage. Hence the risks are minimised for the regulator, the owner, the developer, and the investor. Historically, of the 7 geothermal fields developed for power generation in N.Z., only 2 of the earlier developments have directly resulted in significant loss of surface geothermal features. At Rotorua, a change of bore management policy to raise pressure has caused a significant recovery of geysers and springs. This demonstrates that such features *can* be recovered, and are not necessarily lost irretrievably when pressures decline.

6.5 Sustainable/renewable

An issue for sustainable utilisation is the duration of “reasonably foreseeable use” (eg 1-4 generations, or 25-100 years). Most reservoir modellers would not be confident about predicting geothermal reservoir behaviour beyond about 50 years, and this is probably a reasonable period to choose. Within that time, it is expected that technological advances will have provided access to far greater heat resources deeper within the earths crust. Furthermore, a long-term strategy of cyclic use of existing geothermal reservoirs would have the advantage of encouraging natural recharge of fluids and heat during a “fallow” period of recovery in between periods of heat extraction. Thus the concepts of renewable and sustainable geothermal energy use can be upheld whilst undertaking cyclic extraction of heat by drawing down reservoir pressure. This is analogous to hydroelectric lake storage management, but on a longer scale.

7 Conclusions

When considering the induced effects of geothermal development on the environment, a balanced view is to weigh up the adverse effects against the beneficial effects to determine a net effect that may be mitigated for. Examples of beneficial effects that are often overlooked include: subsidence induced wetlands; thermal ecosystems associated with increased areas of steam-heated ground and surface-disposal of hot water; and reduced gas emissions relative to fossil fuel alternatives. Geothermal plans should recognize the modern approach to utilisation of new resources, by allowing staged development of all but a few “protected” systems, in a manner that minimizes risk, and allows for recovery by adjustments to field management. Optimum size increments should be established by considering the resource knowledge acquired during each stage. Monitoring can provide early warning of adverse effects, and remedial measures can be implemented. If adverse effects on thermal features occur, they can often be reversed by locally managing the subsurface pressures.

8 References

Scott, B.J., Cody, A.D. (2000). Response of the Rotorua geothermal system to exploitation and varying management regimes. *Geothermics 29*, 539-556.

Thain, I.A., Dunstall, M. (2000). 1995-2000 *Update report on the existing and planned use of geothermal energy for electricity generation and direct use in New Zealand*. Proc.World Geothermal Congress 2000, Kyushu-Tohuku, Japan, 481-489.

Regulatory framework and preparation of geothermal power plants in Iceland – practical experience and obstacles

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Abstract

The regulatory framework in Iceland regarding environmental impact assessment and necessary permits must be taken into account at different stages of planning and preparing geothermal power plants. Before deciding on exploitation the next stage following recognition of a feasible geothermal area is the drilling of exploration wells to investigate and model the capacity of the geothermal resources. In some areas the developer must carry out an EIA on exploratory drilling before necessary permits are granted. An EIA is always required before permits are granted for construction of a new geothermal power plant. A study of comparable exploratory drilling projects in three geothermal areas in Iceland reveals great differences in how long it takes developers to obtain the necessary permits. In one case the developer’s choice of drill site was not accepted after two EIA processes. Another project was accepted following an EIA but has not yet been granted necessary permits to start drilling. At the third location permits have been granted for the drilling of seven exploration wells without an EIA being required. A definitive national policy and plan on utilization in geothermal areas would support developers in planning future geothermal power plants and prevent costly investigations during the exploratory stages if they are unlikely to lead to exploitation.

***Keywords**: geothermal, exploration, utilisation, EIA, permits, policy.*

1 Introduction

In recent years there has been a growing interest in Iceland in the exploration and exploitation of high temperature geothermal energy as a clean and renewable energy source. The national policy is to increase use of domestic energy sources, in real terms and in proportion to imported fossil fuel and by the year 2000 the proportion of renewable energy had reached 70% of Iceland's total energy budget (Ministry for the Environment 2002).

The planning of a geothermal power plant can be subject to a wide range of legislation. In some cases this can lead to a complicated and long-term process of permit applications, environmental studies and development planning before consent for the project is granted.

In Iceland environmental impact assessment (EIA) has been carried out on the drilling of exploration wells, geothermal power plants, and extensions of such projects. Comparison of these projects generates valuable information for future planning. Official handling of permit applications, environmental assessment plans and EIA of comparable geothermal projects can vary greatly and obtaining consent for similar geothermal projects has been known to take anything from a few months to a couple of years. The results of this study will hopefully be an aid to future developers planning research and utilisation of high temperature geothermal resources in Iceland.

2 Legal framework

It is impossible to cover the whole legal framework in this paper. The aim is to give an idea of the Icelandic regulatory system regarding permits and environmental aspects and how this must be taken into account when planning and preparing geothermal projects.

2.1 Icelandic legislation

The following is a list of laws (Icelandic Parliament 2003) that primarily concern geothermal project development in Iceland:

- ***Act on Research and Use of Underground Resources No. 57/1998:*** According to this act the developer must apply for an exploration permit before starting further research and drilling of exploration wells. The developer must apply for an utilisation permit before starting construction of a power plant. Developers earn priority to utilisation permits by obtaining exploration permits in geothermal areas.
- ***Energy Act No. 65/2003:*** Developers planning to exploit geothermal resources for producing more than 1 MW electric power must apply for operation permits according to this act.
- ***Environmental Impact Assessment Act No. 106/2000:*** According to this act projects that may have significant effects on the environment are subject to EIA. Developers are responsible for the EIA and bear the cost. The Planning Agency delivers a ruling on the EIA and decides whether a project can be accepted or is opposed.
- ***Planning and Building Act No. 73/1997:*** According to this act to obtain development permits substantial development projects shall be in accordance with development plans and decisions on environmental impact assessment.
- ***Nature Conservation Act No. 44/1999:*** Certain types of landscape and habitats enjoy special protection according to this act. Amongst these are hot springs and other thermal sources, surface geothermal deposits, volcanic craters and lava fields – all of which are frequent features in high temperature geothermal areas.

2.2 Planning a geothermal project

Before starting any planning of research or development the geothermal area will already have been recognized by preliminary field assessment and research, including geological mapping and sampling. The regulatory framework for planning exploration by drilling and exploitation of geothermal resources is shown as a flowchart in Figure 1. The main stages of permit application before construction of a geothermal power plant can start are as follows:

The first stage is to apply for an exploration permit in order that drilling can begin. This stage is very important when investigating geothermal resources for future exploitation. The Planning Agency decides whether an EIA is required. A development permit for drilling can be issued when the Planning Agency has reached a decision and accepted the proposed project.

New geothermal power plants are always subject to an EIA in Iceland. If the developer decides on further development following a feasibility study the next stage is conducting an EIA. Development permits, utilisation permits and permits for operation of the power plant can be issued when the project has been accepted by the Planning Agency.

There has been a shortage of plans and official policy on what areas to utilise or whether they should be protected. A proposed Master Plan (Rammaáætlun 2003) for the utilization of hydro and geothermal energy resources is currently being prepared. A report on the first stage is expected to be made public late summer 2003.

3 Experience and obstacles

The time it takes to obtain consent from the authorities depends not only on official policy. Other determining factors are what plans already exist on development and nature conservation in the area as well as what environmental information is available. In some cases plans must be changed or new plans prepared. Potential geothermal areas are often located in landscapes that are protected by law. Preparation of comparable geothermal projects in similar areas can take different courses when the authorities make their decisions.

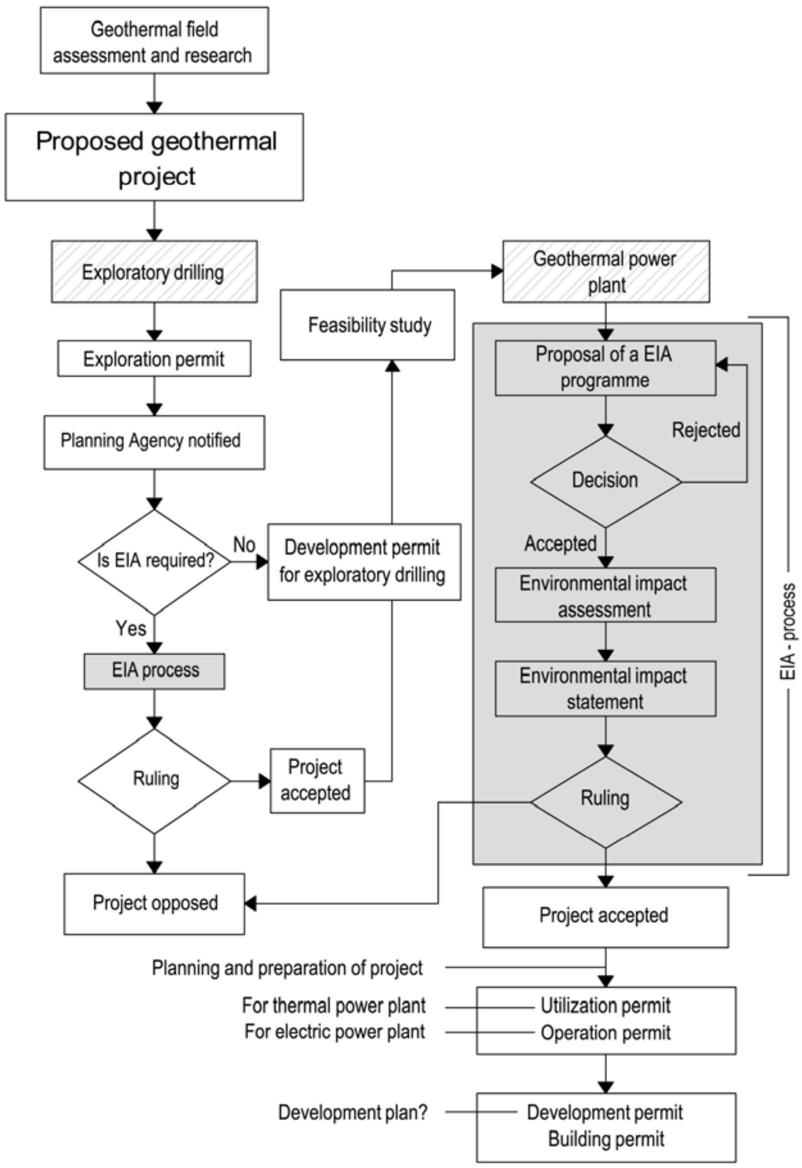

Figure 1: Flowchart on regulatory framework in Iceland.

3.1 Environmental impact assessment

The developer himself pays for most of the research on the geothermal resources in Iceland and he is also responsible for the EIA and collecting necessary environmental data. In many other countries most of the data the developer or his consultants need in order to carry out an EIA is easily obtained from official databases.

It is impossible to plan and prepare a geothermal power plant without the drilling of exploration wells, as this is necessary for further research and modelling on the capacity of the geothermal resources. Decisions on the feasibility of exploitation are based on the results. It can be difficult to assess the environmental impact of exploitation at the exploratory stage because of the authorities' demand for detailed information from the developer. At certain locations requirements for an EIA of the exploratory stage as well as exploitation leads to a repeated EIA process with extra expenses and delayed project development. In most cases the developer is not ready to present an EIA of both stages in the same environmental report (EIS), because the information gathered during the exploratory stage is required for assessing the effects of exploitation.

3.2 Geothermal projects

The object of our study was the official handling of proposed geothermal projects in eleven high temperature geothermal areas in Iceland (Figure 2) (projects prior to enforcement of the Icelandic EIA act in 1993 not included). Examples consisted of exploration permit application (Ministry of Industry and Commerce 2003), notification of projects for decision on EIA requirements, EIA programmes and EIA reports (Planning Agency 2003). Comparison of these cases reveals the main issues in the authorities' opinions on environmental effects of geothermal projects. The following issues are considered to affect their decisions on whether projects should require an EIA:

- Geographical location
- Geology and landscape
- Whether the area is exploited
- Relation to protected areas
- Recreational attraction
- Existing development plan

Projects of exploratory drilling in three geothermal areas are discussed in detail in the following sections: Krafla in NE-Iceland (VGK and Orkustofnun 2002) and Grændalur (VGK, Orkustofnun and Hönnun, 2001) and Hellisheidi, both in SW-Iceland (VGK 2002, 2003). The first project has been accepted after an EIA was carried out, but not all necessary permits have been granted. The second project was partly opposed following an EIA and will most likely not proceed. As far as the third project is concerned all necessary permits for drilling several exploration wells have been granted without an EIA being required.

3.2.1 Krafla

Landsvirkjun plans the drilling of exploration wells in the western part of the Krafla geothermal area in NE-Iceland (VGK 2002). The company received an exploration permit for seven years in 2002. According to the Nature Conservation Act No. 44/1999 and the Act on Conservation of lake Myvatn and the River Laxa No. 36/1974 the project is located in an area of natural interest. Part of the project involves the construction of a road to access the drill site. The Krafla geothermal power plant, recent volcanism and geothermal surface formations in the area attract tourists during the summer.

The Planning Agency (2003) decided that the Krafla project required an EIA. The Minister for the Environment (2001) confirmed the decision. An EIA was carried out and the project was accepted in 2002. Landowners appealed to the Minister for the Environment (2003) who confirmed the ruling. Exploratory drilling has not yet started two and a half years after permit application and must wait for a change to be accepted in the municipal plan.

3.2.2 Grændalur

Sunnlensk Orka proposed a project of exploratory drilling and an access road in the valley Grændalur SW-Iceland (Planning Agency 2003; VGK, Orkustofnun and Hönnun 2001). EIA was required according to an older EIA act No. 63/1993. Part of the project is in the Hengill-area listed as an area of natural interest. Geothermal springs and wetlands, both protected habitats, are common in the non-exploited valley and the area is popular for recreation. A municipal plan is in preparation.

Figure 2: Geothermal projects notified to authorities according to the EIA Act.

After a preliminary EIA the Planning Agency accepted drilling in one location but referred parts of the project to further EIA. A second EIA was carried out according to a new EIA Act No. 106/2000. The Planning Agency ruled against part of the project, due to significant impact on geothermal springs, wetlands, vegetation, geology, landscape and the recreational value of the area. The developer appealed to the Minister for the Environment (2001) who disallowed the ruling and accepted one location for drilling. Opposition to the developer’s first choice of drill site and road construction was confirmed. The exploration permit issued for three years in June 1999 has expired and the project has been postponed.

3.2.3 Hellisheidi

Hellisheidi is south of the Hengill volcano in SW-Iceland. The Hengill area north of the proposed development site is an area of natural interest. Volcanic craters and lava fields, which are specially protected geological features, are common in the area surroundings. The area is popular for recreational activity. There are skiing facilities, roads, power lines and gravel pits in the proposed project area and a municipal plan is in preparation.

In May 2001 Orkuveita Reykjavikur obtained an exploration permit valid fifteen years and drilling of exploration wells started that summer, one year after the company applied for a permit. The exploration project is an important stage in planning exploitation of the geothermal resources and development of a geothermal power plant on Hellisheidi. Four stages of the project have been notified to the Planning Agency (2003) and none have required EIA. Development permits have been issued for seven exploration wells five are completed and two exploration wells will be drilled in 2003. The Planning Agency has accepted an EIA programme and a report is in preparation.

4 Conclusion

Because of the legal framework in Iceland planning of a geothermal power plant can be a complicated process. As discussed in the previous chapter three comparable projects of drilling exploration wells in high temperature geothermal areas have received different official treatment and only one has proceeded. A lack of official policy and plans on where to permit utilisation has made it difficult for developers to plan future exploitation of this renewable energy source.

The Planning Agency has raised the question on whether the impact of exploitation could possibly be assessed before accepting a project of drilling exploration wells (Hólmfrídur Sigurdardóttir 2002). Developers have thought this difficult because of the authorities' demand of detailed environmental information. It is possible that Icelandic authorities have set the standards too high in light of the lack of environmental information. EIA at the exploratory stage should not be the responsibility of the developer.

In our view it is important to simplify the legal framework in Iceland. This will enable authorities to make quick decisions on where to permit exploration and exploitation of geothermal resources at an early stage of project planning. We also ask whether authorities should not themselves carry out a preliminary EIA before granting exploration permits – especially in disputed areas. This would prevent developers from performing costly investigation during the exploratory and EIA stages if they are unlikely to lead to exploitation. A definitive government policy and plan on utilization in geothermal areas would support developers in planning future geothermal power plants.

5 References

Icelandic Parliament (2003). Icelandic legislation. Available from: www.althingi.is. (in Icelandic)

Ministry for the Environment (2001). Ruling on exploratory drilling and road construction in Grændalur, Ölfus municipality. Available in Icelandic from:

http://umhverfisraduneyti.is/interpro/umh/umh.nsf/pages/19-2001Graendalur

Ministry for the Environment (2002). Welfare for the Future Iceland's National Strategy for Sustainable Development 2002–2020. 82 pp. Available in English from:

http://umhverfisraduneyti.is/interpro/umh/umh-english.nsf/pages/welfare

Ministry for the Environment (2003). Ruling on EIA of exploratory drilling in western Krafla area Skutustadahreppur municipality. Available in Icelandic from:

http://www.rettarheimild.is/web/NyirStjornvaldsurskurdir?ArticleID=1035

Ministry of Industry and Commerce. Exploration permits for the Krafla, Grændalur and Hellisheidi area (in Icelandic). Dated May 31st 2002, June 21st 1999 and May 7th 2001.

Planning Agency (2003). Environmental Impact Assessment Act and Planning and Building Act (English translation), decisions on EIA requirements, approving of assessment plans and ruling on EIA, in Icelandic. Available from: www.skipulag.is.

Rammaáætlun (2003). Information on the latest progress of work on a proposed Master Plan for the utilisation of hydro and geothermal energy resources. Available in Icelandic from: www.landvernd.is/natturuafl/index.html.

VGK (2002). Proposal of an EIA programme for a geothermal power plant on Hellisheidi, with electric capacity up to 120 MW_e and 400 MW_t in thermal power (in Icelandic). Unpublished report for Orkuveita Reykjavíkur. 14 pp.

VGK (2003). Hellisheidi. Report on the 3rd stage of an exploratory drilling project for notification. Unpublished report for Orkuveita Reykjavíkur, in Icelandic. 23 pp.

VGK and Orkustofnun (2002). Exploratory drilling in the western Krafla area in the Skútustadahreppur municipality. Environmental impact assessment. Report for Landsvirkjun, in Icelandic, LV-2002/044. 89 pp.

VGK, Orkustofnun and Hönnun, (2001). Exploratory drilling and road construction in Grændalur, in the Ölfus municipality. Environmental impact assessment. Unpublished report for Sunnlensk Orka, in Icelandic. 86 pp.

Sustainable management of geothermal resources

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Abstract

Geothermal energy is a renewable, environmentally friendly energy-source most often associated with volcanic activity, hot crust at depth in tectonically active areas or deep and permeable sedimentary layers. The energy production potential of geothermal systems is primarily determined by the pressure decline caused by production. Sustainable management of a geothermal resource involves utilisation at a rate, which may be maintained for a very long time (100-300 years). Overexploitation of geothermal systems mostly occurs because of poor understanding, due to inadequate monitoring, and when many users utilise the same resource without common management. Careful monitoring and modelling, as well as energy-efficient utilisation, are essential ingredients in sustainable management. Reinjection is also essential for sustainable utilisation of geothermal systems, which are virtually closed and with limited recharge. The Hamar low-temperature geothermal system in the volcanic lava-pile of Central N-Iceland and the geothermal resources in the sedimentary basin below the city of Beijing, P.R. of China have been utilised for decades. They are examples of geothermal resources, of highly contrasting nature, which may each be managed in a sustainable manner. The sustainable potential of the Hamar system is estimated, through modelling, to be greater than 40 kg/s of 65°C water.

Keywords*: Sustainable, management, monitoring, modelling, reinjection, Hamar, Beijing.*

1 Introduction

Geothermal energy is a renewable, environmentally friendly energy-source based on the internal heat of the Earth. It may be associated with volcanic activity, hot crust at depth in tectonically active areas or permeable sedimentary layers at great depth. Thermal springs have been used for bathing, washing and cooking for thousands of years, while geothermal electricity production, and large-scale direct use, started during the first half of the twentieth century. Geothermal energy is now utilised in more than 50 countries worldwide.

With a rapidly growing world-population, and ever-increasing environmental concerns, sustainable development has become an issue of crucial importance for mankind. Geothermal resources have the potential of contributing significantly to sustainable energy use in many parts of the world. The production capacity of geothermal systems is quite variable and different systems respond differently to production, depending on their geological setting and nature. Therefore, comprehensive management is essential for the sustainable use of all geothermal resources.

In this paper sustainable utilisation of geothermal resources will be discussed in view of some available long-term case histories and relevant definitions. Consequently, the principal ingredients of sustainable geothermal resource management will be discussed. The paper is concluded by a discussion of two case studies with particular emphasis on sustainable management of the corresponding resources. One of these involves the Hamar low-temperature geothermal system in

Iceland, and the other one geothermal resources existing in the deep sedimentary basin below the city of Beijing, in the P.R. of China.

2 Sustainable utilisation

The term *sustainable development* became fashionable after the publication of the Brundtland report in 1987 (World Commission on Environment and Development, 1987). There, sustainable development is defined as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs*. This definition is inherently rather vague and it has often been understood somewhat differently.

