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MANAGEMENT OF GEOTHERMAL RESOURCES

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ABSTRACT

Comprehensive and efficient resource management is an essential part of successful geothermal utilization. Such management relies on proper understanding of the geothermal system involved, which depends on extensive data and information. The most important data on a geothermal system's nature and properties are obtained through careful monitoring of its response to long-term production. Physical monitoring involves measuring mass and heat transport through wells as well as changes in reservoir pressure and temperature (energy content). Changes in the chemical content of the fluid produced also need to be monitored. Indirect monitoring involves monitoring reservoir changes through different surface observations; mainly surface elevation measurements, micro-gravity observations and micro-seismic monitoring. There is reason to claim that geothermal resources can be utilized in a sustainable manner, i.e. that certain production scenarios can be maintained for a very long time (100-300 years). This is based on decades of experience of utilizing several geothermal systems, which have shown that if production is maintained below a certain limit it reaches a kind of balance that may be maintained for a long time. Examples are also available where production has been so great that equilibrium was not attained. Such over-exploitation mostly occurs because of poor understanding, due to inadequate monitoring, and when many users utilize the same resource without common management. Geothermal resources can be utilized in a sustainable manner either through constant production below the sustainable limit, step-wise increase in production, intermittent excessive production with breaks and reduced production after a shorter period of excessive production. The sustainable production potential of a geothermal system is either controlled by energy content or by pressure decline due to limited recharge. In the latter case reinjection can increase the sustainable potential of a system considerably. Even though geothermal energy can be considered a clean and renewable source of energy its development has both environmental and social impacts, which need the appropriate attention.

1. INTRODUCTION

Geothermal utilization involves energy extraction from highly complex underground systems and comprehensive and efficient resource management is an essential part of making it successful. Geothermal resource management involves e.g. controlling this energy extraction appropriately and maximizing the benefits from the exploitation without over-exploiting the resource. The production capacity of geothermal systems is often poorly known and they often respond unexpectedly to long-term energy extraction. This is because their internal structure, nature and properties are usually not well determined and can only be observed indirectly. Therefore, the management of geothermal resources is complicated. It involves deciding between different courses of action involving the production strategy in-effect, taking prevailing reservoir conditions into account (Stefánsson *et al.*, 1995, Axelsson and Gunnlaugsson, 2000). The operators of a geothermal resource must have some idea of the possible results of the different courses of action, to be able to make these decisions. Thus, successful management relies on proper understanding of the geothermal system involved. Comprehensive monitoring is the key to this understanding and consequently to geothermal monitoring.

Experience of long-term utilization of numerous geothermal systems worldwide has demonstrated that a certain level of geothermal utilization can be maintained for very long periods (several decades), because a certain quasi-equilibrium between production and recharge is attained. This is the key to sustainable utilization and management of geothermal resources, which implies utilization for very long periods, much longer than conventional amortization periods for energy production (20 -50 years). Sustainable utilization 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 utilize the same resource, without common management. Geothermal resources of highly variable nature may be managed in a sustainable manner, and much can be learned through modelling of the response of geothermal systems to long-term utilization. Sustainable geothermal utilization has been discussed by a few authors during the last decade or so, e.g. Wright (1995), Stefánsson (2000), Axelsson *et al.* (2005) and Rybach and Mongillo (2006). The latter give a good review of the status of geothermal sustainability research.

This paper reviews the management of geothermal resources during utilization, with particular emphasis on monitoring the performance of the boreholes utilized and the production response of the reservoir in question. A few important management issues are discussed along with long-term sustainable utilization of geothermal resources. Key management tools such as geothermal reservoir modelling and reinjection are discussed in a previous paper on the production capacity of geothermal systems and a follow-up paper on reinjection, respectively, by the current author (Axelsson, 2008a and 2008c).

2. GEOTHERMAL RESOURCE MANAGEMENT

The key to successful geothermal development is efficient and comprehensive interdisciplinary geothermal research, both during the exploration and exploitation phases, as well as proper resource management during utilization. Geothermal exploitation involves energy extraction from highly complex underground systems, and geothermal resource management implies controlling this energy extraction, including how to maximise the resulting benefits without over-exploiting the resource.

Comprehensive and efficient management is an essential part of any successful geothermal resource utilization endeavour. Such management can be highly complicated; however, as the energy production potential of geothermal systems is highly variable. The generating capacity of many geothermal systems is, furthermore, not properly defined 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 not fully understood 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 being available.