At the core of the issue of sustainable development is the utilization of the various natural resources available to us today, including the worlds' energy resources. *Sustainability* of geothermal energy production is a topic that has received limited attention, however, even though the longevity of geothermal production has long been the concern of geothermal operators (Wright, 1999; Stefansson, 2000; Rybach *et al.*, 2000; Cataldi, 2001). The terms *renewable* and *sustainable* are, in addition, often confused. The former concerns the nature of a resource while the latter applies to how a resource is utilized.

The energy production potential of geothermal systems is highly variable. It is primarily determined by pressure decline due to production, but also by the available energy content. Pressure declines continuously with time, particularly in systems that are closed or with small recharge. Production potential is, therefore, often limited by lack of water rather than lack of thermal energy. The nature of the geothermal systems is such that the effect of "small" production is so limited that it can be maintained for a very long time (hundreds of years). The effect of "large" production is so great, however, that it cannot be maintained for long.

In many cases several decades of experience have shown that by maintaining production below a certain limit a geothermal system reaches a certain balance, which may be maintained for a long time. Figure 1 shows such an examples from the Laugarnes geothermal system in SW-Iceland. It shows that even though production was increased by an order of magnitude in the sixties, through the introduction of down-hole pumps, which resulted in a reservoir pressure drop corre-sponding to about 120 m of water level, production and water level have remained relatively stable during the last three decades. This indicates that the reservoir has found a new semi-equilibrium, with ten times the natural recharge. Another good example is the Matsukawa geothermal system in Japan, where relatively constant electrical energy production (23.5 MW) has been maintained for more than three decades (Hanano, 2002).

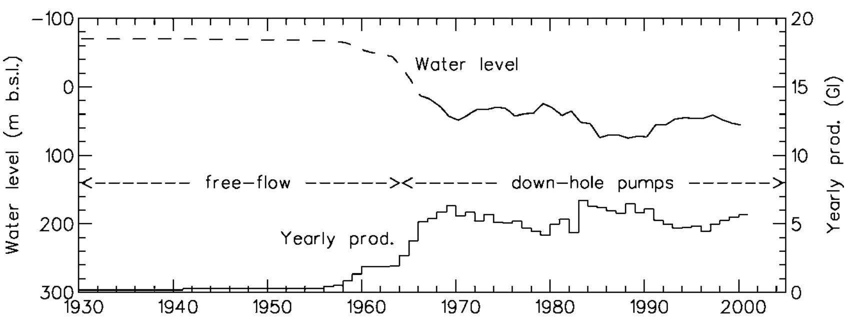

Figure 1: The production and water level history of the Laugarnes geothermal system in SW-Iceland.

Other examples are available where production has been so great that equilibrium was not attained. A good example of this is the Geysers geothermal field in California. Twenty geothermal power plants, with a combined capacity of about 2000

MW, were constructed in the field. A drastic pressure drop in the reservoir caused steam production to be insufficient for all these power plants and production declined steadily from 1985 to 1995, as shown in Fig. 2. A relatively stable production has been maintained since 1995, partly through reinjection. The recharge to the Geysers field, therefore, appears to limit the production that can be maintained in the long run.

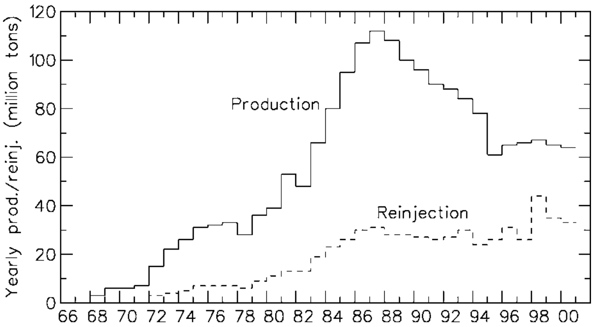

Figure 2: Production- and reinjection history of The Geysers geothermal field in California (Barker, 2000).

Axelsson *et al.* (2001) propose the following definition for the term "*sustainable production of geothermal energy from an individual geothermal system*". This definition does neither consider economical aspects, environmental issues, nor technological advances, all of which may be expected to fluctuate with the times.

For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, $\boldsymbol{E_0}$*, below which it will be possible to maintain constant energy production from the system for a very long time (100-300 years). If the production rate is greater than* $\boldsymbol{E_0}$ *it cannot be maintained for this length of time. Geothermal energy production below, or equal to* $\boldsymbol{E_0}$*, is termed* ***sustainable production*** *while production greater than* $\boldsymbol{E_0}$ *is termed* ***excessive production.***

This definition applies to the total extractable energy, and depends in principle on the nature of the system in question, but not on load-factors or utilization efficiency. It also depends on the mode of production, which may involve spontaneous discharge, pumping, injection or periodic production. The value of $\mathbf{E_0}$ is not known a priori, but it may be estimated on the basis of available data (by modelling). Fig. 3 presents a schematic drawing illustrating the difference between sustainable and excessive production.

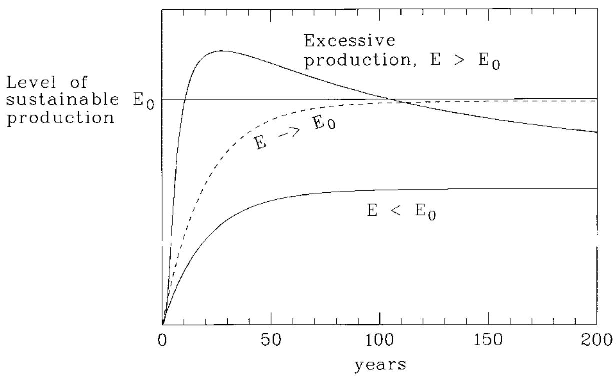

Figure 3: A schematic figure illustrating the difference between sustainable and excessive production.

3 Geothermal management

Geothermal resource management involves controlling energy extraction from geothermal systems underground so as to maximise the resulting benefits, without over-exploiting the resource. It involves deciding between different courses of action aimed at improving operating conditions, addressing unfavourable reservoir conditions, which may have evolved, or incorporating improvements in production strategy (Stefansson *et al.*, 1995, Axelsson and Gunnlaugsson, 2000). The operators of a geothermal resource must have some idea of the possible results of different courses of action, to be able to make these decisions.

The generating capacity of geothermal systems is often poorly known and they often respond unexpectedly to long-term energy extraction. This is because the internal structure, nature and properties of these complex underground systems are often poorly known and can only be observed indirectly. Successful management relies on proper understanding of the geothermal system involved, which in turn relies on adequate information on the system. The pressure decline, which is the primary factor in determining generating capacity, is for example controlled by the size of a system, permeability of the rock and water recharge (i.e. boundary conditions).

When geothermal systems are over-exploited, production from the systems has to be reduced, often drastically. Overexploitation mostly occurs for two reasons. Firstly, because of inadequate monitoring, and data collection, understanding of systems is poor and reliable modelling is also not possible. Therefore, the systems respond unexpectedly to long-term production. Secondly, when many users make use of the same resource/system without common management or control. Examples of the latter are The Geysers, mentioned above, and large sedimentary basins in Europe and the P.R. of China.

In addition to energy-efficient utilisation, monitoring, modelling, and reinjection may be looked upon as the main ingredients in efficient, modern geothermal resource management (Axelsson and Gunnlaugsson, 2000; Axelsson *et al.*, 2002). Careful monitoring, throughout the exploration- and exploitation history of a geothermal reservoir, leads to proper understanding of its nature and successful management of the resource. Mathematical models are developed on the basis of these data, with the purpose of extracting information on conditions, nature and properties of a system, calculate response predictions and estimate production potential, and for management purposes by estimating the outcome of different management actions. Finally, reinjection should be considered an integral part of any modern, sustainable, environmentally friendly geothermal utilisation. It started out as a method of waste-water disposal for environmental reasons, but is now also being used to counteract pressure draw-down, i.e. as artificial water recharge, and to extract more of thermal energy in reservoir rock (Stefansson, 1997). One of the main problems/concerns associated with injection is the possible cooling of production wells (thermal breakthrough), which has discouraged the use of injection in some cases.

4 Case studies

We conclude this paper by discussing two case studies related to sustainable management. One of these is the Hamar low-temperature geothermal system in Central N-Iceland, where modelling based on long-term monitoring has been employed to estimate the sustainable potential of the system. The other study involves the geothermal resources, which are known to exist in the deep sedimentary basin below the city of Beijing, in the P.R. of China. This latter resource is of an entirely different nature, and requires full reinjection for sustainable utilisation, as well as common management, to avoid overexploitation.

4.1 The Hamar geothermal system, N-Iceland

The Hamar geothermal field in Central N-Iceland is one of numerous low-temperature geothermal systems located outside the volcanic zone of the island. The heat-source for the low-temperature activity is believed to be the abnormally hot crust of Iceland, but faults and fractures, which are kept open by continuously ongoing tectonic activity also play an essential role by providing the channels for the water circulating through the systems and mining the heat (Axelsson and Gunnlaugsson, 2000). This small geothermal system has been utilized for space heating in the near-by town of Dalvik since 1969. Two production wells, with feed-zones between depths of 500 and

800 m, in the basaltic lava-pile, are currently in use and the reservoir temperature is about 65°C. The average yearly production from the Hamar system has varied between 23 and 42 l/s, and the total production during the 33-year utilisation history has amounted to 32,000,000 m^3. This production has caused a very modest pressure decline of about 3 bar (30 m).

Careful monitoring has been conducted at Hamar during the last two decades and Figure 4. shows the most significant of these data, the production and water-level data. These data have been simulated by a lumped parameter model, which has been updated regularly, as also shown in the figure. Such models have been successfully used to simulate the pressure response of numerous geo-thermal systems world-wide (Axelsson and Gunnlaugsson, 2000).

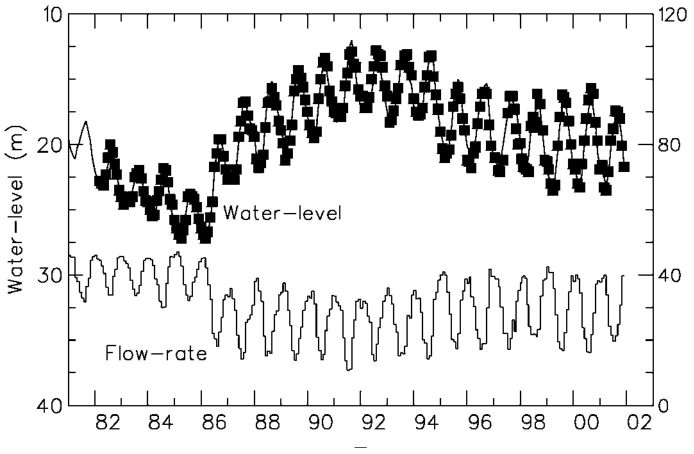

Figure 4: Last two decades of the production history of the Hamar geothermal system, the water-level history having been simulated by a lumped-parameter model (squares = measured data, line = simulated data).

The Hamar system appears to have been utilised in a sustainable manner during the last three decades. The production history is too short, however, to establish whether the current level of utilisation is sustainable according to the definition in chapter 2 above. Therefore, the sustainable production capacity of the system (E_0 in the definition) has been estimated through modelling. A simple method of modelling was used in which pressure- and temperature changes were treated separately.

The lumped parameter model, already mentioned, was used to simulate (predict) the pressure changes (water level) in the Hamar geothermal system for a 200-year production history. The results are pre-sented in Fig. 5 for a 40 kg/s long-term average production. The model used is actually a semi-open model where the response is in-between the responses of the extreme cases of a closed system and an open one. It may be mentioned that the two extremes indicate that the uncertainty in the prediction is only about ±30 m at the end of the prediction period. The results also show that the system should be able to sustain more than 40 kg/s, with down-hole pumps at depths of 200-300 m.

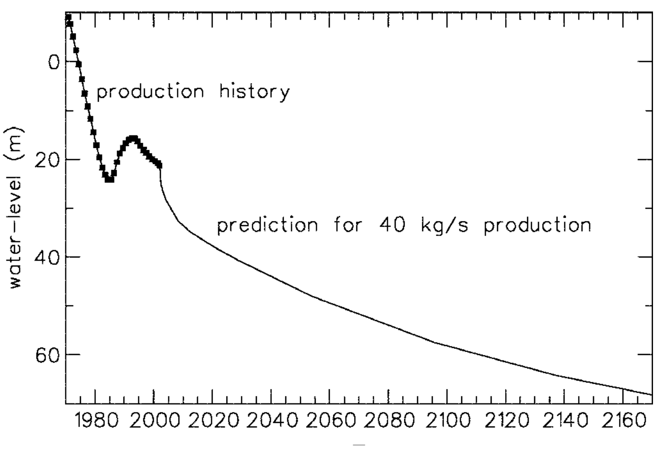

Figure 5: Predicted waterlevel (pressure) changes in the Hamar geothermal system for a 200-year production history.

The eventual temperature drawdown in the Hamar system, due to colder water inflow, is estimated through using a very simple model of a hot cylindrical (or elliptical) system surrounded by colder fluid (Bodvarsson, 1972). This model is used to estimate the time of the cold-front breakthrough. The size of the system, which is highly uncertain, has been estimated to be at least 0.5 km^3, on the basis of geophysical data. The principal results are presented below, for a few production scenarios, and for two different volumes. Reservoir porosity between 5 and 15% is assumed.

Table 1: Estimated cold-front breakthrough times for the Hamar geothermal system.

Production (kg/s)	Volume = 0.5 km^3	Volume = 1.0 km^3
20	470 years	940 years
40	240 years	470 years
60	160 years	310 years
80	120 years	240 years
100	94 years	190 years

These results indicate that if we again assume a production history of the order of 200 years that it should be possible to maintain production of at least 40 kg/s for this period, assuming the conservative reservoir volume. It may also be mentioned that it only takes about 15-45 years to replace the water in-place in the conservative reservoir volume at a production rate of 40 kg/s.

The above results clearly indicate that the long-term production potential of the Hamar geothermal reservoir is limited by energy-content rather than pressure decline (lack of water). We can also conclude that the sustainable rate of production is >40 kg/s and that E_0 >11 MW_{th} (assuming a reference temperature of 0°C).

4.2 Geothermal resources under Beijing, P.R. of China

Beijing City is situated on top of a large and deep sedimentary basin where geothermal resources have been found at depth. These resources owe their existence to sufficient permeability at great depth (1-4 km) where the rocks are hot enough to heat water to exploitable temperatures. Major faults and fractures also play a role in sustaining the geothermal activity. Discussion of sustainable management of the Beijing geothermal resources by Axelsson *et al.* (2002) is the basis for the following. The reader is referred to that paper for more details.

The Beijing basin has been divided into ten geothermal areas on the basis of geological and geothermal conditions. The best-known are the Urban and Xiaotangshan areas, which have been utilised since the 70's and 80's, respectively (Liu *et al.*, 2002). Plans are being made to increase geothermal utilisation in Beijing, in particular for space heating, in order to help battle the serious pollution facing the city. The reservoir rocks in the Urban and Xiaotangshan systems are mostly limestone and dolomite and the yearly production from the Urban and Xiaotangshan fields corresponds to an average production of about 110 and 120 kg/s, respectively. This has resulted in a water level draw-down of the order of 1.5 m/year in the two fields. The water level has declined at an apparently constant rate in spite of the average

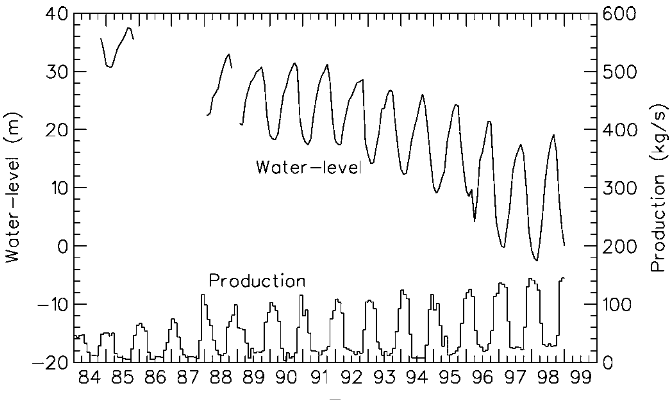

Figure 6: Part of the production and water-level history of the Xiaotangshan geothermal field in Beijing (Axelsson *et al.*, 2002).

production remaining relatively constant (see Figure 6). This clearly indicates that the underlying reservoirs have limited recharge and, in fact, act as nearly closed hydrological systems.

One of the Beijing geothermal fields is the so-called Shahe field. It is located in the north part of the city, south of the Xiaotangshan field, and has an area of about $100km^2$ (Axelsson, 2001; Xu, 2002). A few wells have been drilled in the Shahe field, most of them poorly productive. A well drilled in 1999-2000 in the Lishuiqiao area in the easternmost part of the field, ShaRe-6, turned out to be quite productive, however. It is drilled to a depth of 2418m, and produces from a Cambrian limestone formation. This well has been utilised for three years now with a careful monitoring program in place, and lumped parameter model has been used to simulate the data collected (Axelsson *et al*., 2002). The results show clearly that the Shahe reservoir is an almost closed system (with limited recharge). Figure 7 shows water level predictions for well ShaRe-6 calculated by the lumped parameter model for an 8-year period, based on an average yearly production of 20 l/s. It is clear from the predictions that a considerable, constantly increasing, waterlevel drawdown may be expected in the reservoir.

Predictions with reinjection show that reinjection will be essential for sustainable utilisation of this reservoir. Without reinjection its potential appears to be quite limited. The Shahe reservoir suffers, in fact, from a lack of water. More than sufficient thermal energy is in-place in the geothermal reservoir, however, because of the great volume of resource, and reinjection will provide a kind of artificial recharge.

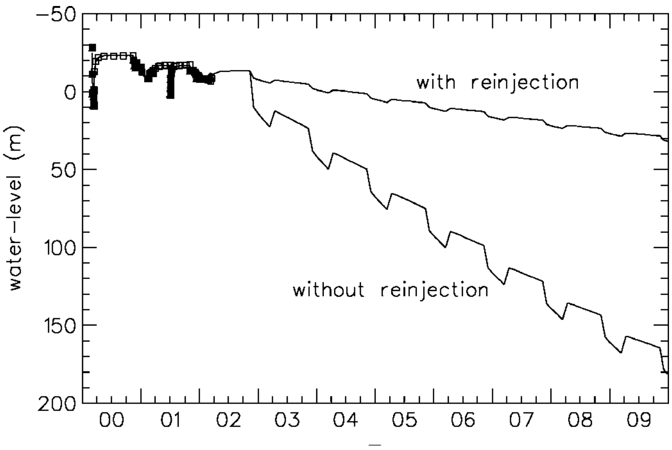

Figure 7: Results of modelling calculations for well ShaRe-6 in Beijing. Predictions for utilisation scenarios with 80-90% reinjection and without reinjection are shown.

These results clearly indicate that reinjection will be essential if plans for increased use of the geothermal resources in Beijing are to materialise in a sustainable manner. Reinjection has not been part of the management of the Beijing resources so far; therefore, careful testing is essential for planning of future reinjection. Such testing has been limited in Beijing up to now, and not enough information is thus available to estimate the sustainable potential (E_0) of the Beijing resources.

Another important aspect is essential for sustainable management of the geothermal resources in Beijing, and to avoid over-exploitation and over-investment in deep wells and surface equipment. This is efficient common management of the geothermal resources, because many different users may be utilising the same reservoir. The production possible from a specific well will most certainly be limited (reduced) by interference from other nearby production wells. Because the resources are limited, utilisation of different wells, in different areas, needs to be carefully harmonised.

5 Concluding remarks

To conclude, the following should be emphasised: Sustainable geothermal utilisation involves energy production at a rate, which may be maintained for a very long time (100-300 years). This requires efficient management in order to avoid overexploitation, which mostly occurs because of lack of knowledge and poor understanding as well as in situations when many users utilise the same resource, without common management. Energy-efficient utilisation, as well as careful monitoring and modelling, are essential ingredients in sustainable management. Reinjection is also essential for sustainable utilisation of geothermal systems, which are virtually closed and with limited recharge.

Two case studies have been presented involving geothermal resources, of highly contrasting nature. It is proposed that each of them may be managed in a sustainable manner. The Hamar low-temperature geothermal system in N-Iceland is an example where modelling based on long-term monitoring has been employed to estimate the sustainable potential of a geothermal system. The results indicate that the long-term (200 years) production potential of the system is limited by energy-content rather than pressure decline (lack of water). The sustainable rate of production at Hamar is estimated to be greater than 40 kg/s, corresponding to more than 11 MW_{th}.

The geothermal resources in the sedimentary basin below the city of Beijing, P.R. of China, appear to be vast. Yet, available information shows that they are limited by lack of fluid recharge rather than lack of thermal energy. Therefore, re-injection is a prerequisite for their sustainable utilisation. Common management, to harmonise the production by different users, and minimise interference, is also essential, as well as energy-efficient utilisation.

6 References

Axelsson, G. (2001). Preliminary assessment of the Shahe geothermal reservoir in Lishuiqiao, Beijing, P.R. of China. Orkustofnun, report GAx-2001/03, 6 pp.

Axelsson, G. and E. Gunnlaugsson (convenors). (2000). *Long-term Monitoring of High- and Low-enthalpy Fields under Exploitation*. International Geothermal Association, World Geothermal Congress 2000 Short Course, Kokonoe, Kyushu District, Japan, May 2000, 226 pp.

Axelsson, G., V. Stefánsson and Y. Xu. (2002). Sustainable management of geothermal resources. *Proceedings of the International Symposium on Geothermal and the 2008 Olympics in Beijing*, Beijing, October 2002, pp. 277-283.

Axelsson, G., A. Gudmundsson, B. Steingrimsson, G. Palmason, H. Armannsson, H. Tulinius, O.G. Flovenz, S. Bjornsson and V. Stefansson (2001). Sustainable production of geothermal energy: suggested definition. *IGA-News*, Quarterly No. 43, January-March 2001, pp. 1-2.

Barker, B. (2000). The Geysers: Past and Future. *Geothermal Resources Council Bulletin*, 29, pp. 163-171.

Bodvarsson, G. (1972). Thermal problems in the siting of reinjection wells. *Geothermics*, 1, pp. 63-66.

Cataldi, R. (2001). Sustainability and renewability of geothermal energy. *Proceedings of the International Scientific Conference on Geothermal Energy in Underground Mines*, Ustron, Poland, November 2001, 4 pp.

Hanano, M. (2002). Sustainable steam production in the Matsukawa geothermal field, Japan. Submitted to *Geothermics*, 19 pp.

Liu, J., X. Pan, Y. Yang, Z. Liu, X. Wang, L. Zhang and W. Xu. (2002). Potential assessment of the Urban geothermal field, Beijing, China. *Proceedings of the International Symposium on Geothermal and the 2008 Olympics in Beijing*, Beijing, October 2002, pp. 211-217.

Stefansson, V. (1997). Geothermal reinjection experience. *Geothermics*, 26, pp. 99-130.

Stefansson, V. (2000). The renewability of geothermal energy. *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, May-June 2000, pp. 883-888.

Stefansson, V., G. Axelsson, O. Sigurdsson and S.P. Kjaran. (1995). Geothermal reservoir management in Iceland. *Proceedings of the World Geothermal Congress 1995*, Florence, Italy, May 1995, pp. 1763-1768.

World Commission on Environment and Development, 1987: *Our Common Future*. Oxford University Press, Oxford, 400 pp.

Wright, P.M., 1999: The sustainability of production from geothermal resources. Lectures presented at the United Nations University Geothermal Training Programme, Reykjavik, September 1999, 42 pp.

Xu, Y., 2002: Assessment and modelling of geothermal resources in the Lishuiqiao area, Beijing, P.R. of China. *UNU Geothermal Training Programme*, Reykjavik, report in press.

Vegetation and invertebrates in three geothermal areas in Iceland

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Abstract

The ecosystem of geothermal areas is poorly known both in Iceland and elsewhere. Information lack in general and studies that have been carried out in Iceland have mostly been descriptive. Knowledge about the ecosystem of these areas is an important consideration as these areas will be more and more important in the future, not only for energy extraction but also for recreation and conservation. A better understanding of these ecosystems is important as it may contribute to improved decisions in terms of utilization. The objective of this study was to demonstrate the distribution of vegetation and invertebrates in relation to physical and chemical parameters. Three geothermal areas in Iceland were selected for this study and the communities of vegetation and invertebrates and soil characteristics were studied along a soil temperature gradient. Results of this study indicate that soil temperature is a dominating environmental factor in explaining the distribution of different species at these sites, as well as soil characteristics. Species diversity and composition at warmer spots was different from the colder ones, but also there was a difference in pH and carbon content of the soil. Furthermore, a difference appeared among sites that are most likely due to different location, elevation and weather condition.

Keywords: *geothermal areas, species/heat relationships, species diversity.*

1 Introduction

Geothermal activity is common in Iceland and in near future it is expected that utilization of geothermal energy will increase and more areas will be disturbed. It is evident that the activity will not only be important in the future for energy extraction, but also for tourism and nature conservation. However, today little is known about the ecosystem of these areas and the relationship of organisms with the unique environment. Therefore, it is vital to gather basic information about these areas, which can be used for management purpose and decisions of how and if these area should be utilized.

Previous studies on geothermal areas in Iceland have mostly been focused on utilization of the geothermal energy (e.g. Palmason *et al*. 1985; Bjornsson 1990). The ecosystems on the other hand have rarely been studied, and the studies that have been carried out are mostly descriptive (Tuxen 1944; Petursson 1958; Steindorsson 1964; Kristjansson and Alfredsson 1986). The situation is similar in other countries, where geothermal activity exists, with a major gap in the knowledge of the ecology of these areas.

An ecological study was carried out in three geothermal sites in Iceland during year 2001, on the request of the National Energy Authority. The aim of this project was to demonstrate the distribution of vegetation and invertebrates in relation to physical and chemical parameters in geothermal areas in Iceland. In this paper we will discuss the species diversity for vegetation and invertebrates found at the three sites, and how it changed along a soil temperature gradient.

2 Study sites and methods

Figure 1: Location of study sites in Iceland.

Three geothermal sites were selected for the study, two in the Southwest (Reykjanes and Olkelduhals) and one in Northeast (Theistareykir) (Figure 1). Reykjanes is located about 20 m a.s.l. and near the seashore. The geothermal surface covers about 2 km² (Idnadarraduneytid 1994) and is characterized by fumaroles and solfataras. Olkelduhals belongs to the Hengill area, which is one of the biggest geothermal areas in Iceland and takes over 100 km² (Idnadarraduneytid 1994). The research area is located about 400 m a.s.l. and the active geothermal surface is hot steaming ground. Theistareykir is about 350 m a.s.l. The thermal area is about 19 km² and it is mostly on flat land where solfatara, steaming ground and sulphur sinter are present (Palmason *et al*. 1985: Idnadarraduneytid 1994).

At each site two transects were extended from the hottest to the cool part. Within each transect 4–5 plots (10 x 10 m) were chosen subjectively to represent vegetation that was as homogeneous as possible within each plot, but encompassed what appeared to be differences in vegetation composition and soil temperature found at that site. Within each plot 8 subplots (33 x 100 cm) were placed randomly and within them all measurements were made. All data were collected in summer 2001.

Soil characteristics: Soil temperature was measured in July, two measurements in each subplot at 10 cm depth. For determination of pH and carbon content of the soil, two samples were collected with a soil core (5.2 cm in diameter) to a depth of 10 cm in each plot. Samples were dried at room temperature and samples from each plot were combined into one composite sample before analysis. Determination of pH was performed for samples that were rewetted with deionised water to a saturated paste and measured with a glass electrode (McLean 1982). The soil carbon content was analysed by means of a Leco–CR 12 Carbon Analyzer (Nelson and Sommers 1982).

Vegetation: Cover for vascular species and for mosses and lichens as a group was estimated visually in each subplot by using a percent scale. To obtain a comprehensive view of moss and lichen species, samples of mosses and lichens were taken within each plot. These sampling methods provide information about the species diversity within each study site.

Invertebrates: Three pitfall traps (7.5 cm in diameter) within a plot were used to catch invertebrates living on the ground. The trapping period was from beginning of July to the end of August in Theistareykir, and from end of June to beginning of September in Reykjanes and Olkelduhals. The traps were emptied twice over the period in Theistareykir and every other week in the other two sites. The traps contained ethylene glycol (antifreeze) to kill and preserve the catch. In some cases the liquid evaporated nearly or completely from traps at the warmest spots, which in those cases gave a minimum catch. All specimens were counted and identified to species when possible, but only those identified to species were used in analysis.

3 Results

3.1 Soil characteristics

In general, the soil temperature was higher in Reykjanes and Olkelduhals than in Theistareykir (Figure 2). The highest temperature within a plot was 79ºC in Olkelduhals, in Reykjanes it was 67ºC and 38ºC in Theistareykir. At the coolest part of each transect the soil temperature was measured around 14ºC in Reykjanes and 8–9ºC at the other two sites.

Carbon content of the soil was higher in cooler soil than warm soil, but same trend was not seen for pH (Figure 3). Great variability was within each site in carbon and pH. Smallest amount of carbon (0.1%) was measured in Theistareykir but highest in Olkelduhals (8.5%). The pH was lowest (1.9) in Theistareykir but highest (8.0) in Reykjanes.

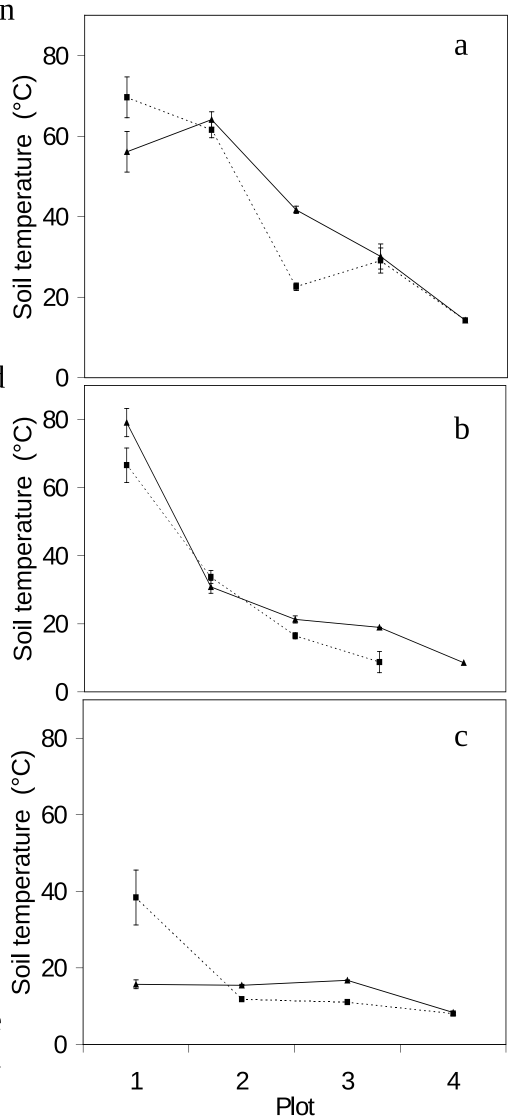

Figure 2: Soil temperature (ºC) at 10 cm depth (+/- SE) in plots at a) Reykjanes, b) Olkelduhals and c) Theistareykir. The two transects are shown.

3.2 Vegetation and invertebrates

Number of vascular plant species was 51 in Theistareykir, 44 in Olkelduhals and 39 in Reykjanes. Moss species found in Olkelduhals were 35, 30 in Reykjanes and 25 in Theistareykir. Lichen species were 18 in Theistareykir, but 12 and 13 in Olkelduhals and Reykjanes, respectively. In Theistareykir were 146 invertebrate species identified, 109 in Olkelduhals and 103 in Reykjanes.

Number of vascular species and invertebrates within a plot decreased as soil temperature increased (Figure 4.a and d). Lichens showed similar pattern, but on the other hand number of moss species did not show a clear respond to soil temperature (Figure 3.3.b and c). Within the hotter plots in Reykjanes and Olkelduhals, mosses (e.g. *Campylopus introflexus*, *Gymnocolea inflata* and *Archidium alternifolum*) were dominating in the vegetation but in Theistareykir these plots were almost barren. As the temperature decreased other moss species became dominant and in some cases replaced the ones that were abundant at hotter plots. Vascular plant species found at these hot plots were for example *Agrostis stolonifera*, *Thymus praecox*, *Alchemilla alpina* and *Ophioglossum azoricum*. Most of these species were also found at cooler plots, and their cover tended to increase as the temperature decreased. Lichens were rarely found within hot plots but the most common lichen species found, within both hot and cool plots, was *Peltigera canina*.

Dominating invertebrate species differed among the study sites. The spider *Erigone atra* dominated the hotter plots in Reykjanes, but beetles were most common in Olkelduhals and Theistareykir, such as *Bembidion bipunctatum* and *Nebria gyllenhali*. These species were not found at the colder plots. Species common at the colder plots (e.g. parasitic hymenopterans *Trimorus pedestris* and *T. ovata* and harvestman *Mitopus morio*) decreased in number as temperature increased and some were not found at the hottest plots at all.

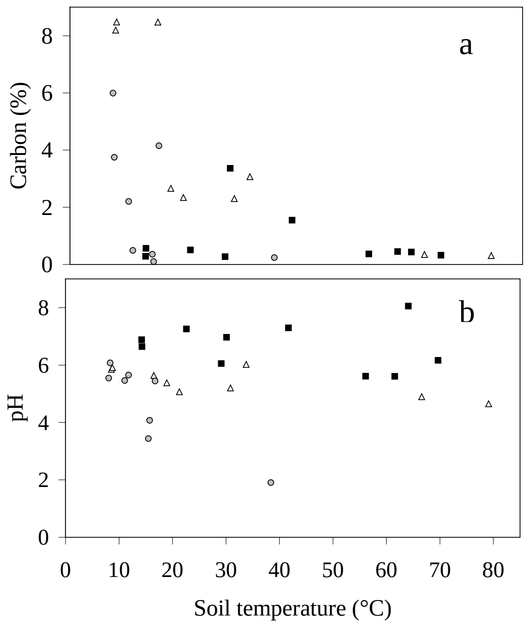

Figure 4: a) Soil carbon and b) pH of the upper 10 cm layer in plots within each site. Reykjanes is a box, Olkelduhals is a triangle and Theistareykir is a circle.

4 Discussion

The environment of geothermal sites are unique because of special conditions, which is usually characterized by steep gradients in soil temperature and humidity, high acidity and unusual concentration of minerals and elements (Burns 1997; Glime and Hong 1997). These conditions are likely to affect both flora and fauna that can be quite different from the surroundings (Halloy 1991, Burns 1997, Convey *et al.* 2000). In this study warm soils were in general characterized by low carbon values (<0.5% C), but it increased as the temperature decreased (Figure 3). The pH in soil was in most cases within the near neutral range (6–8), which favours nitrogen and phosphorus availability and microbiological activity for nitrogen fixation (Tucker *et al.* 1987). But as acidity becomes more extreme it strongly affects plants ability to take up certain nutrients and that might be the case within the barren plots at Theistareykir, where pH was measured as low as 1.9. Furthermore, at low acidity aluminium toxicity have shown to have a great influence on plants (Andersson 1988).

Our results indicated that soil temperature influence the species diversity in most cases (Figure 4). Number of vascular plant species showed a clear negative response to increased soil temperature and other researches have shown that vegetation at geothermal sites is closely related to soil temperature in the root zone (Given 1980; Glime and Iwatsuki 1994). The heat tolerance of normal plant cell activity has been shown to range from 45-55ºC, although some cells can survive at higher temperature (Konis 1949). Similar to other studies, this study showed that mosses can survive in the heat considerably well, which can be explained to some extent by lack of roots and that soil temperature is lower at the soil surface than for instance at 10 cm depth (Given 1980, Glime and Hong 1997). Some of these mosses (e.g. *Gymnocolea inflata*) were only found at high temperatures and therefore can be identified as geothermal species. Although soil temperature was somewhat lower at Theistareykir, compared with the other two sites, the hottest plots remained almost barren (Figure 4). This lack of vegetation might be explained by low soil pH within the plots (Figure 3). Unlike the mosses, few lichens were found at areas with soil temperature over 50ºC. Similar pattern have been found at other geothermal areas where lichens seemed to avoid hot humid areas (Kappen and Smith 1980, Glime and Iwatsuki 1990).

Unfortunately studies on the ecology of terrestrial invertebrates at geothermal areas are lacking generally so still we have little knowledge of the effects of geothermal heat on invertebrate species. This study showed that the number of invertebrate species decreased with Increase in temperature (Figure 4). Furthermore, agreeing with Olafsson (2000) many species living at high soil temperatures were not found in colder neighbouring areas and vice versa. The species that only were found at high temperatures in this study, e.g. *Bembidium bipunctatum* and *Nebria gyllenhali*, have been found in cold habitats further away (Sadler and Dugmore 1995, Olafsson 2000) so they are not restricted to geothermal areas. A study carried out at geothermal warm spots in the Andes at 6000 m a.s.l. similarly showed that most of the taxa found there were not found in neighbouring mountains. They were related to taxa from lower humid areas, hundreds or thousands of kilometres away (Halloy 1991).

The first results of this study indicated that soil temperature play a strong role in determining the distribution of species, it must however act in consort with other factors, e.g. pH and carbon content in soil. It is for example evident that location; weather conditions and elevation may influence the distribution of the organisms as well.

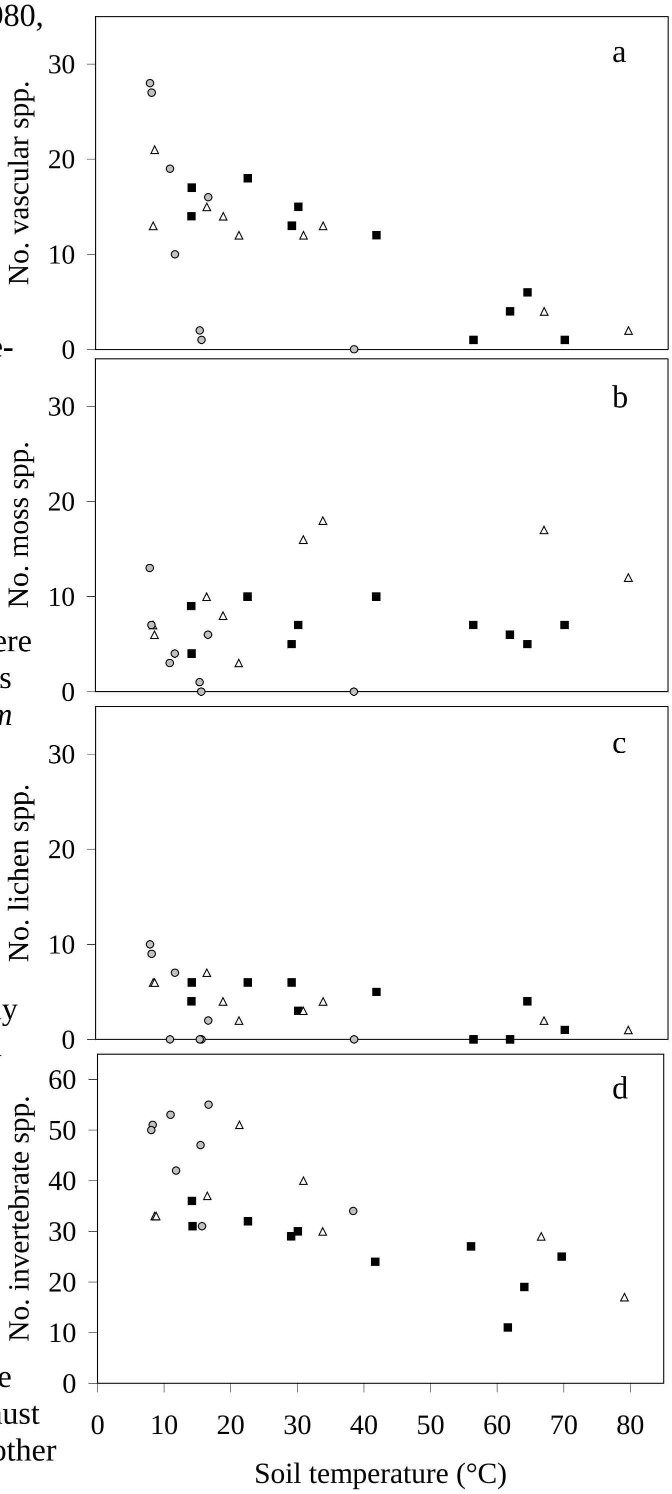

Figure 4: Species diversity; number of a) vascular plants, b) mosses, c) lichen and d) invertebrates within each plot. Reykjanes is a box, Olkelduhals is a triangle and Theistareykir is a circle.

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5 References

Andersson, M. (1988). Toxicity and tolerance of aluminium in vascular plants. *Water, Air, and Soil Pollution*, Vol. 39, pp. 439-462.

Bjornsson, A. (1990). *Jardhitarannsoknir. Yfirlit um edli jardhitasvaeda, jardhitaleit og vinnslu jardvarma.* Report from the National Energy Authority, OS–90020/JHD–04, Reykjavík.

Burns, B. (1997). Vegetation change along a geothermal stress gradient at the Te Kopia steamfield. *Journal of The Royal Society of New Zealand*, Vol. 27 (2), pp. 279–294.

Convey, P., Smith, R.I., Hodgson, D.A., and Peat, H.J. (2000). The flora of the South Sandwich Islands, with particular reference to the influence of geothermal heating. *Journal of Biogeography*, Vol. 27, pp. 1279–1295.

Given, D.R. (1980). Vegetation on heated soil at Karapiti, central North Island, New Zealand, and its relation to ground temperature. *New Zealand Journal of Botany*, Vol. 18, pp. 1–13.

Glime, J.M. and Hong, W.S. (1997). Relationships of geothermal bryophyte communities to soil characteristics at Thermal Meadow, Hotsprings Island, Queen Charlotte Islands, Canada. *Journal of Bryology*, Vol. 19, pp. 435–448.

Glime, J.M. and Iwatsuki, Z. (1990). Niche characteristics of Cladonia lichens associated with geothermal vents in Japan. *Ecological Research*, Vol. 5, pp. 131–141.

Glime, J.M. and Iwatsuki, Z. (1994). Geothermal communities of Ponponyama, Hokkaido, Japan. *Journal of Hattori Bot. Lab.*, Vol. 75, pp. 133–147.

Halloy, S. (1991). Islands of life at 6000 m altitude: The environment of the highest autotrophic communities on earth (Socompa volcano, Andes). *Arctic and Alpine Research,* Vol. 23, pp. 247–262.

Idnadarraduneytid (1994). Innlendar orkulindir til vinnslu raforku. Idnadarraduneytid, Reykjavík.