An important element of geothermal resource management involves controlling energy extraction from a geothermal system in order to avoid over-exploitation of the underlying resource. 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 thus poor, and reliable modelling is also not possible. Therefore, the systems respond unexpectedly to long-term production. Secondly, cases where the same resource/system is utilized by many users, without implementing common management or control (see chapter 4).

Management of a geothermal resource involves deciding between different courses of action in the exploitation of the resource (Grant *et al.*, 1982; Stefánsson *et al.*, 1995; Axelsson and Gunnlaugsson, 2000; Axelsson, 2003). Most often management decisions are made to improve the operating conditions of a geothermal reservoir. In some cases unfavourable conditions may have evolved in a reservoir, while in others improvements in production technology may justify changes in production strategy. The operators of a geothermal resource must have some idea of the possible results of the different courses of action available, to be able to make these decisions. This is why careful monitoring is an essential ingredient of any management program.

Geothermal resource management may have different objectives (Stefánsson *et al.*, 1995). These may include:

1) Minimising operation costs,
2) maximising energy extraction from a given resource,
3) ensuring the security of continuous energy delivery,
4) to counteract reservoir changes such as lowered pressure and/or increased boiling,
5) minimising environmental effects,
6) avoid operational difficulties like scaling and corrosion and
7) to adhere to the energy policy of the respective country.

Real management objectives are quite often a mixture of two or more of such objectives, as listed above.

One of the more difficult aspects of reservoir management is to determine the most appropriate time span for a given option. There are cases, for example, where depleting a given reservoir in a few years time is most advantageous from a purely financial point of view. This is usually unacceptable from a political or sociological point of view, where a reliable supply of energy for a long time is considered more valuable (see later).

Some of the management options, which are commonly applied in geothermal resource management, are (Stefánsson *et al.*, 1995):

a) Modification of production strategy (increased/reduced production),
b) application of injection or changes in injection strategy,
c) drilling of additional wells such as in-fill or make-up wells,
d) changes in well-completion programs (casings etc.),
e) lowering of down-hole pumps,
f) search for new production areas or drilling targets and
g) search for new geothermal systems.

3. MONITORING OF GEOTHERMAL SYSTEMS

Management of a geothermal reservoir relies on adequate information on the geothermal system in question (Stefánsson *et al.*, 1995). In general the basic information required for a successful management program involves (basis of modelling):

- Knowledge on the volume, geometry and boundary conditions of a reservoir.
- Knowledge on the properties of the reservoir rocks, i.e. permeability, porosity, density, heat capacity and heat conductivity.
- Knowledge on the physical conditions in a reservoir, determined by the temperature and pressure distribution.

Data yielding this knowledge through appropriate interpretation is continuously gathered throughout the exploration and exploitation history of a geothermal reservoir. The initial data comes from surface exploration, i.e. geological, chemical and geophysical data. Additional information is provided by exploratory drilling, in particular through logging and well testing. The most important data on a geothermal system's nature and properties, however, are obtained through monitoring of its response to long-term production. Careful monitoring of a geothermal reservoir during exploitation is, therefore, an indispensable part of any successful management program. If the understanding of a geothermal system is adequate, monitoring will enable changes in the reservoir to be seen in advance. Timely warning is thus obtained of undesirable changes such as decreasing generating capacity due to declining reservoir pressure or steam-flow, insufficient injection capacity or possible operational problems such as scaling in wells and surface equipment or corrosion. The importance of a proper monitoring program for any geothermal reservoir being utilised can thus never be over-emphasised.

Monitoring the physical changes in a geothermal reservoir during exploitation is in principle simple and only involves measuring the (1) mass and heat transport, (2) pressure, and (3) energy content (temperature in most situations). This is complicated in practise, however (Axelsson and Gunnlaugsson, 2000). Measurements must be made at high-temperatures and pressures and reservoir access for measurements is generally limited to a few boreholes, and these parameters cannot be measured directly throughout the remaining reservoir volume.

The parameters that need to be monitored to quantify reservoir's response to production may, of course, differ somewhat, as well as methods and monitoring frequency, from one geothermal system to another (Kristmannsdóttir *et al.*, 1995; Axelsson and Gunnlaugsson, 2000). Monitoring may also be either direct or indirect, depending on the observation technique adopted. Below is a list of directly observable basic aspects that should be included in conventional geothermal monitoring programs:

1) Mass discharge histories of production wells (pumping for low-temperature wells).
2) Temperature or enthalpy (if two-phase) of fluid produced.
3) Water level or wellhead pressure (reflecting reservoir pressure) of production wells.
4) Chemical content of water (and steam) produced.
5) Injection rate histories of injection wells.
6) Temperature of injected water.
7) Wellhead pressure (water level) for injection wells.
8) Reservoir pressure (water level) in observation wells.
9) Reservoir temperature through temperature logs in observation wells.
10) Well status through diameter monitoring (calliper logs), injectivity tests and other methods.