Kappen, L. and Smith, C.W. (1980). Heat tolerance of two *Cladonia* species and *Campylopus praemorsus* in a hot steam vent area of Hawaii. *Oceologia (Berl.),* Vol. 47, pp. 184–189.

Konis, E. (1949). The resistance of maquis plants to supramaximal temperatures. *Ecology*, Vol. 30, pp. 425–429.

Kristjansson, J.K. and Alfredsson, G. A. (1986). Lifriki hveranna. *Natturufraedingurinn*, Vol. 56 (2), pp. 49–68.

McLean, E.O. (1982). Soil pH and lime requirement. In: *Methods of soil analysis*, A.L. Page, R.H. Miller & D.R. Keeney (Eds), Part 2, 2nd ed. Agronomy No. 9. American Society of Agronomy and Soil Science Society of America, Madison, pp. 199–224.

Nelson, D.W. and Sommers, L.E. (1982). Total carbon, organic carbon, and organic matter. In: *Methods of soil analysis*, A.L. Page, R.H. Miller and D.R. Keeney (Eds), Part 2, 2nd ed. Agronomy No. 9. American Society of Agronomy and Soil Science Society of America, Madison, pp. 539–579.

Olafsson, E. (2000). *Landliddyr í Thjorsarverum. Rannsoknir 1972 – 1973.* Fjolrit Natturufraedistofnunar, Reykjavik. 159 pp.

Palmason, G., Johnsen, G.V., Torfason, H., Saemundsson, K., Ragnars, K., Haraldsson, G.I. and Halldorsson, G.K. (1985). *Mat a jardvarma Islands*. Report from the National Energy Authority, OS-85076/JHD-10, Reykjavik.

Petursson, S. (1958). Hveragrodur. *Natturufraedingurinn*, Vol. 28, pp.141–151.

Sadler, J.P. and Dugmore, A.J. (1995). Habitat distribution of terrestrial Coleoptera in Iceland as indicated by numerical analysis. *Journal of biogeography*, Vol. 22, pp. 141–148.

Steindorsson, S. (1964). *Grodur a Islandi*. Almenna bokafelagid, Reykjavik. 189 pp.

Tucker, G.B., Berg, W.A. and Gentz, D.H. (1987). pH. In: *Reclaiming mine soils and overburden in the western United States: analytic parameters and procedures*, R.D. Williams and G.E. Schuman (Eds), Soil Conservation Society of America, Ankeny, pp. 3–26.

Tuxen, S.L. (1944). *"The Hot Springs, their Animal Communities and their Zoogeographical Significance"*. The Zoology of Iceland, Vol. I (11), Ejnar Munksgaard, Copenhagen and Reykjavik, 206 pp.

CO_2 emission from Geothermal Plants

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Abstract

Geothermal energy is considered to be a benign energy source as regards environmental impact. One of its impacts is the release of the greenhouse gas, CO_2, to the atmosphere. In a recent survey by the IGA it was shown that in comparison with the burning of fossil fuels there is a considerable advantage to using geothermal energy. Mitigating circumstances for geothermal power plants include the possibility of cascading uses such as industrial production, space heating, greenhouse culture etc. that can be run parallel with the power production and reduce the gas emission per energy unit. The CO_2 emitted from geothermal plants is already part of the CO_2 cycle, no new CO_2 is being produced as is the case in fossil fuel plants. Furthermore this CO_2 is usually removed from the cycle where there is already vigorous degassing from geothermal and volcanic areas and it is possible that the addition to the atmosphere is negligible. Studies already carried out to this effect have in fact suggested that this is the case. Thus it is suggested that background emission from geothermal areas be estimated before the total added from a power plant is estimated. On the basis of the results of such studies Italy has decided not to include geothermal CO_2 emission as part of their anthropogenic greenhouse gas emission reported in connection with international agreements. Recently Iceland has decided to take the same course of action.

Keywords: *Geothermal, environment, cascade, greenhouse gas, anthropogenic, inventory.*

1 Introduction

Environmentally geothermal energy is generally considered a benign energy source. One of the impacts that have been considered is release of the greenhouse gas CO_2 to the environment even though this has been shown to be much less than from fossil fuel power plants (Fig. 1). Further mitigating circumstances are that geothermal power plants are in some cases parts of multiple purpose plants constituting industrial production, space heating, greenhouse industry etc. thus reducing emission per unit production. Furthermore it has been proposed that the CO_2 emission from power plants is just emission that has been transferred from one location to another in the CO_2 cycle and that natural degassing from volcanic and geothermal areas and the emission from a power plant is only an insignificant part of the total emission. In this paper these ideas will be examined with reference to published results from a variety of locations.

2 CO_2 Emission from Geothermal and Volcanic Areas

2.1 International Geothermal Association Survey

The International Geothermal Association (2002) carried out a survey of CO_2 emission from geothermal power plants with the aim of showing the environmental advantage of geothermal energy in mitigating global change. The results were summarised with reference to emission expressed as g/kWh in relation to production in MW_e (Table 1). The total range for all plants was 4-740 g/kWh with weighted average 122 g/kWh.

Figure 1. CO_2 emission from various types of power plants (After Hunt 2000)

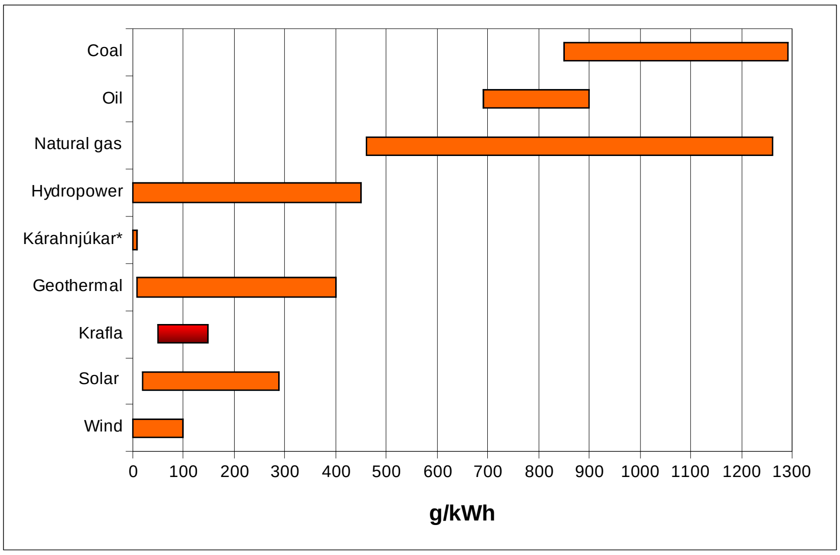

Table 1. CO_2 emission and total running capacity of power plants divided into 9 emission categories (International Geothermal Association (2002)

Emission category g/kWh	Running capacity MW_e	Average g/kWh
>500	197	603
400-499	81	419
300-399	207	330
250-299	782	283
200-249	346	216
150-199	176	159
100-149	658	121
50-99	1867	71
<50	2334	24

In the report it is suggested that the natural emission rate pre development be subtracted from that released from the geothermal operation, citing Larderello as an example of a field where a decrease in natural release of CO_2 has been recorded and shown to be due to development.

2.2 Origin of CO_2 in Geothermal Areas

Geothermal systems are often located in volcanic areas or other areas of high CO_2 flux of magmatic origin but CO_2 may also be derived from depth where it is mainly produced by metamorphism of marine carbonate rocks. There is a large flux through soil but groundwater where present is also often rich in dissolved CO_2. Processes of natural generation are independent of geothermal production. The output is very variable but usually quite substantial. Estimated output from several volcanic and geothermal areas is shown in Table 2. There seems to be no difference between producing and non-producing areas.

The most thorough investigation of the proportion of CO_2 emitted through various conduits was done by Favara et al. (2001), but estimates of fractions emitted through groundwater on the one hand but soil and fumaroles on the other have been made at Mammoth Mountain (Sorey et al. 1998, Evans et al. 2002, Gerlach et al. 2001) and

Furnas (Cruz et al. 1999). The results for these areas are listed in Table 3. Calculations for some of the areas listed in Table 2 and a few others give a mean CO_2 flux in g $m^{-2}day^{-1}$ as 200.

Table 2 CO_2 output from some volcanic and geothermal areas

Area	Megaton/year	Reference
Pantellera Island, Italy	0.39	Favara et al. (2001)
Vulcano, Italy	0.13	Baubron et al. (1991)
Solfatara, Italy	0.048	Chiodini et al. (1998)
Ustica Island, Italy	0.26	Etiope et al. (1999)
Mid-Ocean Volcanic System	30-65	Gerlach (1991)
Popocatepetl, Mexico	14.5-36.5	Delgado et al. (1998)
Mammoth Mountain, USA	0.055-0.2	Sorey et al. (1998), Evans et al. (2002), Gerlach et al. (2001)
White Island, New Zealand	0.95	Wardell and Kyle (1998)
Mt. Erebus, Antarctica	0.66	Wardell and Kyle (1998)
Geothermal systems, New Zealand	0.002-0.048	Seaward and Kerrick (1996)
Furnas, Azores, Portugal	0.01	Cruz et al. (1999)
Total	1000	Delgado et al. (1998)

Table 3. Relative CO2 emission through different conduits from three areas (Favara et al. 2001, Sorey et al. 1998, Evans et al. 2002, Gerlach et al. 2001)

	Pantelleria Island	Furnas Volcano	Mammoth Mountain
Soil %	81	49 [1)]	63-90 [1)]
Focussed degassing %	7		
Fumarole %	0.0004		
Bubbles %	3		
Groundwater %	9	51	10-37

[1)] Total flow directly to atmosphere

2.3 CO_2 Emission from Geothermal Areas in Iceland

The CO_2 emission from geothermal plants in Iceland has been recorded since the early 1980s when it was 48000 tons per year up to now. Last year it was 155000 tons. In the early years power production was extremely low but the relatively high CO_2 emission was due to a gas pulse in Krafla associated with the Krafla fires (Ármannsson et al. 1982). Two attempts at estimating natural flow resulted in 148000 tons/year assuming all flow was through fumaroles (Ármannsson 1991) and 2.1 million tons/year based on estimates of heat flow (Arnórsson 1991). The latter would include flow through soil and water. At the same time Ármannsson (1991) estimated the proportion of CO_2 emitted from producing plants and that emitted naturally, again assuming that all but a negligible portion was emitted through fumaroles and found that most CO_2 is emitted naturally while the reverse was the case for H_2S (Fig. 2).

In 1984 a well in Svartsengi started producing dry steam. This steam contained orders of magnitude more CO_2 than previous steam from that and other wet wells. A steam cap had formed and in 1993 another well specifically drilled to produce from the steam cap was added. Finally two more wells producing from the steam cap were added in 1999 and 2001 respectively. The influence of these wells can be seen in Fig. 3 showing CO_2 emission from Svartsengi (Ólafsson 2003). Other changes are due to variable production from the area.

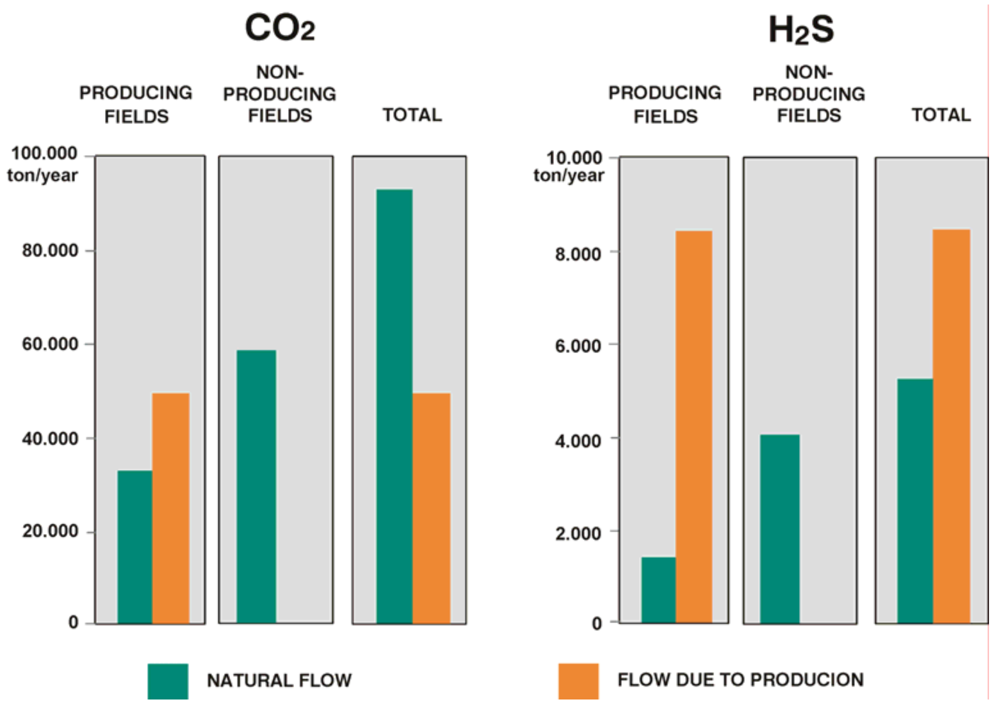

Figure 2 CO_2 and H_2S emission from producing and non-producing fields

The concentration of CO_2 in the steam cap has decreased gradually and is now about half what it was in 1984. Natural fumaroles have been formed and release to the atmosphere has apparently increased. If on the other hand all the brine boils to steam a drastic reduction in natural flow to the surface can be expected corresponding to production. While the brine is boiling down there will be an initial increase, the magnitude of which will gradually diminish.

Of the three main producing areas in Iceland two, Nesjavellir and Svartsengi, are space heating plants as well as power plants whereas the third one; Krafla just produces electricity. In Table 4 there is comparison between CO_2 and S (expressed as SO_2) emission per kWh for the power production and if the space heating is accounted for. Krafla and Svartsengi are a little above the world average for power production but a very small amount of CO_2 is emitted from Nesjavellir. The figure for Svartsengi is much improved when space heating is accounted for.

3 Inventories

Iceland is party to international conventions requiring inventeries of anthropogenic airborne material. The most important ones are:

- FCC: Framework Convention on Climatic Change
- CLRTAP: Convention on Long-Range Transboundary Air Pollution

The first is a UN convention and a panel has issued regulations on how to calculate and present the contents of the inventories. The second which is a European convention has now adopted a comparable set of rules. The Kyoto protocol according to which nations undertake to limit their emissions has not been signed by Iceland. Iceland has signed several protocols associated with CLRTAP but none of those have taken effect yet. Iceland has published inventories since 1990 and the geothermal component of CO_2 emission has increased from about 3.5% to about 5% during this time (Hallsdóttir 2001). Taking into account the large amount of natural emission and the fact that the CO_2 emission can be regarded as being

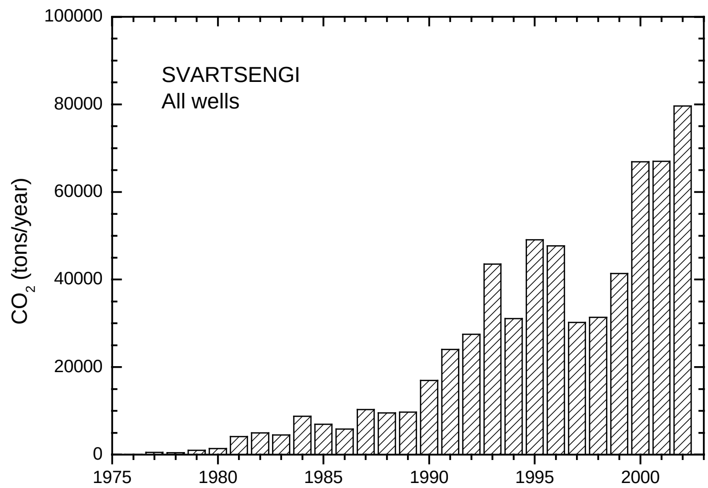

Figure 3 CO_2 emissions from Svartsengi 1976-2002

Table 4 CO_2 and S (expressed as SO_2) emission per kWh from Iceland's major geothermal power plants

Plant	Power production only		Total production	
	CO_2 g/kWh	S as SO_2 g/kWh	CO_2 g/kWh	S as SO_2 g/kWh
Krafla	152	23	152	23
Svartsengi	181	5	74	2
Nesjavellir	26	21	10	8

transferred in its location rather than being an addition to the CO_2 cycle Italy has decided not to consider CO_2 emission from geothermal plants as anthropogenic and does not include it in their inventory (Ruggeri, pers. comm.). Last year Iceland followed suit temporarily (Hallsdóttir, pers. comm.).

No studies have been carried out on CO_2 emission through soil in Iceland. If it is comparable to other parts of the world the Krafla area, which is intensely volcanic and has recently had eruptions with increased gas flow to the surface (Ármannsson et al. 1982), should emit at least the average 200g $m^{-2}day^{-1}$. The geothermal area has been estimated to be about 50 km^2 which means that natural emission could be > 1 million tons CO_2/year if the amount of gas is above average. In 2001 the total CO_2 emission from the power plant was 73000 tons, which is quite small in comparison. The flow through soil might be smaller in other areas but it seems a worthy undertaking to set up a network to estimate it.

4 Acknowledgements

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5 References

Ármannsson, H. (1991). Geothermal energy and the environment. In Geoscience Society of Iceland. *Conference on Geology and Environmental Matters. Programme and Abstracts*, pp.16-17 (In Icelandic).

Ármannsson, H., Gíslason, G. and Hauksson, T. (1982). Magmatic gases aid the mapping of the flow pattern in a geothermal system. *Geochim. Cosmochim. Acta*, Vol. 46, pp. 167-177.

Baubron, J-C., Mathieu, R. and Miele, G. (1991). Measurement of gas flows from soils in volcanic areas: the accumulation method (abstract). In *Proc. Int. Conf. on Active Volcanoes and Risk Mitigation, Napoli 27 August-1 September 1991*.

Arnórsson, S. (1991). Estimate of natural CO_2 and H_2S flow from Icelandic high-temperature geothermal areas. *Conference on Geology and Environmental matters. Programme and Abstracts*, pp.18-19 (In Icelandic)

Chiodini, G. Cioni, R., Guidi, M., Raco, B. and Marini, L. (1998). Soil CO_2 flux measurements in volcanic and geothermal areas. *Appl. Geochem*., Vol. 13, pp. 543-552.

Cruz, J.V., Couthinho, R.M., Carvalho, M.R., Óskarsson, N. and Gíslason, S.R. (1999). Chemistry of waters from Furnas volcano, São Miguel, Azores: fluxes of volcanic carbon dioxide and leached material. *J. Voc. Geoth. Res.*, Vol. 92, pp. 151-167.

Delgado, H., Piedad-Sànchez, N., Galvian, L., Julio, P., Alvarez, J.M. and Càrdenas, L. (1998). CO_2 flux measurements at Popocatépetl volcano: II. Magnitude of emissions and significance (abstract). *EOS Trans. AGU*, Vol. 79(45), Fall Meeting Suppl., p. 926.

Etiope, G., Beneduce, P., Calcara, M., Favali, P., Frugoni, F., Schiatterella; M. et al. (1999). Structural pattern and CO_2-CH_4 degassing of Ustica Island, Southern Tyrrhenian basin. *J.Volc. Geoth. Res.*, Vol. 88, pp. 291-304.

Evans, W.C., Sorey, M.L., Cook, A.C., Kennedy, B.M., Shuster, D.L., Colvard, E.M., White, L.D. and Huebner, M.A. (2002). Tracing and quantifying magmatic carbon discharge in cold groundwaters: lessons learned from Mammoth Mountain, USA. *J.Volc. Geoth. Res.*, Vol. 114, pp. 291-312.

Favara, R., Giammanco, S., Inguaggiatio, S. and Pecoraino, G. (2001). Preliminary estimate of CO_2 output from Pantelleria Island volcano (Sicily, Italy): evidence of active mantle degassing. *Appl. Geochem*., Vol. 16, pp. 883-894.

Gerlach, T.M. (1991). Etna's greenhouse pump. *Nature*, Vol. 315, pp. 352-353.

Gerlach, T.M., Doukas, M.P., McGee, K.A. and Kessler, R. (2001). Soil efflux and total emission rates of magmatic CO_2 at the Horseshoe Lake tree kill, Mammoth Mountain, California, 1995-1999. *Chem. Geol*., Vol. 177, pp. 101-116.

Hallsdóttir, B. (2001). Emission of air polluting substances and emission inventory. *Energy Symposium. Energy Culture in Iceland. Basis for policy making*. (Ed. M.J. Gunnarsdóttir). Samorka, pp. 308-316.

Hunt, T.M. (2001). *Five lectures on environmenta effects of geothermal utiliztion*. United Nations University. Geothermal Training Programme 2000– Report 1, 109 pp.

International Geothermal Association (2002). *Geothermal Power Generating Plant CO_2 Emission Survey*. A report, 7 pp.

Ólafsson, M. (2003). *Svartsengi. Chemical monitoring 1996-2002*. Orkustofnun report (in press).

Seaward, T.M. and Kerrick, D.M. (1996). Hydrothermal CO_2 emission from the Taupo Volcanic Zone, New Zealand. *Earth Planet. Sci. Lett*., Vol. 139, pp. 105-113.

Sorey, M.L., Evans, W.C., Kennedy, B.M., Farrar, C.D., Hainsworth, L.J.and Hausback, B. (1998). Carbon dioxide and helium emissions from a reservoir of magmatic gas beneath Mammoth Mountain, California. *J. Geophys. Res*., Vol. 103, pp. 15,303-15,323.
Wardell, L.J. and Kyle, P.R. (1998). Volcanic carbon dioxide emission rates: White Island, New Zealand and Mt. Erebus, Antarctica (abstract). *EOS Trans., AGU*, Vol. 79(45), Fall Meeting Suppl., p. 927.

Ecological risk assessment of Nesjavellir co-generation plant wastewater disposal on Lake Thingvallavatn, SW-Iceland

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Abstract

Production of electricity and hot water for district heating by Nesjavellir geothermal power plant in SW-Iceland utilizes high temperature steam, which contains various trace elements. The waste fluid from the plant is either pumped into shallow drill holes that connect to underground water or disposed of in the Nesjavellir stream, which disappears into the lava and finds its way into Lake Thingvallavatn, a rift lake of high conservational value. Here we evaluate data on temperature and quantities of trace elements in the geothermal wastewater discharged from the power plant and at lakeshore springs, and in biological samples of an aquatic plant, a gastropod snail, in the salmonid fish arctic charr and in sediments at Varmagja and at a control site, Vatnskot. Before the wastewater reaches the lake, trace elements are modified through chemical reactions or diluted to such an extent that there is little reason for concern except for arsenic. All trace elements in lake shoreline springs were within the international water quality criteria for protection of aquatic life except for arsenic. Aluminium was also found in concentrations that cause some concern. In most situations wave action ensures efficient mixing of the spring water at geothermally influenced sites with cold lake water precluding detrimental effects of elevated temperature and trace elements. However, following the development of electricity production at Nesjavellir since 1998 the disposal large amounts of 42°C cooling water has caused a rise in temperature at shoreline springs from around 12°C to around 20°C. This is of some concern at sheltered sites. There was no detectable rise or accumulation of trace elements in biological samples taken at Varmagjá, one of the geothermally influenced sites. However, taking into account the conservational value of Lake Thingvallavatn, sound wastewater management by deep re-injection and regular monitoring of trace elements and spring water temperature should be adopted.

Key words: *ecological risk, Nesjavellir co-generation plant, wastewater disposal, lake ecology, assessment.*

1 Introduction

Ecosystems are composed of the biological community (producers, consumers and decomposers) and various abiotic components (physical and chemical). Within ecosystems, a complex interaction of physical and biochemical cycles exist. In this sense ecosystems continually undergo change at various time scales. However, many ecosystems have developed over a long period of time and organisms have become adapted to their environment. In addition, ecosystems have an inherent capacity to withstand and assimilate stress based on their unique physical, chemical, and biological properties. Nonetheless, systems may become unbalanced by natural factors, including drastic changes in climatic variations, or due to human activities. Any changes especially rapid ones, can have detrimental effects.

Adverse effects due to human activities, such as release of toxic chemicals or heat in industrial effluents, may affect many components of aquatic ecosystem, the magnitude of which will depend on both biotic and abiotic, site-specific characteristics. In evaluation and planning, aquatic ecosystems should be viewed as whole units, not just in terms of isolated organisms affected by one or a few pollutants.

As chemicals or substances are released into the environment through natural processes or human activities, they may enter aquatic ecosystems as solutes which can enter the biological community. Some chemicals can partition into particulate phase, in which case the particles may remain in the water or may be deposited into the bed sediments where the contaminants can accumulate over time. Sediments may thus act as long-term reservoirs for contaminants (CCME, 2001).

Thingvallavatn is a rift lake located in SW Iceland and of high conservational value (Jónasson, 1992, 2003). The lake is 90% fed by underground springs with main springs entering in the north at a temperature of 2.8-3.5°C. Warmer groundwater enters the lake in the southwest from the Hengill geothermal area (Ólafsson, 1992). Since 1990 The Reykjavík Hot Water Company (now Reykjavík Energy) has utilized the Hengill geothermal resource in the Nesjavellir Power Plant, first by producing hot water for district heating and later by adding facilities for generation of electricity for the national grid.

The power plant at Nesjavellir utilizes high temperature steam, which contains various trace elements. The waste fluid from the plant is either pumped into shallow drill holes that connect to underground waterways or disposed of in the Nesjavellir stream, where it disappears into the lava and finds its way into Thingvallavatn. A study of the chemical composition of effluents from 4 geothermal drillholes sampled in the Nesjavellir field in the years 1983-1984 showed high concentrations of arsenic (5.6-310 µg/l) (Ólafsson, 1992). In the following years (1984-1991), while the geothermal field was being developed, arsenic concentrations rose markedly in two geothermally affected lakeshore springs, at Varmagja (from 0.6-2.2 µg/l) and Eldvik (from 0.7-4.7 µg/l). From these studies Olafsson (1991) concluded that arsenic was the only constituent of the geothermal effluent likely to be of concern in Thingvallavatn. Although trace elements were low in the affected springs and the arsenic concentration was within limits considered safe for the fresh water biota, precautionary monitoring measures were recommended (Snorrason and Jónsson, 1995).

Direct release of hot wastewater from a standard steam cycle power plant into an existing natural waterway leads to an increase in temperature, which can have a very significant impact on communities of aquatic plants and animals. In serious cases this results in a complete change of the community whereby high temperature tolerant species take over. In milder cases water temperature variation among sites may create differences in the physiological and behavioural advantages among aquatic organisms hence influencing their competitive ability and distribution as indicated by Taniguchi et al. (1998). At the present the electricity production phase at the Nesjavellir plant is a steam cycle design, which uses cold fresh water for cooling of condensed steam. Based on the geothermal wastewater disposal data, used and unused brine discharged from the power plant and separator station at an average flow rate of 32.89-11.4 kg/s at 79.9-100°C are discharged in the shallow boreholes or the nearby Nesjavellir stream that disappears into Nesjahraun lava at Lækjarhvarf (Figure 1). This mixes with groundwater, which flows some 3.8 km to the lake Thingvallavatn. About 109.07-169.86 kg/s of condensed steam (57.03-65.62°C), and 736.8-756.13 kg/s of cooling water at 57.6-64.6°C are also discharged into shallow drillholes (data from Reykjavik Energy). Variation in wastewater discharged exists between typical winter and summer months with level of cooling water disposed off being high in summer.

When geothermal wastewater reaches a lake via streams or springs, it mixes with lake water causing dilution of solutes and lowering of temperature. The effectiveness of this mixing process depends on wind driven currents and on local conditions at the point of entry, e.g. to what extent the site is sheltered from mixing currents. In Thingvallavatn wind action is frequent and spring water is quickly and effectively mixed with lake water (Snorrason, 1982). Therefore, any effects of high temperature or potentially harmful solutes in springs affected by geothermal effluents or wastewater, are predicted to be local and restricted to the spring sites (Snorrason and Jónsson 1995).

This paper is a collective review from an ecological risk assessment perspective of various chemical and biological studies on Lake Thingvallavatn and its environs. This is based on temperature and trace elements data for geothermal wastewater at the Nesjavellir power plant and lake shoreline springs i.e. Varmagjá, Eldvík and Markagjá (VGK, 2000), and trace element data from biological samples taken at one of the affected springs at Varmagjá and a control site, Vatnskot, at the northern shore. The samples represent the trophic levels of the local communities; i.e. an aquatic vascular plant (*Myrophyllum alterniflorum*), a gastropod snail (*Lymnea peregra*), a fish (arctic charr *Salvelinus alpinus*), and lake sediment, and cover the years 1989, 1994-6, and 2000 (Snorrason and Jónsson, 1995, 1996, 2000).

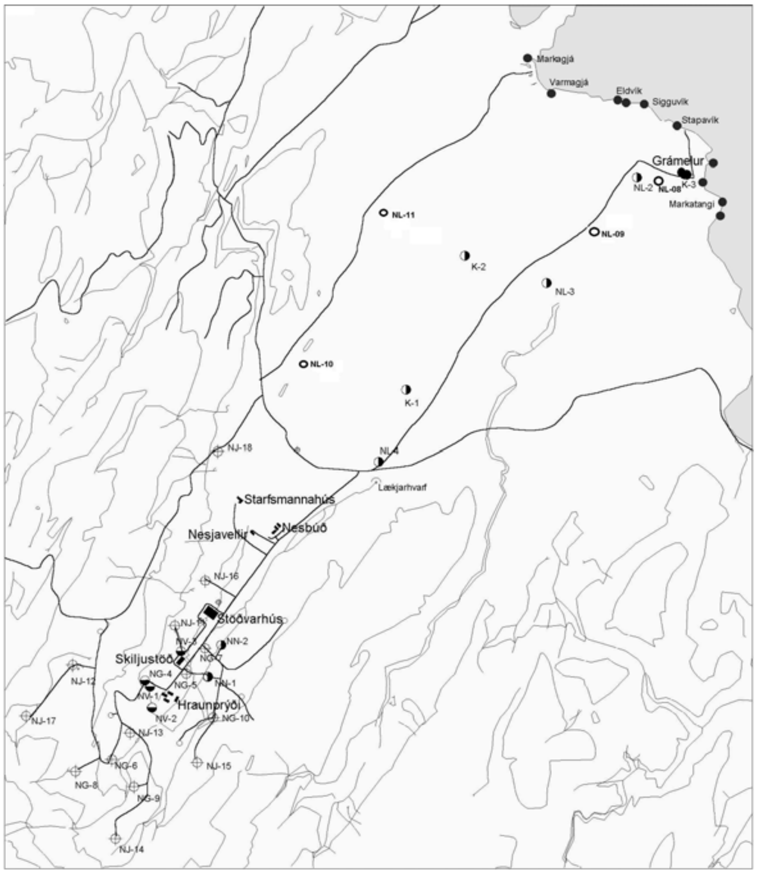

Figure 1: Nesjahraun geothermal wastewater runoff area. Positions of monitoring drill-holes (◑) and lake shoreline springs (●), Varmagjá and Eldvík, inside the affected area, and Markagjá, just outside the affected area, are indicated.

2 Assessment and discussion

2.1 Influence of increased geothermal discharge on lake ecology

The underground flow of geothermal water through the Nesjahraun area has been subjected to a study model based on empirical data from tracer experiments and experimental drilling. Based on injecting a sodium fluorescin tracer the geothermal water has been traced from Lækjarhvarf down to lakeshore springs (Kjaran and Egilson, 1986, 1987). According to these studies the flow was confined to a rather narrow area between Markagjá in the north and Stapavík in the south, the core of the flow being situated upwards of the Varmagjá area (Kjaran and Egilson, 1986, 1987; Ólafsson, 1992). Temperature profiles from experimental drillholes in Nesjaharaun show that the flow of the geothermal water is also confined vertically to a narrow zone a few meters above the cooler ground water table (Hafstað, 2001).

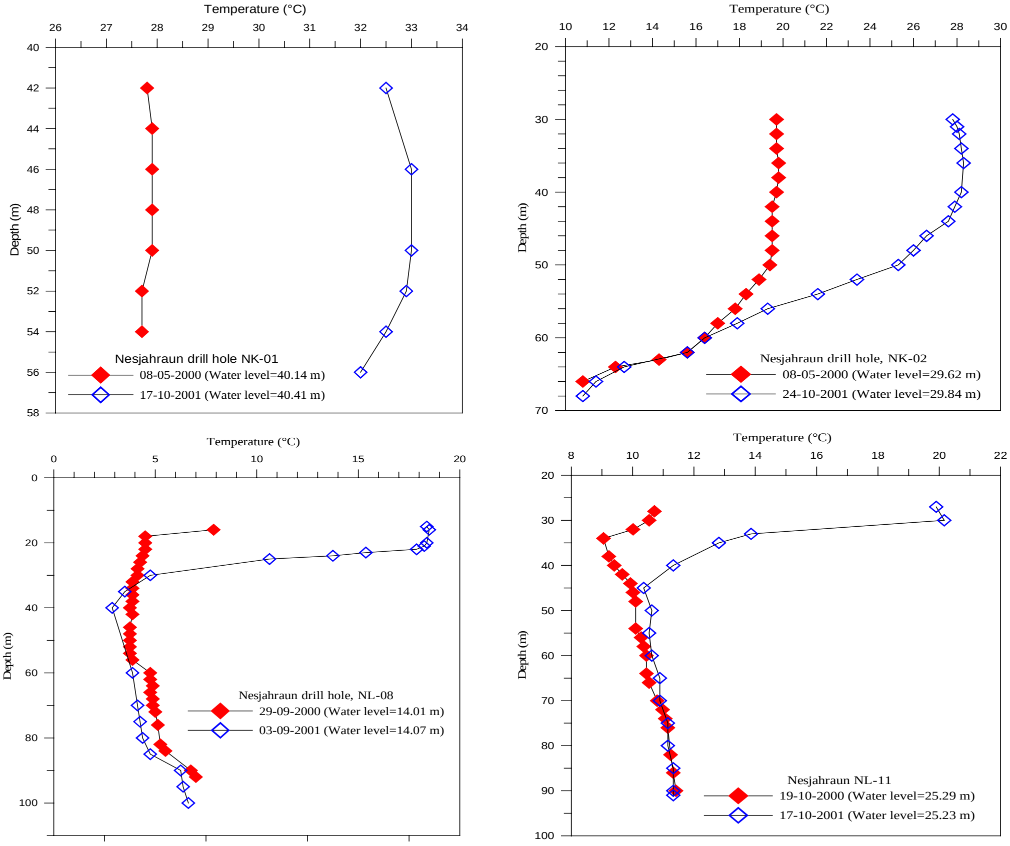

Figure 2: Changes in temperature profiles in four monitoring drillholes in the Nesjavellir lava following a 50% increase in waste water discharge from the geothermal power plant at Nesjavellir in 2001 (Hafstað, 2001).

This means that the main, central stream of geothermal wastewater does not mix much with colder ground water. The most significant change in the system stems from the added disposal of “unusable” cooling water coming from the turbines generating electricity first deployed in October 1998. This addition now amounts to an average of 736.8-756.13 kg/s at 57.6-64.6°C but sometimes can be as high as 1447.6 kg/s of water. The effect of this is clearly seen in changes of temperature profiles in several monitoring drill holes in the Nesjavalla lava from the spring of 2000 to the autumn of 2001 (Hafstað, 2001), when the electricity generation facilities had been in full operation for less than a year. These data show a marked rise in temperature of the central stream of geothermal water (Figure 2, NK-01 and NK-02) and an extension of the warm water tongue at the eastern and western edges (Fig. 2, NL-08 and NL-11).

The volume increase in warm water disposal from the powerplant is also seen in elevated temperatures the thermally affected springs at Varmagjá (a rise from 13-21°C) and Eldvík (a rise from 13-18°C) (unpublished data from Reykjavík Energy) and judging by elevated temperatures in drill holes at the edges of the warm water tongue we expect to see elevated temperatures in springs further to the south of Eldvík.

The effects of elevated spring temperatures in Nesjavallahraun on Thingvallavatn will only be on a local scale. In calm weather tongues of warm water floating on the surface may form temporarily. Such layering is likely to break down quickly due to wave action when the wind picks up. The elevated temperatures are likely to affect the winter ice along the shore between Markagjá and Grámelur with more extensive, permanent openings. Any large scale effects of elevated spring temperature on the Thingvallavatn ecosystem are not expected. Efficient water mixing (Snorrason, 1982) causes temperature drop to the normal lake temperature a few meters away from points of inflow. Hence, the normal cold water adapted benthic algal communities will not be affected (Jónsson, 1992). However, changes can be expected to the benthic communities of plants and animals in the nearest neighbourhood of the springs, particularly in Varmagjá, which, due to its isolation from the lake, is somewhat sheltered from wave action.

2.2 Transport of trace elements by geothermal discharge

To assess potential ecological risk of pollution by nutrients, minerals and trace elements from surface disposal of wastewater from the power plant, concentrations of trace elements in the wastewater have been measured and their fate during flow have been evaluated by measuring concentrations in two of the affected springs, Varmagjá and Eldvík, in the main fresh water source of the plant at Grámelur, and in Markagjá, which is not affected by geothermal activity (Ólafsson, 1992; VGK, 2000). Some of these chemicals, such as SiO_2, K, Al and As, are in high concentrations in the separator water from the plant and can potentially be used as markers for the level of influence of the waste water on the ground water and natural springs in the Nesjavellir area. On its way to the lakeside springs the separator water mixes with the “unusable” cooling water and to some extent with cold ground water. This dilutes the concentration of the above chemicals. The permeable bedrock may also retain some of the chemicals (e.g. the SiO_2). Despite this a clear chemical signal is seen from the cold water well at Grámelur in the east to Varmagjá in the west, the signal being consistently highest in Eldvík (Figure 2.2) (VGK, 2000). In 2001 the production of electricity was increased by 50%. This lead to a 100% average increase in discharge of cooling water while discharged separator water increased by approximately 25%. This could mean a further dilution of geothermal signal chemicals in the ground water.

In the summer of 2000 arsenic concentration was slightly above the recommended 5.0 µg/l Canadian water quality guidelines for protection of aquatic life (CCME, 2001) in the Eldvík spring (5,97 µg/l). Arsenic exists as arsenate (As^{V}) and arsenite (As^{III}). In geothermal water, arsenic exists as arsenate, which is a thermodynamically stable form of arsenic and less toxic (Webster and Timperly, 1995). This however could be reduced to As^{III} by blue-green algae (cyano-bacteria) in the lake springs (Webster and Timperly, 1995). Its high level makes it significant due to its toxicity to aquatic organisms that are influenced by temperature, pH, organic matter content

(Jonnalagadda and Prasada Rao, 1993) and phosphates (Ólafsson, 1992). Other trace elements in separator water and lake springs were below the recommended water quality guidelines for protection of aquatic life. Aluminium was first measured in the year 2000 (VGK, 2000). The concentration in the separator water is rather high, 1670 µg/l, and in the Eldvík springs, the level was 349 µg/l much above the recommended 5-100 µg/l Canadian water quality guidelines for protection of aquatic life (CCME, 2001). Such levels are toxic though toxicity depends much on the form of Al in solution, with Al^{+3} being most toxic. In natural waters Al are generally quite low, usually less than 100 µg/l. however at lower water pH (less than 4) and higher pH (more than 9), Al concentration be much higher making the water toxic to aquatic life. The concentration was also above the lowest biological risk level (LBRL) Swedish criteria of 80 µg/l of Al for protection of fish such as brown trout, *Salmo trutta* (Löfgren and Lydersen, 2002).

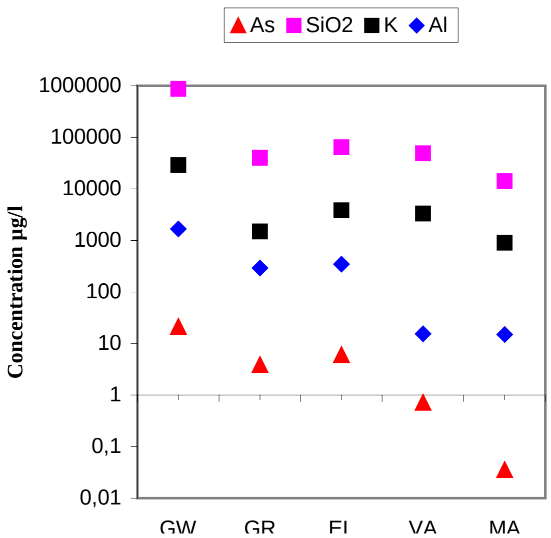

Figure 3: Concentrations of "signal elements" SiO_2, K, Al and As in separator water from the power plant (GW), cooling water well at Grámelur (GR), in two affected springs, Eldvík (EL) and Varmagjá (VA), and an unaffected spring, Markagjá (MA). Based on samples taken in May 2000 (VGK, 2000).

2.3 Trace metals in biological samples

In general the levels of the measured trace elements were low in the biological samples and there was no difference between the geothermally affected site, Varmagja in Thorsteinsvik, and the control site, Vatnskot. Apart from measurement errors the variation seen must be attributed to natural background variation (Snorrason and Jónsson, 2000).

The only trace element showing significant variations in time was Pb (Figure 4. In 2000 Pb in lake sediment at Vatnskot was 42 µg/g (dry weight basis), which is about 20 times the background level. This is above the interim sediment quality guidelines (ISQGs) (ISQG) but within the probable effect level (PEL) according to the Canadian sediment quality guidelines for protection of aquatic life (CCME, 2001). Pb vas also found in at elevated concentratoions in samples of *Myrophyllum alterniflora* in Vatnskot in 1995 and 2000 (about 170 and 10 times the background level, respectively). Such deviations from a background level are likely due to point sources of lead in the form of lead weights and strings of fishing gear that has been lost or left lying.