Monitoring programs have to be specifically designed for each geothermal reservoir, because of their individual characteristics and the distinct differences inherent in the metering methodology adopted. Monitoring programs may also have to be revised as time progresses, and more experience is gained, e.g. monitoring frequency of different parameters. The practical limits to manual monitoring frequency are increasingly being offset by computerised monitoring, which actually presents no upper limit to monitoring frequency, except for that set by the available memory-space in the computer system used. Data transmission through phone networks is also increasingly being used. Figures 1-3 show examples of different kinds of direct monitoring data (Axelsson, 2003).

Indirect monitoring involves monitoring the changes occurring at depth in geothermal systems through various surface observations and measurements. Such indirect monitoring methods are mainly used in high-temperature fields, but also have a potential for contributing significantly to the understanding of low-temperature systems. These methods are mostly geophysical measurements carried out at the surface; airborne and even satellite measurements have also been attempted. All these methods have in common that a careful baseline survey must be carried out before the start of utilization, and repeated at regular intervals.

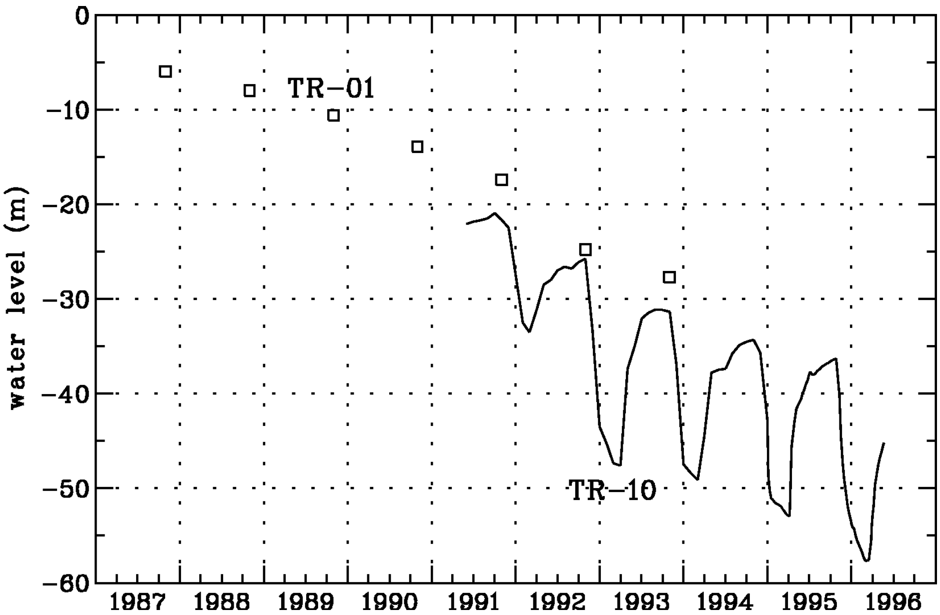

FIGURE 1: The water-level history of the Tanggu geothermal system in Tianjin, China, during 1987 – 1996 (Axelsson and Dong, 1998). It demonstrates the distinct difference between intermittent (yearly) monitoring and continuous monitoring.

Some of the indirect monitoring methods are well established by now, while others are still in the experimental stage or have met limited success. A review of the geothermal literature reveals that the following methods have been used (Axelsson and Gunnlaugsson, 2000):

a) Topographic measurements.
b) Micro-gravity surveys.
c) Electrical resistivity surveys.
d) Ground temperature and heat-flow measurements.
e) Micro-seismic monitoring.
f) Water level monitoring in ground water systems.
g) Self-potential surveys.

The reasons why these methods are seldom used in low-temperature fields are the fact that physical changes in low-temperature systems are generally not as great as in high-temperature systems as well as relatively high costs. A few of the methods are rather widely used in high-temperature fields, such as (a), (b) and (e).