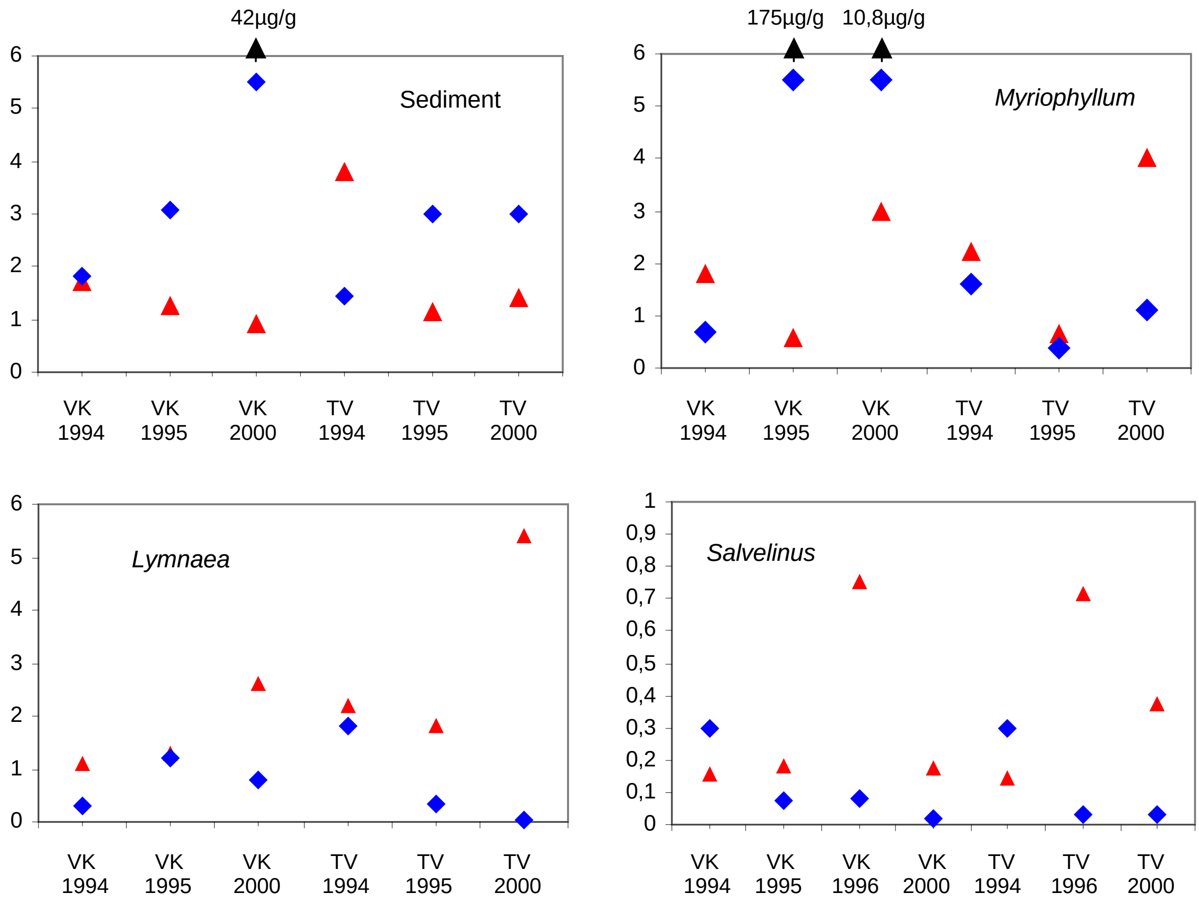

Figure 4: Average concentrations (µg/g) of As (triangle) and Pb (diamond) in biological samples at Varmagjá in Thorsteinsvik (TV) and Vatnskot (VK, control station at the north shore of Thingvallavatn). The samples represent different throphic levels; lake sediment; an aquatic plant, *Myriophyllum*; a gastropod snail, *Lymnaea* peregre; a fish, *Salvelinus alpinus*. Concentrations in the fish samples are on wet weight basis. Concentrations in the other samples are on dry weight basis. (↑) High Pb-concentrations, data points in parentheses are set at the detection limit for the method used this year but are most likely to be lower (data from Snorrasson and Jónsson, 2000).

3 Conclusions

After the start of electricity generation at the Nesjavellir Power Plant increased discharge of hot water has lead to a marked temperature rise, - from 13–20°C, of geothermally affected lakeside springs. Concentration levels of measured solutes in Nesjavellir geothermal power plant wastewater and Thingvallavatn shoreline springs are mostly within the acceptable international environmental quality guidelines on protection of watercourses and lakes. From an ecotoxicological point of view, arsenic and aluminium seem to be the only constituents of the geothermal effluents from the Nesjavellir Power Plant that could potentially affect the ecosystem of Thingvallavatn. In the year 2000 arsenic concentration in the Eldvík spring water was slightly above the recommended 5.0 µg/l Canadian guideline limit for protection of aquatic life. The level of aluminium was several times higher than the recommended 5-100 µg/l Canadian water quality guidelines for protection of aquatic life (CCME, 2001). Efficient, wind driven mixing of spring water with lake water (Snorrason, 1982) precludes any large-scale effects of elevated temperature and chemical concentrations in affected springs. Hence, any biological effects, are expected to be strictly localized. Despite of this, the high conservational value of Thingvallavatn and its surroundings calls for stringent wastewater management. The amount, temperature and chemical composition of wastewater and potentially affected lakeside springs should be closely monitored. The local biota at spring sites should be assessed for effects of increased temperature and chemical effects. To minimize local effects deep reinjection of geothermal wastewater and further cooling of the turbine coolant is recommended.

Acknowledgements

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4 References

CCME. (2001). *Canadian environmental quality guidelines*. Canadian Council of Ministers of Environment, http://www.ccme.ca/ceqg_rcqe/english/E1_06.pdf

Hafstað, H. T. (2001). *Nesjavellir: Temperature measurement in wastewater run-off area*. Orkustofnun, report ÞHH-2001-13 (in Icelandic), 18 pp.

Jónasson, P.M., ed. (1992). Ecolology of oligotrphic, subarctic Thingvallavatn, Iceland. *Oikos*.

Jónasson, P.M. (2002). Verndun Þingvalla og Þingvallavatns. In: *Þingvallavatn. Undraheimur í mótun*, eds., Jónasson, P.M., and Hersteinsson, P., Mál og menning, Reykjavík, pp. 248-281.

Jonnalagadda, S.B. and Prasada Rao, P.V.V. (1993) Toxicity, Bioavailabity and Metal speciation. *Comp. Biochem. Physiol*. Vol. 106C, No. 3, pp. 585-595.

Jónsson, G.S. (1992). Photosynthesis and production of epilithic algal communities in Thingvallavatn. *Oikos, 64*, 222-240.

Kjaran, S.P. and Egilson, D. (1986). Nesjavellir. Áhrif affallsvatns frá fyrirhugaðri jarðvarmavirkjun á vatnsból við Grámel (86-03). – Vatnaskil (in Icelandic).

- and Egilson, D. (1987). Ferlun grunnvatns á Nesjavöllum. – Vatnaskil (in Icelandic).

Löfgren, S. and Lydersen, E. (2002). *Heavy metal concentrations in the Nordic lakes in relation to presently used Critical Limits – a state of the art review*. ICP Waters report 67/2002.

Ólafsson, J. (1992). Chemical characteristics and trace elements of Thingvallavatn. *Oikos*, 64, 151-161.

Snorrasson, S. (1982). *The littoral ecosystem and the ecology of* Lymnaea peregra *in lake Thingvallavatn, Iceland*. University of Liverpool, Ph.D thesis, Liverpool, 429pp.

Snorrason, S. S., and Jónsson G. St. (1995). *Assessment of trace elements in biological samples from Varmagja and Vatnskot*. University of Iceland, Institute of biology, report I, (in Icelandic).

Snorrason, S. S., and Jónsson G. St. (1996). *Assessment of trace elements in biological samples from Varmagja and Vatnskot*. University of Iceland, Institute of biology, report II, (in Icelandic).

Snorrason, S. S., and Jónsson G. St. (2000). *Assessment of trace elements in biological samples from Varmagja and Vatnskot*. University of Iceland, Institute of biology, report III, (in Icelandic) 19 pp.

Taniguchi, Y., Rahel, F.J., Novinger, D.C. and Gerow, K.G. (1998). Temperature mediation of competitive interactions among three fish species that replace each other along longitudinal stream gradients. *Canadian Journal of Fisheries and Aquatic Sciences,* 55, 1894-1901.

VGK. (2000). Nesjavallavirkjun Áfangi 4B. Stækkun rafstöðvar úr 76 í 90 MW. Mat á umhverfisáhrifum. (in Icelandic) 115 pp

Webster, J.G. and Timperly, M.H. (1995). Biological impacts of geothermal development. In: Brown, K.L. (convenor), *Environmental aspects of geothermal development*. World Geothermal Congress 1995, IGA pre-congress course, Pisa, Italy, May 1995. 97-117.

Environmental management at Olkaria geothermal project, Kenya

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Abstract

Geothermal development can have numerous impacts, which if not mitigated can make geothermal resource not environmentally viable. Geothermal utilization can cause surface disturbances, physical effects due to fluid withdrawal, noise and emissions of chemicals. It can also affect the neighbouring communities either socially or economically. The environmental impacts can be mitigated by using several mitigating measures like reducing the drill pad sizes, rehabilitating the opened areas by planting grass and trees, and putting in place monitoring programs. The emissions of greenhouse gases to the atmosphere are far less than with most other energy resources. With the new Environmental Management and Co-ordination Act 1999, KenGen requires to put in place an effective Environmental Management System (EMS) and possibly seek ISO 14000 certification so as to be compliant with all national and international environmental standards.

Keywords: *Olkaria, Hellsgate, environment, impacts, monitoring, geothermal.*

1 Introduction

There is a general shift of concern by industrialists from economic viability of a project to greater emphasis on environmental viability (Armannsson, 1997). Compared to other usable energy sources in Kenya geothermal energy is favorably placed and has been dubbed, " clean energy source" by Environmentalists. Although a clean source it has some environmental impacts but the beauty of geothermal compared to others is that the impacts associated with its development could be mostly mitigated.

The most important environmental impacts brought about by geothermal development include surface disturbance during drilling whereby alot of civil works take place such as access roads for drilling, pipeline routes and well pads. These can lead to serious degradation of the landscape. Particular care must be taken in unstable terrain such as the North-East Olkaria area. Rehabilitation of these areas is carried out in-order to restore the integrity and aesthetic character of the surroundings. Others are physical effects due to fluid withdrawal, noise, chemical emissions and socio-economic effects.

The aim of this paper is to update the reader on the geothermal environmental impacts and the mitigation options practiced at Olkaria, which has led to the co-existence between Kenya Electricity Generating Company (KenGen) and Kenya Wildlife (KWS), as this project is located in Hells-Gate National Park. KWS is legally entrusted with the management of this Park and the conservation of all types of fauna and flora found therein. KenGen on the other hand is involved in the exploration and production of geothermal power within the environs of Hells Gate National Park by virtue of Gazette Notice No. 585 dated 2nd March 1973.

This led to the signing of a memorandum of understanding between these two corporate bodies on 20th September1994 (Agreement on Geothermal Development in

Hells Gate and Longonot National Parks, 1994). KenGen is a member of the Hells Gate and Longonot Management Committee. KWS and KenGen hold joint quarterly meetings on Memorandum of Understanding (MoU).

2 Surface disturbances

Geothermal power development begins with surface exploration studies once a geothermal prospect area has been identified. These studies may include surface geological mapping, geophysical studies and geochemical sampling. Surface exploration has the least environmental effects. There are no major environmental impacts for instance when carrying out surface geological mapping as it only involve walking over the exploration area. There could be slight environmental impact due to the construction of access tracks for geochemical and geophysical measurements.

Land is required for drill pads, access roads, steam lines, power plant and transmission lines. At Olkaria a big chunk of this land is in Hells Gate National Park that is why the scenery and fauna conservation needs attention as the Park attracts many tourists. In this area removal of vegetation is minimised unless it is absolutely necessary like when constructing drilling pads and roads. A drill pad at Olkaria about 3200 m^2 before the pads used to be larger and could be as large as 5000 m^2. The exposure of such an area of 3200 m^2 or 5000 m^2 at each well site creates erosion hazard. This leads to removal of alot of the natural vegetation, which is not desirable as vegetation in Hells Gate National Park is food for the wild animals. The vegetation also helps in soil erosion control.

KWS and KenGen hold joint quarterly meetings to discuss and agree on plans for expansion of exploration and development. All the drill pads together with the ponds are rehabilitated after drilling and well testing by planting *Tarchonanthus camphoratus* (Mleleshwa), *Acacia drepanolobium* and the indigenous grasses like star grass (Figure 1).

Figure 1: Picture showing well OW-708 site rehabilitated with star grass and Acacia.

The tree seedlings are raised in the project tree nursery. The problem of tree growing in this project is that the survival percentage is very low because the wild animals feed on them.

So well rehabilitated sites with star grass without trees is a common feature at Olkaria North East area.

Drill rig seen from a far may be a prominent feature during drilling and this can cause visual impact, but disappear after the start of production. Some people on the other hand find drill rigs magnificently beautiful, like the school and college groups, who visit the project.

Road construction in steep areas like North East Olkaria normally involves extensive intrusion into the landscape and can cause serious erosion hazard with consequent loss of vegetation cover. Provided the road surface itself is stabilised with murram or is tarmaced as most of them are in Olkaria, the runoff is diverted at regular intervals before it accumulates to problem levels, and the situation can be kept under control. Clearing land for roads before determining the best alignment can cause serious problems. In the MoU meetings KenGen and KWS do discuss on plans for expansion of exploration areas development, in this regard they discuss and agree on road designs and construction for the purpose of harmonizing the transport network within Hells Gate National Park. At Olkaria today a team comprising of the Surveyor, Environmental Scientist and Civil Superintendent has to peg the area for the road before actual road construction works commences. Olkaria I and Olkaria II power plant that is nearing completion are located on a fairly flat area. These locations therefore do not have a severe impact on the landscape. Once again re-vegetation or some other sort of slope stabilisation and appropriate drainage is a priority. Pipeline corridors are typically 3-5 m wide during construction depending on the pipe size. Access roads may be needed for construction and maintenance. After construction of the pipes, planting star grass, “Mleleshwa” and Acacia Sp, rehabilitates the corridors. The steam pipelines are often painted to blend into the landscape. The pipelines for Olkaria I plant were not painted and visual impact is evident but that for Olkaria II are painted to blend with the Olkaria Environment.

Transmission lines require a corridor about 40m free from overlying vegetation for a 220kV line, like the one which will be constructed from Nairobi to Olkaria II plant. Access roads will be required for the construction of large steel pylons. The ones for Olkaria II line will be between 35-40m high. There exists a 132kV line as well for Olkaria I plant. In smaller power developments, wooden poles placed adjacent to the roads provide satisfactory electricity transmission like the current 8MW from Olkaria III plant are using the 33kV Narok line. The 220kV line will pose several environmental challenges, as it will have 15 towers for the 220kV line and 8 for the 132kV line. Access roads will be required; this means substantial interference with Hells Gate National Park but this will not be permanent, as it will stop when the project is completed. All possible surface disturbances should be incorporated in an environmental impact report prior to exploitation and optimum solutions devised in co-operation with all concerned.

Untidiness in the vicinity of drilled wells and other constructions can cause unacceptable eyesores. Inspection of sites is one of the monitoring programs conducted by the environmental team in the project. Biannual internal audits are also carried out to correct the same.

3 Noise

Noise is one of the most irritating disturbances to the environment from geothermal development, particularly during the construction and operation phases. Noise can be considered as "unwanted sound" and any development should aim at minimising this impact (Brown, 1995). Noise intensity is measured in decibels denoted dB (A). At Olkaria the levels are measured by use of a hand held integrating-averaging sound level meter. Noise that is specific to geothermal is drilling noise, which rarely exceeds 90dB, and the noise from a discharging well mostly under flow test, which may exceed 120dB. Using silencers this noise can be brought down to about 85dB, the noise acceptable to occupational safety authorities for people working for eight hours. So even with good designs for noise reduction workers must use ear protectors both during drilling and discharge tests.

The number and locations of the stations for noise monitoring were selected after carrying out an extensive survey to determine the potential noise sources in the project area. Thirteen (13) sites were designated as noise monitoring sites or stations. The noise level measurements are taken twice a week in all the monitoring sites or stations.

Table 1. Mean Environmental Noise level in dB (A) from 1996-1999.

Station	**1995**	**1996**	**1997**	**1998**
Power station	90.8	90.2	89.7	86.6
Offices	68.4	68.6	67.8	71.4
W/Shops	56.2	53.7	50.5	52.4
KWS Olkaria G	49.5	48.2	44.5	45.5
L/View estate	46.0	43.8	44.0	41.6
L/Side estate	44.7	42.7	42.9	40.3
Geology lab.	63.4	nd	nd	69.5
N370	67.9	86.4	nd	nd
X-2 Camp	59.4	54.6	nd	Nd
OW-10	nd	nd	63.5	62.5
Seal Pit 1	nd	nd	64.5	67.5
Seal Pit 2	nd	nd	69.3	68.8
Stores	nd	nd	66	59.3

NOTE: nd: Not determined; OW: Olkaria Well

The occupational health and Safety criteria in Kenya, regardless of hearing protection is 85dB (A) average noise level in a work place for an employee working 8-hour day. Other than the power station and the N370 rig, which have levels above Occupational exposure, limit the rest have levels far below.

4 Thermal effluents

Wasteheat is contained in the wastewaters and some in the steam. The heat contained in the steam is the principal heat used to generate electricity. Olkaria I plant uses a cooling tower to vent out the heat to the atmosphere contained in the condenser outflow and the main impact resulting from this is on the local climate. Localised slight heating of the atmosphere and an increased incidence of humidity lead to fogging a common feature at Olkaria I power station area from June to August. The foggy conditions occur during the early hours of the morning and clears by 9.00 a.m. The hot wastewater when disposed off on the surface like during well testing can have some effect on the surrounding vegetation by scorching the plants dry. Carry-over from wells under discharge have negative effects on local vegetation with shrubs and trees being scalded by escaping steam, this was evident when well OW-714 was under test (Were, 1997). This effect is not permanent as the vegetation heals after the rains. To mitigate this impact at Olkaria of hot waste water on vegetation deep reinjection will be the solution. Like waste water from OW-27, OW-31 and OW-33 are reinjected to well OW-03. Most of the geothermal wastewater is disposed off by deep reinjection.

5 Water usage

Water is required for drilling as drilling fluid, it is used during the construction phases for compaction, and it is required for reinjection well testing and is needed for cooling water in the power station. A small amount is required for domestic use at the staff housing estates and at the offices. There will obviously be an impact on the Lake Naivasha, which is the source of this supply. A typical production well at Olkaria drilled to a depth of 2200 m can utilise up to 100,000 m^3 of water some or all of which may be lost to the formation. Negligible amounts of water are required for cementing. Completion testing and injection testing can use up to 10,000 tonnes of water per day. The amount of water used during construction is relatively small, and for Olkaria I plant which utilises a cooling tower system water is required only at startup after which recycling and re-use is practiced. The Ministry of water has granted Olkaria project permission to pump water from Lake Naivasha by issuing the Company with an abstraction license. The reason why the Olkaria Geothermal project is implementing the Eco cycle in most of its activities is because the water it uses is from Lake Naivasha, which is a highly significant national freshwater resource in a semi-arid area. Apart from the invaluable fresh water it provides, it also supports large and important economic activities – mainly flower growing and geothermal power generation. The Lake is thus a major contributor to Kenya's GDP and to the socio-economic development of the country as a whole. It is a Ramsar Site of international significance. KenGen is a member of Lake Naivasha Riparian Association. (LNRA) whose membership are all stakeholders who own riparian land, and a community based management plan (The Lake Naivasha Management Plan) for sustainable use of the Lake. Lake Naivasha Management Implementation Committee has been formed to implement the management plan. Representation of the committee is from KenGen, Municipal Council, Local administration, Kenya Wildlife Service, International Union for Conservation of Nature (IUCN) and Lake Naivasha Growers Group. In the management plan various stakeholders have developed codes of conduct to govern their activities with respect to the Lake. For the energy sector, KenGen has developed a comprehensive code of conduct and all power producers including the IPPs operating in the vicinity of the Lake are expected to adhere to it. The efforts of LNRA have been recognized by winning the Ramser wetland Conservation Award at the 7^{th} Meeting of the Contracting Parties that was held in San Jose, Costa Rica, in May 1999. There is a continuous monitoring programme to monitor the physical and the chemical properties of the water. During drilling water is recycled from the sumps, which assists to stop drilling effluent from flooding and polluting the environment.

6 Solid wastes

Geothermal development produces significant amounts of solid waste, therefore suitable disposal methods need to be found. Because of the heavy metals particularly arsenic, which are contained in geothermal waters, these solid wastes are often classified as hazardous waste. During drilling, wastes are produced in the form of drilling muds, petroleum products from lubricants, fuels and cement wastes. Drilling muds are either lost through circulation in the well or end up in the drilling sumps as solid waste for disposal. Since a lot of fuel and lubricants are used when drilling a single well, (approx. 300,0000 liters of diesel) storage and transport of these products should follow sound environmental practice as stipulated in the new KenGen Environmental Policy. Cements are not normally considered hazardous, although some constituents like silica may be hazardous on their own. During operation of the power plant, as for Olkaria I plant, there is special provision for safe storage of lubricants and fuels. The principal solid wastes are cooling tower sludges, which may contain mercury. The waste brine from the power station that contains traces of solid wastes (heavy metals) is safely disposed to the infiltration pond avoiding any spills, but the plan is to reinject all this wastewater into one of the wells. The other major solid waste is construction debris and normal maintenance debris. All these are transported safely avoiding any spills along the way to a designated disposal site or landfill near well OW-3, which is periodically monitored and audited, to see that it is environmentally safe.

7 Chemical discharge

Chemicals are discharged to the atmosphere via stem steam and into ground water systems via the liquid portion. Hydrogen Sulphide gas emission is the major gas that causes the greatest concern due to its unpleasant smell and toxicity at moderate concentrations. At the Olkaria Geothermal Power plant measurements done in November-December 1991 recorded maximum 1-minute concentration of 1.25 ppm (Sinclair Knight & Partners, 1994). Measurements in the steam plume from 0W-709 recorded concentrations of around 0.15 ppm. Hydrogen Sulphide gas is measured at Olkaria by using a Sambre PM 200 series of personal gas monitors, which is designed to continuously monitor one gas. Monitoring is done three times in a week for most locations around the power station and at least once in a week for those sites further away. There are a total of ten main monitoring sites for H_2S (Table 2). These are distributed to cover residential areas (the Lakeside and Lakeview estates), occupational workplace areas (Power station, Seal Pit 1 and 2), workshop, stores, administration block (Adm) areas of predominant wind direction (well OW-10) and entry points to Hells Gate National Park through Olkaria (KWS Olkaria gate and Gate near well 22).

The occupational exposure limit (O.E.L) of H_2S in work places is 10ppm for an averaged 8-hour day. It is important to note that H_2S levels at Olkaria are far below the occupational exposure limit, maximum figure recorded was at the power station 4.40 ppm (Table 2).

Table 2. H_2S concentrations (ppm) at various locations around Olkaria I Power plant (Environmental BOC report 1999).

	W/S	P/S	Admin	SP1	SP2	W-10	W-22	KWS	LV
AV	0.02	0.5	0.05	0.16	0.2	0.09	0.06	0.02	0
MAX	0.8	4.4	1.3	2.8	3.4	1.3	1	0.2	0.1
MIN	0	0	0	0	0	0	0	0	0
MED	0	0.2	0	0	0	0	0	0	0

NOTE:

KWS: Kenya Wildlife Service
LV: LakeView Estate
W/S: Workshop

P/S: Power station
Adm: Administration
SP: Seal Pit
W: Well Site

Carbon dioxide, which is usually the major constituent of geothermal gas, and methane have been causing concern because of their role as greenhouse gases. However the carbon dioxide emission from geothermal plants is small compared to that of fossil fuel plant (Table 3) and therefore any energy production by fossil fuels that can be replaced by geothermal energy is environmentally desirable. Carbon dioxide and methane from geothermal is a negligible source. Minor gases that cause concern, i.e. Hg, NH_3 and B have not been found in dangerous concentrations in most of the geothermal plants in the world. At Olkaria these gases are not monitored in the emissions but are analysed in the geothermal wastewaters.

Separators (silencers) are often inefficient and large quantities of water may be ejected from them over large areas as spray containing substances as boron that are harmful to plant life at high concentrations and arsenic. Also high concentration of silica is deposited on the ground. The main potential pollutants in the liquid effluents and which are monitored on quarterly basis at Olkaria include, arsenic, boron, mercury, lithium, zink, lead and cadmium (Table 4). The concentration levels at Olkaria have been found to be below the optimum limits, above which these environmental components are considered contaminated or polluted. Surface disposal of such water may be quite hazardous and can cause damage to flora and fauna as substances like As and Hg have been known to accumulate in plants and animals. This will not be desirable considering that our developments are taking place in Hells Gate National Park. The most effective method of solving the pollution by geothermal wastewater (liquid effluent) is the reinjection of the spent fluids.

Table 3. Emissions of carbon dioxide and sulphur from some types of power plant (Armannsson, 1998)

Plant type	Specific	CO2 g/kWh	S g/kWh
Fossil fuel	Coal	1000	11
	Oil	850	11
	Gas	550	0.005
Geothermal	Steam	96	6
	HDR	0	0
Solar	SEGS	140	0
	Battery	0	0
Nuclear		<1	0
Hydropower		0	0

Table 4. Some chemical contaminants monitored at Olkaria.

	Li	Cu	Zn	As	Cd	Ba	Hg	Pb	B
Sludge	-	1.6	0.47	0.017	<1	0.167	0.001	0.6	-
Soil	0.4	1.63	13.5	-	0.123	5.1	-	3.05	-
Vegetation	0.7	0.54	10.3	-	0.03	1.2	-	1.25	-
Waste Water	1.28	<dl	<dl	-	<dl	<dl	-	0.1	5.1
Lake Water	<dl	<dl	0.02	0.001	0.001	0.001	0.001	0	0.11

8 Socio-economic effects

Olkaria geothermal project is located within Hells Gate National Park. Oserian Development Company, which grows cut flowers for export, is approximately 1.2 km to the north-northeast of the Olkaria II power plant whose construction begins in August. Lake Naivasha is approximately 5.3 km to the north. This shows clearly that the project is surrounded by very sensitive Landuse systems. It is interesting to note however that Olkaria project has more positive impacts to the neighbours than many people think. Some of the positive impacts associated with this project include, the tarmacking of the Moi South Lake road, which has “opened up” the area. It has made Hells Gate National Park more attractive to tourists and the maintenance cost of vehicles has reduced drastically for all the road users attracting public transportation in this area, which was a problem before. It has been observed that most of the visitors who visit this Park are attracted more by the power plant than the animals. Olkaria project has provided free piped water to the local community (The Maasai), allows their children to go to the project school, incase of an emergency they can get health services from the dispensary. The project assists the community with transport from the station, as there are no public vehicles.. The observed negative impact is a temporary increase in employment and the importation of an outside labourforce during construction. This calls for various services, and it has been observed that this puts a strain on the traditional way of life and “leave a scar” when the construction work is completed. It is the wish of Olkaria project management not to have contractors staying in the residential areas together with company employees.

9 Monitoring programs

The following monitoring programs are carried out at Olkaria Geothermal project.

1. Monitoring of noise emissions at sensitive receptor sites
2. Hydrogen Sulphide gas monitoring
3. Meteorological weather monitoring
4. Precipitation chemistry monitoring
5. Chemical elements of environmental significance in wastewater, soil and vegetation
6. Monitoring of vegetation patterns
7. Potable water quality monitoring

10 The environmental management and co-ordination act, 1999

This act is operational. It is an act of parliament to provide for the establishment of an appropriate legal and institutional framework for the management of the environment and for matters connected therewith. The functions will be carried out by an Authority to be known as National Environment Management Authority (NEMA). This act may affect our operations by delaying our projects because of the many licenses, which will be required to be obtained unlike before this act. For example the following licenses will be required for geothermal development.

1. Environmental impact assessment license.
2. Effluent discharge license
3. Excess noise permit
4. Effluent discharge permit
5. Emission license
6. Disposal site permit

Another thing, which will affect geothermal development, is the penalties for polluters as the authority, which will be, formed will be entering any premise or land

and auditing their activities. This calls for the project to immediately put in place an effective Environmental Management System (EMS) and probably have the company seek ISO-14000 certification.

11 Conclusion

Geothermal energy is relatively clean energy source. The possible environmental impacts from its exploitation include surface disturbance, physical effects due to heat effects, emission of chemicals and socio-economic effects. All these impacts can be minimized. Putting in place monitoring programmes can check the unforeseen impacts, which only appear during operational phase of geothermal development. Olkaria geothermal project has not degraded the quality of the environment of Hells Gate National Park. To avoid problems with the new Environmental Management and Co-ordination Act KenGen requires to put in place an effective Environmental Management System (EMS) and seek ISO 14000 certification.

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12 References

Armaannsson, H. (1997). *The most important environmental effects of geothermal exploitation*. Orkustofnun. Annual General Meeting Report.

Agreement on Geothermal Development in Hells Gate and Longonot National Parks. (1994).

Brown, K.L. (1995). In: Brown K.L. (Convenor). Environmental Aspects of Geothermal Development. *World Geothermal Congress1995, IGA pre-congress course, Pisa, Italy* pp. 39-55.

Kubo, B.M. (1997). *Preliminary environmental assessment for drilling in the Krisuvik-Trolladyngja area, SW-Iceland*. UNU Reports, pp. 221-247.

Kubo, B., Kollikho, P; Were, J. (1999). *Environmental Report for the second BOC meeting.* Unpublished Kengen Internal Report.

Kubo, B., Kollikho, P., Were, J., Wetang'ula, G. (1999). *Environmental issues relating to the proposed development in Olkaria (III).* Unpublished Kengen Internal Report.

Sinclair Knight and Partners. (1994). Environmental assessment report for Northeast Olkaria Power Station Development Project.

Rapid environmental assessment tool for the extended Berlin geothermal field project

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Abstract

Environamental Impact Assessment (EIA) is a tool used in the planning of development strategies and projects, and its use has been adopted into planning regulations in El Salvador. The historical development of EIA shows that a number of attemps have been made to improve the quality of the EIA analysis by seeking to improve the accuracy of the judgement, resulting in a number of formats being developed for EIA analyses in. In any the judgements will be subjetive, either in whole or in part. This is a consequence of many factors: the lack or inadequacy of baseline data, the time frame provided for data adquisition and analysis, the terms of reference provided for the EIA, and the capacity of the assessors to cover a wide range of issues. Even where quantitative environmental data is available, the overall use of this data requires a subjetive judgement of the possible impact, its spatial scale and potencial magnitude A new method for EIA to allow subjetive judgements to be quantitatively record, thus providing both impact evaluation and a record that can be re-assessed with the passage on time, is the Rapid Impact Assessment Matrix (RIAM), which is applied in the Extended Berlin Geothermal Field Project. Gethermal development experts successfully applied this method making the enviromental assessment easy and rapid with economical benefits for the company. It even resulted in an easy process for environmental legal evaluators.

Keywords: *Rapid EIA tool, RIAM, environmental, evaluation, Berlín geothermal field.*

1 Introduction

An extended Berlín geothermal field project was designed to increase installed capacity from 56 MW to 85 MW, which will cover national market electric power demand, through natural resources exploitation. The extent covers an area of 7.5 km^2 located in the southeast part of the Berlin Geothermal Power Plant area, which is planned to be implemented from 2003 to 2005. The project is designed in two phases:

PHASE - I: Technical (geoscientific) investigation in the southeast part of the geothermal field, through deep exploratory drilling of 3 wells in different pads for production and reinjectio purposes. If the results are promising, then the drilling program will continue.

PHASE - II: The program will cover 12 drilling wells, pipelines and a surface equipment system and the third unit of 28 MW in order to complete the installed capacity of 85 MWe. Table 1 shows the zones and type of activities of the project.

Table 1: Characteristics of the project.

ZONE	PHASE 1	PHASE 2
Las Crucitas	1 production well	3 production wells
Los Cañales	1 production well	3 production wells
San Antonio Guallinac	1 reinjection well	2 reinjection well
Berlin Power Plant Existing		Unit 3, steam pipelines and reinjection well

2 Environmental analysis

As part of the strategy implemented by Geotérmica Salvadoreña (GESAL) environmental permission was obtenined in order to get the resolution from El Salvador environmental authorities for the "Extended Berlin Geothermal Field Project", which includes the following steps:

- Identification of main activities for the project execution (civil work and drilling wells)
- Characterization and inventory of the environmental factors for access roads and drilling well zones
- Identification of an Impact Matrix
- Preliminar Impact Assessment Matrix
- Using Rapid Impact Assessment Matrix (RIAM) to evaluate positive and negative impacts of the project according to the Environmental Impact Assessment (EIA)
- Results analysis using software applied to the project

A team of four experts covering the disciplines of geologist, biologist, sociologist and a chemist were involved in each of the developed stage. The environmental analysis was a success due to the data base fed to the software from the time of identification until the assessment matrixes, which provided environmental management plan in an easy and rapid manner with economical benefits for the company and the easy process for environmental legal evaluators, where available.

3 Methodology and procedure

The environmental assessment consists of four stages:

a) Brain storm during a participative workshop session with specialist for impacts identification comparing scenarios with work project and significant impacts and those significant, positive, negative and the indifferent ones.

b) A second participative workshop to prioritize positive and negative potential impacts, using a preliminary assessment matrix based on the environmental components designed in the RIAM. Table 2 shows the score given to each of the criteria in groups A and B weight of to each category.

c) Rapid Impact Assessment Matrix (RIAM) Method is based on standard definition of the important assessment criteria as well as the means by which semi-quantitative values for each of these criteria can be collected to provide and accurate and independent score for each condition. The impacts of project activities are evaluated against the environmental components and for each component a score is determined, which provides a measure of the impact expected from the component. The important assessment criteria fall into two groups:

Group A: Criteria that are of importance to the condition, and which can individually change the score obtained.

Group B: Criteria that are of value to the situation, but individually should not be capable of changing the score obtained.
The value ascribed to each of these groups of criteria is determined by the use of a series of simple formulae. The scores for individual components may be determined on a defined basis by the use of these formulae. The process can be expressed:
(A1) * (A2) = AT
(B1) + (B2) + B3 = BT
(AT) * (BT) = ES is the assessment score for the condition.

d) Complete Environmental Assessment

Table 2: Preliminary environmental assessment.

						Environmental
PRIORITIZED IMPACTS	A1	A2	B1	B2	B3	Score
Physical / Chemical						
Change in land uses	1	-1	3	2	1	**-6**
Levels noise increase	1	-1	2	2	2	**-6**
Change in soil permeability	1	-1	3	2	2	**-7**
Soil accidental spills polution	2	-1	2	2	2	**-12**
Biological / Ecological						
Flora elimination	0	0	1	2	3	**0**
Fauna migration	0	0	1	2	3	**0**
Loss hábitat	0	0	1	2	3	**0**
Sociological / Cultural						
Employment	2	1	2	2	3	**14**
Traffic increase	2	1	2	2	3	**14**
Rural internal roads improvement	2	1	3	1	1	**10**
Landscape alteration	1	0	3	2	2	**7**
Safety labor and publics health	1	0	2	2	1	**0**
Crops and housing incidents	1	0	1	2	1	**0**
Extent services	1	1	2	2	3	**7**

Environmental Components: The RIAM requires a specific evaluation of the components to be defined through the process of “scoping” and these environmental components will be in one of the four categories that are described as follows:

- Physical / Chemical (PC): Covering all physical-chemical aspects of the environment
- Biological / Ecological (BE): Covering all biological aspects of the environment
- Sociological / Cultural (SC): Covering all human and cultural aspects of the environment
- Economic / Operational (EO): To qualitatively identify the economic consequences of the environment change, both temporary and permanent impacts.

For the analysis of the results, in the category of the component (SC) of the preliminary assessment matrix (Table 2), it was subdivided in components (SC) and (EO) as part of the requirement of RIAM.

Assessment criteria: The criteria should be defined for both groups, and be based on fundamental conditions that maybe affected by changes rather than be related with project activities (see Table 3).

Table 3: Assess criteria.

Category	SCALE	Description
A1: Importance of condition	4	Important to national / international Interest
	3	Important to Regional / national Interests
	2	Important to inmediately outside the local condition
	1	Important only the local condition
	0	No importance
A2: Magnitude of change-effect	+3	Major positive benefit
	+2	Significant improvement in “status quo”
	+1	Improvement in “status quo”
	0	No change / “status quo”
	-1	Negative change to “status quo”
	-2	Significant negative dis – benefit or change
	-1	Major dis-benefit or change
B1: Permanence	1	No change / not applicable
	2	Temporary
	3	Permanent
B2: Reversibility	1	No change / not applicable
	2	Irreversible
	3	Irreversible
B3: Cumulative	1	No change / not applicable
	2	Non – cumlative /single
	3	Cumulative / synergistic

The method of the RIAM allows the carrying out out of a global analysis of the results, based on the individual environmental score (ES) for each component, which are classified in ranges and can thus be compared to each other. Table 4 provides the established ranges for the conversion of scores obtained.

The enclosed Table 4, shows the 16 components analyzed for the project, individual score (punctuations) and equivalence in the band of ranges (RB), as well as a global summary of the total punctuation. Once these are classified, they are shown individually or contained according to the component type and presented numerically (see Table 5 at the end of the paper) or as histograms.

Table 4: Band of ranges.

ENVIRONMENTAL SCORE (ES)	BAND OF RANGES	DESCRIPTION
+72 at +108	+E	Changes / Major positive Impacts
+36 at +71	+D	Changes / significant positive Impacts
+19 at +35	+C	Changes / moderate positive Impacts
+10 at +18	+B	Changes / positive Impacts
+1 to + 9	+A	Changes / lightly positive Impacts
0	N	Non changes / “status quo” / not applicable
-1 to – 9	-A	Changes / lightly negative impacts
-10 at –18	-B	Changes / negative impacts
-19 at –35	-C	Changes / moderate negative impacts
-36 at –71	-D	Changes / significant negative impacts
-72 at –108	-AND	Changes / Major negative impacts

4 Analysis of results

The summary of the total marks given (Table 5), as well as the histograms of Figure 1 (at the end of the paper), which contains all the components, and the comparison of the data of Table 4, the actions adopted by the Extended Berlin Geothermal Field Project, prevents the following environmental aspects:

- Changes in environment for negative impacts due to soil spill pollution (-12 / -B); changes slightly negative impacts due to increase in noice level or the use of machinery (-6 / -A), both inside the category of the physico chemical factors. See Figure 1.
- There won't be changes in the natural state ("status quo") for 7 impacts foreseen in the 4 analyzed categories.
- There will be positive socio-economic changes from the operation (Ranges from +1 up to +35, equivalent to the bands A, B and C), according to the results of the graph.

5 Conclusions

A key aspect of the project is that it has considered measures of environmental control in each of the activities and will be incorporated in the final designs of civil works and drilling of wells. Also to improve the access roads and opportunity of temporary employments in the area, reason for which the realization of the project helps sustain good employment prospects for the communities.

The Rapid Impact Assessement Matrix (RIAM) method, including project activities and the influence area knowledge of enviromental team were important to environmental analysis. The last studies took from 4 to 5 months, whereas only 1.5 months were needed for the same studies in this case saving the company US$ 60,000 in cost.

6 References

Arevalo, A. (1998). *Environmental aspects of the Berlin geothermal power station in El Salvador;* searching report, geothermal training in Iceland Book.

Christopher M.R. Pastakin. (1998). *The Rapid Impact Assessment Matrix,* RIAM Horsholm.

Lopez, R. and Arevalo, A. (2000). *Environmental diagnostic of Berlin geothermal power station*, GESAL Co. Book, El Salvador C.A.

Table 5: Total analysis for component.

Significant impacts		ES	RB	A1	A2	B1	B2	B3
FQ1	Land use changes	8	A	1	1	3	3	2
FQ2	Level noise increase	-6	-A	1	-1	2	2	2
FQ3	Soil permeability changes	0	N	1	0	1	1	1
FQ4	Soil uncertainty changes	0	N	0	0	1	1	1
FQ5	Soil pollution spills	-12	-B	2	-1	2	2	2

Biological and ecological component (BE)

Significant impacts		ES	RB	A1	A2	B1	B2	B3
BE6	Flora elimination	0	N	0	0	1	2	3
BE7	Habitat loss	0	N	0	0	1	2	3

Sociological and Cultural component (SC)

Significant impacts		ES	RB	A1	A2	B1	B2	B3
SC8	Geoscientics research	27	C	3	3	1	1	1
SC9	Landscape alteration	0	N	1	0	3	2	2
SC10	Labor and public accidents	0	N	1	0	2	2	1
SC11	Rural roads improvement and zone risk lessen	10	B	2	1	3	1	1

Economic and operational component (EO)

Significant impacts		ES	RB		A2	B1	B2	B3
EO12	Tourism opportunity	14	B		1	2	2	3
EO13	Access roads improvement	10	B		1	3	1	1
EO14	Extend services	7	A		1	2	2	3
EO15	Land Acquisition	0	N		0	3	3	3
EO16	Employment opportunity	14	B		1	2	2	3

SUMMARY OF PUNCTUATION

Range	-108	-71	-35	-18	-9	0	1	10	19	36	72
	-72	-36	-19	-10	-1	0	9	18	35	71	108
Class	-E	-D	-C	-B	-A	N	A	B	C	D	E
FQ	0	0	0	1	1	2	1	0	0	0	0
BE	0	0	0	0	0	2	0	0	0	0	0
SC	0	0	0	0	0	2	0	1	1	0	0
EO	0	0	0	0	0	1	1	3	0	0	0
Total	0	0	0	1	1	7	2	4	1	0	0

Figure 1: Project Global Grafic Analysis.

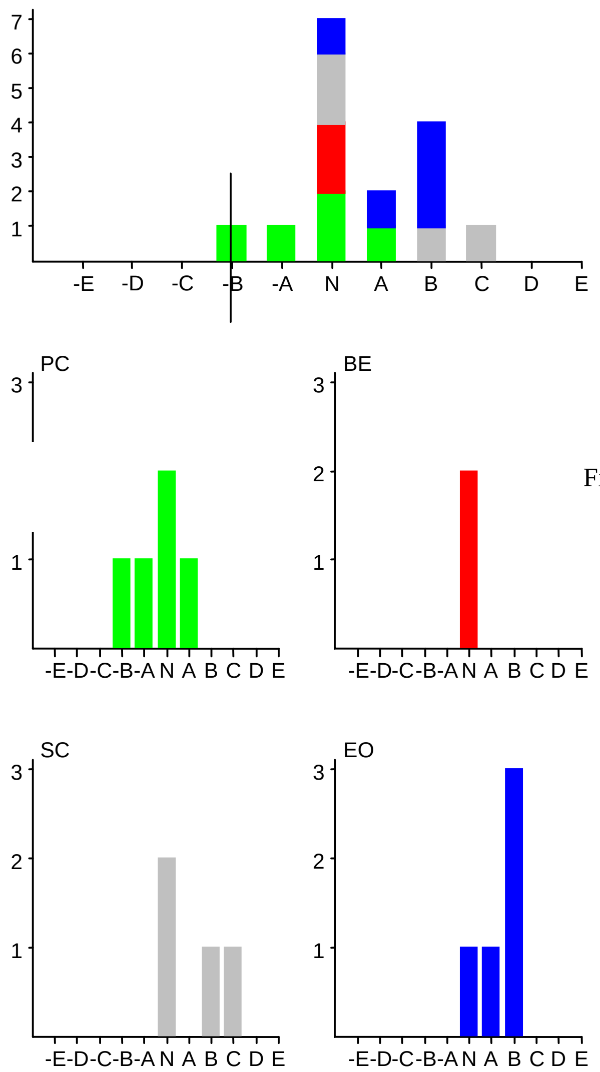

Figure A

Figure B

Figure C

Figura D

Two dimensional subsidence modelling at Wairakei-Tauhara, New Zealand

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Abstract

Subsidence at Wairakei-Tauhara due to almost 50 years of geothermal fluid extraction was modelled by two dimensional finite-element analysis. The software accommodates variable rock properties, including non-linear stress-strain behaviour, and pre-consolidation history. A good match to historical subsidence in time and space was achieved with a single set of rock properties for each geological unit, apart from two local zones with different permeability. Compared to previous 1-D subsidence modelling, this study shows a greater sensitivity to changes in reservoir pressure and strong control over the location of subsidence by the morphology of the lowest unit in the Huka Falls Formation. It is predicted that subsidence may lead to subsurface shear failure, which will enhance vertical permeability, and therefore cause an acceleration of subsidence rates.

Keywords: *Wairakei, Tauhara, subsidence modelling.*

1 Introduction

Almost 50 years of geothermal power generation at Wairakei, mainly without reinjection, has caused extensive pressure decline within the reservoir, and subsidence of the ground surface. This locally exceeds 15 m, which is greater than at any other geothermal field. The Tauhara geothermal field (Figure 1) is hydrologically connected to Wairakei, and following declining pressures in the 1960s, there has been up to 2.5 and 1.6 m of subsidence in two separate subsidence bowls (Figure 1). In recent years, a new area of subsidence has formed in southern Tauhara, near the Taupo urban area.

Wairakei power plant (commissioned 1958) extracts about 140,000 tonnes per day (tpd) of fluid. Partial reinjection (begun 1996), now comprises about 40,000 tpd. Poihipi power plant on the western side of Wairakei (commissioned 1997) produces 4,800 tpd from a shallow steam zone, with all condensate reinjected outside the field. A development at Tauhara that will extract another 20,000 tpd (with full reinjection) should occur by 2005, and further expansion is planned for Wairakei (Contact 2001, Geotherm 2001). Past 1-D modelling by Allis and Zhan (1997) and others has been used to predict future subsidence. However, there are significant limitations with the 1-D method; hence the need for detailed 2-D modelling.

Subsidence due to exploitation has been documented at many geothermal fields, including the Geysers (Mossop and Segall 1997), Svartsengi (Eysteinsson 2000) and Cerro Prieto (Glowacka *et al*. 2000), but at rates that are typically an order of magnitude smaller than at Wairakei-Tauhara. Accordingly, little modelling or future prediction has been applied to geothermal subsidence outside of New Zealand. Much greater subsidence and more refined modelling has been applied to oil/gas and groundwater reservoirs, such as the Ekofisk, Beldridge and Lost Hills oil/gas fields (*e.g*. Chin et al 1993, Fossum and Fredrich 2000), and lessons from these examples have been applied in this study.

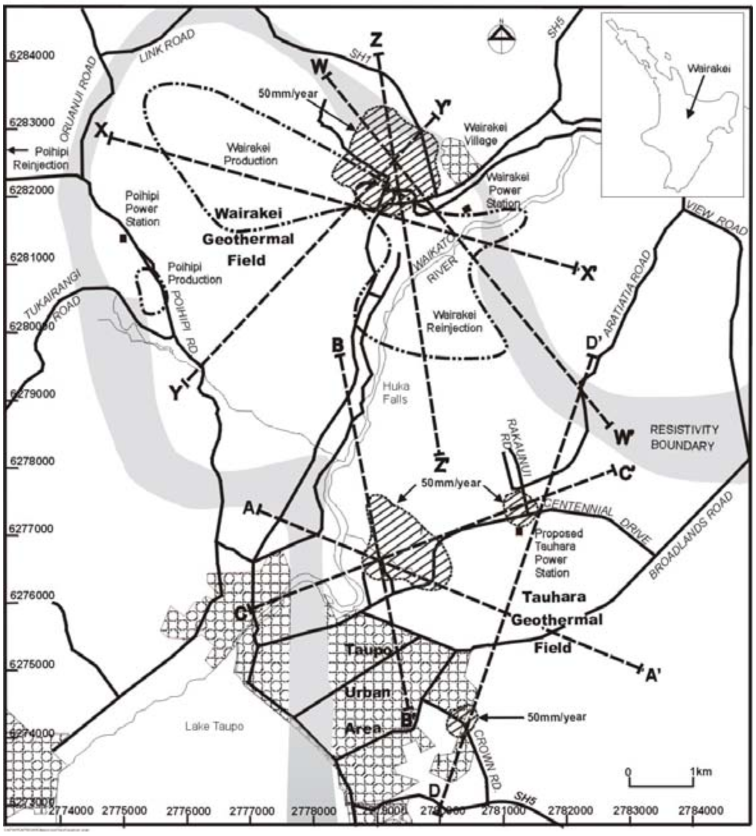

Figure 1: Location map of Wairakei and Tauhara, New Zealand.

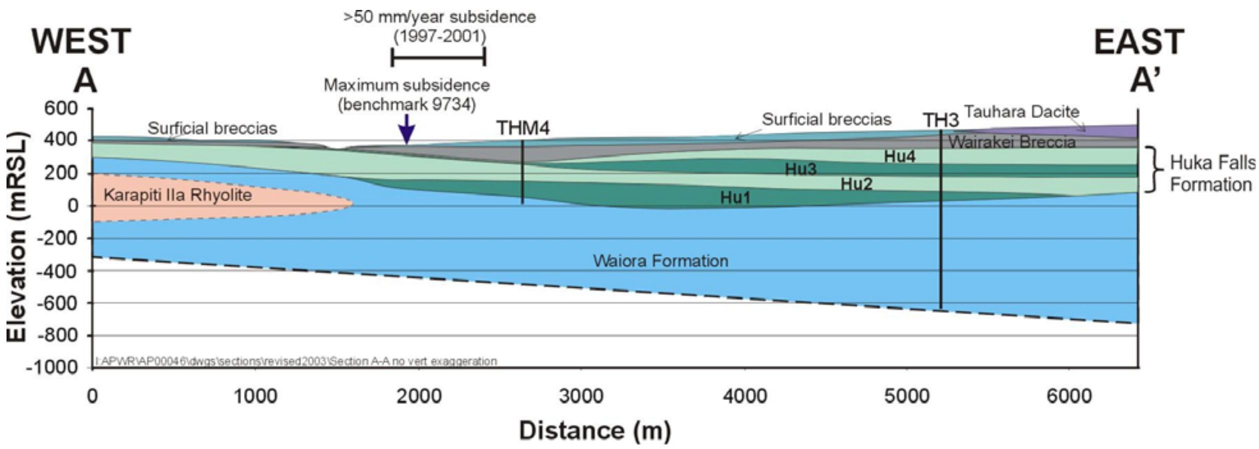

Figure 2: Geological cross section A-A' (no vertical exaggeration).

2 Geology

The geology of Wairakei-Tauhara has been described by numerous authors, dating back to Grindley (1965). A cross-section corresponding to one of the subsidence model profiles is shown in Figure 2. The units that are most significant for this study are:

Waiora Formation: pumice breccia and ignimbrite layers, with interbedded sediments and interlayered extrusive rhyolite lava flows (including Karapiti Rhyolite). This formation is the main productive reservoir at Wairakei, and the major pressure decline due to production has occurred within this formation. In most of the field it is overlain by:

Huka Falls Formation: lacustrine sediments and pumiceous breccias, the latter comprising pyroclastic flow deposits and their re-worked equivalents. Grindley (1965) distinguished four members (Hu1-Hu4, with Hu1 being the oldest): **Hu1** and **Hu3**, porous but low permeability mudstones, **Hu2,** moderately permeable unconsolidated pumice breccia that forms a shallow aquifer, and **Hu4**, fine sandstone and mudstone, forming a partial aquiclude.

Above the Huka Falls Formation are younger pyroclastics and minor lake sediments, which as a whole constitute groundwater aquifers, though locally perched.

3 Two dimensional subsidence modelling

Eight 2-D models were developed using the finite element analysis code Plaxis Version 7.2 on the sections shown in Figure 1. The main advantages of 2-D over past 1-D modelling are:

- It is based on the known geological structure.
- It allows more advanced definition of geotechnical properties (*e.g.* permeability varying with void ratio, non-linear stress-strain behaviour, and pre-consolidation stress history).
- It incorporates the coupled Biot Theory, modified to account for non-linearity, plasticity, and stress changes in the 2-D plane strain.
- Fluid flow and pressure changes can be modelled both horizontally and vertically.
- Horizontal and vertical permeability can be set independently. Strongly anisotropic permeabilities are consistent with the nature of these units (particularly the Huka Falls Formation lacustrine mudstones) and with reservoir model data.

3.1 Input data

There is limited laboratory test data on the geotechnical properties of units in the Wairakei-Tauhara geothermal system (*e.g.* cohesion, friction angle, permeability, stiffness, void ratio, and stress-strain behaviour). An initial set of geotechnical properties was derived from previous studies involving similar materials (including Robertson 1984; Kelsey 1987; Allis 1999; Fairclough 2000; and Grant 2000). These properties were optimised to match the model subsidence trend from 1950 with subsidence measurements. A single consistent set of reference parameters (which are adjusted by the model to account for stress state, void ratio, and pre-consolidation pressure) was used throughout, with two exceptions. Beneath the Wairakei subsidence bowl, enhanced permeability was introduced for near-vertical permeable zones (faults or hydrothermal eruption vents) that fed hot springs there. A zone of low permeability was introduced to explain the delayed pressure response in southern Tauhara.

Historical reservoir pressure and temperature data from the Contact reservoir model was used for Wairakei, with some modifications to fit field measurements reported by Clotworthy (2001) and geological controls. With limited historical data for Tauhara, input pressures were interpolated from reservoir models. For assessing future subsidence under the status quo scenario, future pressures were assumed to remain unchanged over the next 50 years. Reservoir model predictions were used for other scenarios, including O'Sullivan's (1999) prediction of a 2 bar incremental pressure decline at Tauhara for the 20,000 tpd development.

4 Results and discussion

4.1 Matches in space

The model match to historical subsidence along one of the 2-D profiles is shown in Figure 3. Although the magnitude of subsidence will depend on the thickness of the compacting layer, the slope of the lower boundary controls the rate of subsidence. Subsidence is most rapid where where there are inclined sidewalls on the edge of the consolidating unit, so the fluid can flow laterally out of the mudstones. This explains why the subsidence is greatest at specific locations. The subsidence bowl will shift and enlarge as the pressure change propagates further into the Hu1 unit.

A similar match was obtained on most model profiles; expect those, which parallel the structural contours on the base of the compacting layer. The third dimension (out-of-plane) drainage that will result causes the model to under-estimate subsidence on these sections.

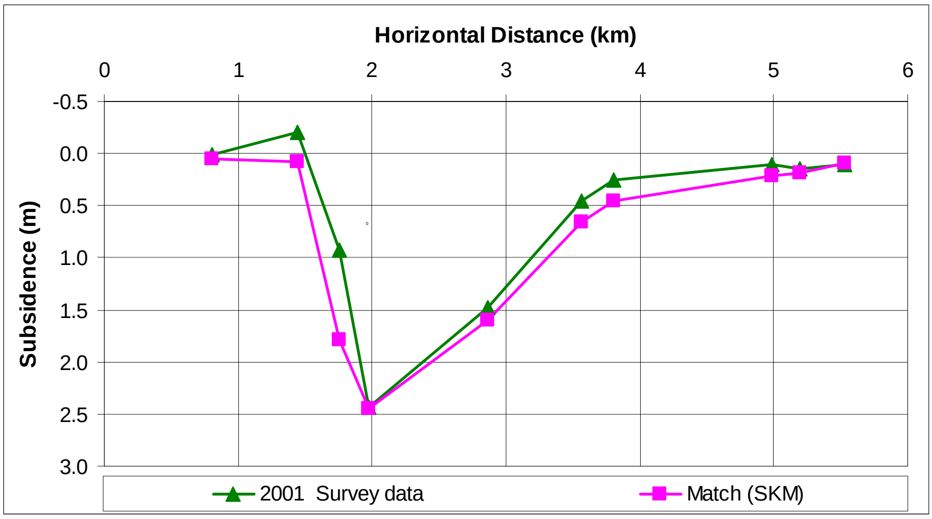

Figure 3: Comparison of actual and calculated subsidence to date, section A-A'.

4.2 Matches in time

The model match with time for two benchmarks is shown in Figures 4 and 5, including predicted subsidence for the next 50 years. The model subsidence at P128 (near the centre of the Wairakei subsidence bowl) correctly simulates the acceleration of subsidence in the early 1960's and subsequent decrease in the subsidence rate towards the late 1980's and early 1990's, though the model generally overstates subsidence by 10-15%. Benchmark 9734 (near the centre of the Tauhara subsidence bowl) was first monitored in 1997; so prior subsidence was calculated by comparing with adjacent benchmarks. A good match was achieved to past subsidence.

4.3 Future predictions

Future subsidence at Wairakei and Tauhara was predicted to 2052, based on various development options, including the status quo, the 20,000 tpd Tauhara development going ahead, the proposed Wairakei expansion going ahead, and total shutdown in 2026. Predictions for two benchmarks are presented in Figures 4 and 5.

Under the status quo scenario, the rate of subsidence will continue slowly decreasing, but subsidence will continue to 2052 and beyond. Total (including past) subsidence to 2052 is predicted to exceed 26 m at P128 (Wairakei), and 5 m at 9734

(Tauhara). Any additional fluid extraction will increase subsidence rates and total subsidence significantly. In contrast, based on 1-D modelling, Allis (1999) predicted that the 20,000 tpd Tauhara development would have no significant effect on future subsidence rates. A total shutdown would result in a small, gradual rebound, though most subsidence is not reversible.

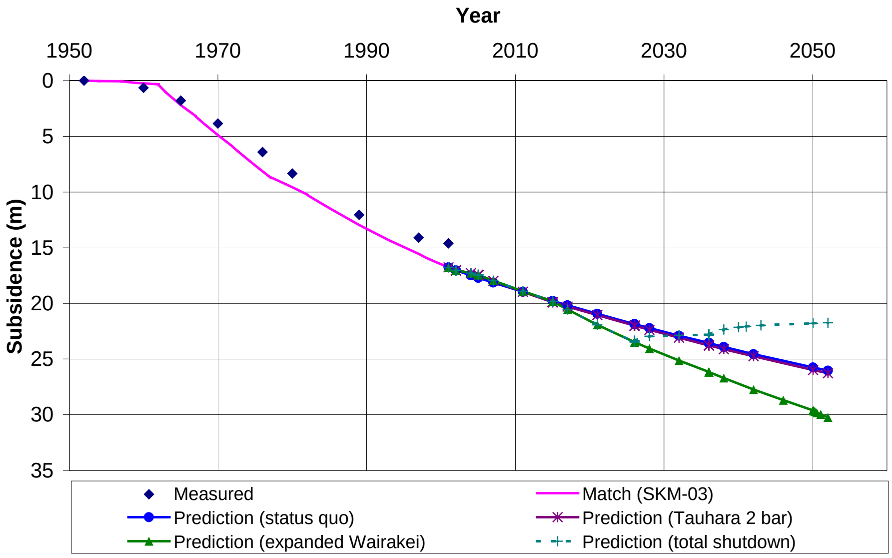

Figure 4: History matching for benchmark P128, Wairakei subsidence bowl.

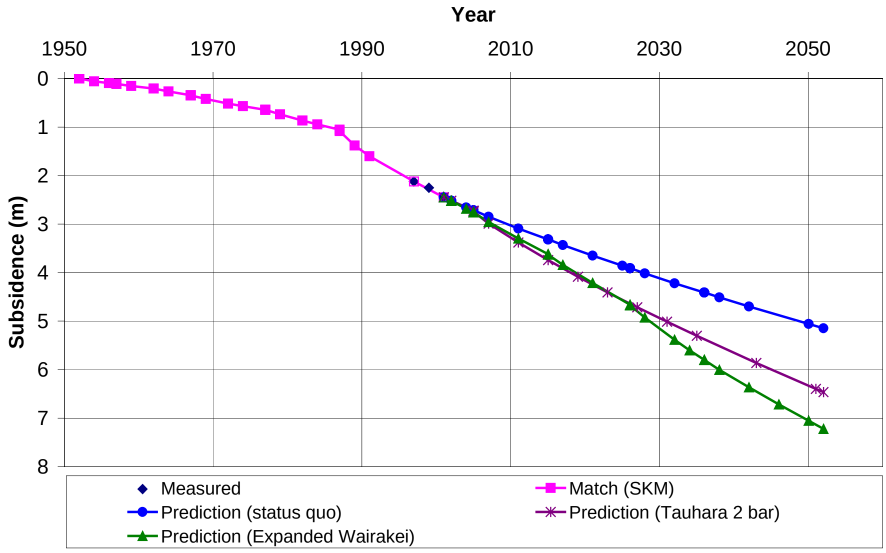

Figure 5: History matching for benchmark 9734, Tauhara subsidence bowl.

5 Other effects

Detailed modelling indicates that shear failure may occur in the Huka 1 unit at differential settlements of about 0.8° (approximately 1:70 tilt) at the ground surface. The precise value will vary because the thickness and depth of units vary, but this provides a sensible guideline for future monitoring of ground deformation. Differential subsidence of this magnitude has already occurred in places, including around the Wairakei and northern Tauhara subsidence bowls. Subsurface shear failure is likely to cause enhanced vertical permeability, and therefore an acceleration of subsidence rates, and possibly thermal activity due to increased steam upflow and/or groundwater drainage.

At all of the subsidence bowls, differential settlement could potentially cause damage to structures and infrastructure. However, because subsidence rates are sensitive to small pressure changes in underlying formations, and because the subsidence location is controlled by the geology, targeted reinjection could potentially reduce future subsidence.

6 Conclusions

Geothermal subsidence at Wairakei and Tauhara has been analysed using two-dimensional finite element modelling. The models indicate that subsidence at Wairakei and Tauhara is largely occurring by compaction of the Hu1 mudstone layer as it responds to an exploitation-induced pressure decline in the Waiora Formation.

By 2052, total subsidence will be 26-30 m at Wairakei, and 5-7 m at Tauhara, depending on future extraction rates. Subsidence is predicted to cause damage to structures and infrastructure, but future subsidence could potentially be reduced with targeted reinjection.

Acknowledgements

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7 References

Allis, R.G. (1999). Statement of evidence, prepared for Contact Energy.

Allis, R.G., and Zhan, X. (1997). *Potential for subsidence due to geothermal development of Tauhara Field*. Institute of Geological and Nuclear Sciences report for Contact Energy.

Chin, L., Boade, R.R., Prevost, J.H., Landa, G.H. (1993). Numerical simulation of shear-induced compaction in the Ekofisk reservoir. *Int. J. Rock. Mech. Min. Sci & Geomech. Abstr* 30: 1193-1200.

Clotworthy, A. (2001). *Wairakei geothermal field reservoir engineering review*. Unpublished report prepared for Environment Waikato.

Contact Energy Ltd. (2001). *Wairakei geothermal power plant: applications for resource consents and assessment of environmental effects*. Application to Environment Waikato.

Eysteinsson, H. (2000). Elevation and gravity changes at geothermal fields on the Reykjanes Peninsula, SW Iceland. *Proceedings World Geothermal Congress* 2000: 559-564.

Fairclough, A. (2000). Prediction of dewatering related settlement in Waihi Township, New Zealand. *NZ Geomechanics News* 59: 47-48.

Fossum, A.F., Fredrich, J.T. (2000). Constitutive models for the Etchegoin Sands, Belridge Diatomite, and Overburden Formations at the Lost Hills oil field, California. Report by Sandia National Laboratories for the US Department of Energy.

Geotherm Group Ltd. (2001). *Geothermal project resource consent applications and assessment of environmental effects*. Application to Environment Waikato, August 2001.

Glowacka, E., Gonzalez, J., Nava, F.A. (2000). Subsidence in Cerro Prieto geothermal field, Baja California, Mexico. *Proceedings World Geothermal Congress* 2000: 591-596.

Grant, M.A. (2000). Projected subsidence at Tauhara. *Proc. 22nd NZ Geothermal Workshop*, Auckland University 2000: 247-250.

Grindley, G.W. (1965). *The geology, structure, and exploitation of the Wairakei Geothermal Field, Taupo, New Zealand*. NZ Geological Survey bulletin 75. DSIR, Wellington.

Kelsey, P.I. (1987). *An engineering geological investigation of ground subsidence above the Huntly East mine*. Report for NZ Energy Research and Development Committee, p73-74.

O'Sullivan, M.J. (1999). Statement of evidence, prepared for Contact Energy.

Robertson, A. (1984). Analysis of subsurface compaction and subsidence at Wairakei geothermal field, New Zealand. Unpublished M.Sc. thesis, University of Auckland.