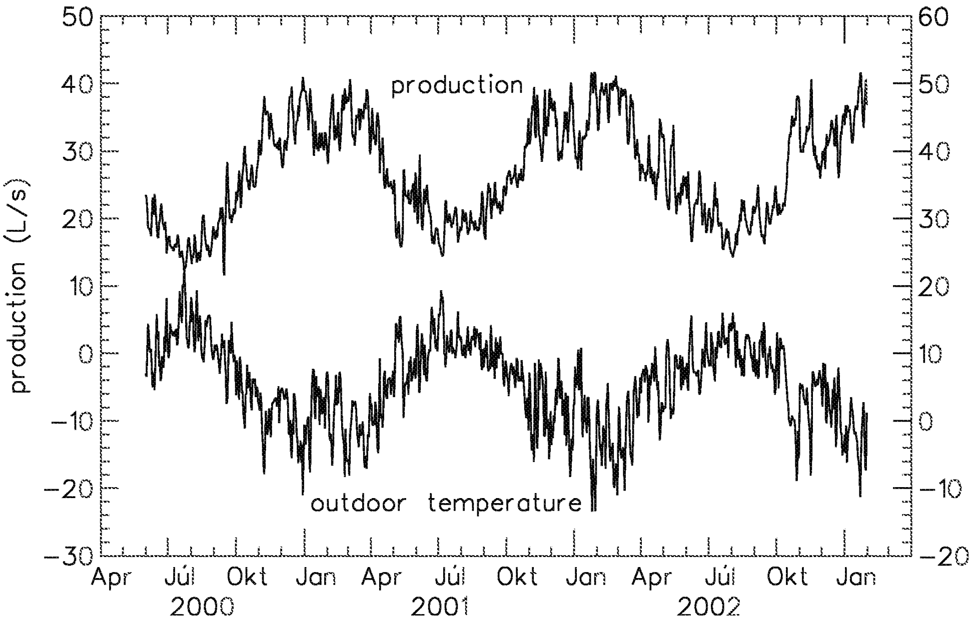

FIGURE 2: An example of highly detailed data (production and outdoor temperature) collected through computerized monitoring at the Urridavatn low-temperature geothermal system near Egilsstadir, E-Iceland (Axelsson, 1991). Note that all variations in outdoor temperature are reflected in variations in production.

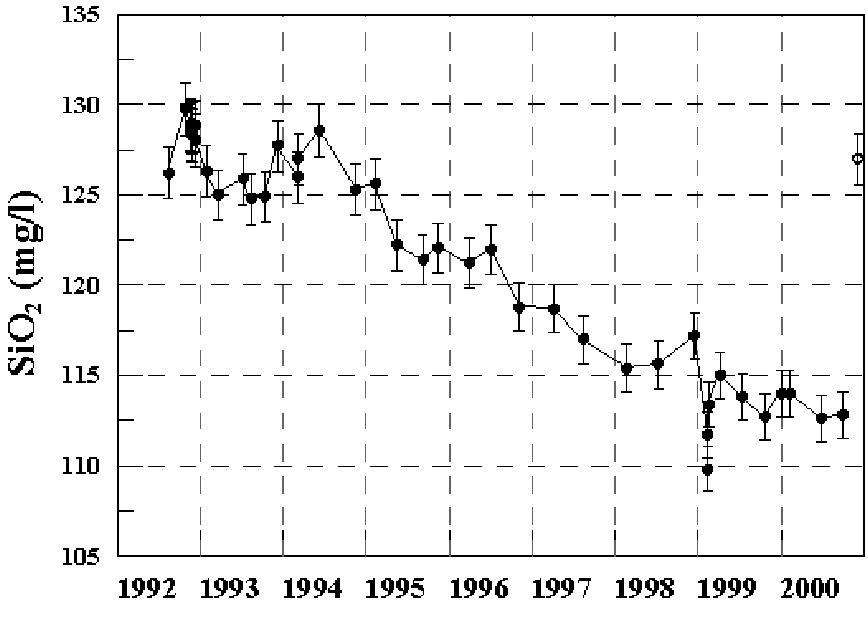

FIGURE 3: Changes in silica content of water produced from the Thelamork low-temperature geothermal system in Central N-Iceland during 1992 – 2000 (Björnsson *et al.*, 1994). The data is interpreted as reflecting inflow of colder water (with lower silica content) into the geothermal system.

Topographic measurements are carried out to enable detection of ground elevation changes, mostly subsidence. This may occur in all geothermal systems during exploitation because of compaction of the reservoir rocks, following fluid withdrawal. Re-injection may also cause topographic changes (uplift).

Micro-gravity monitoring has been used successfully in a number of geothermal fields. Changes in gravity can provide information on the net mass balance of a geothermal reservoir during exploitation, i.e. the difference between the mass withdrawal from a field and the recharge to the reservoir. The mass-balance effects of enlarging steam-zones may also be seen through gravity monitoring. In addition, the mass-balance effects of re-injection may be detected by gravity monitoring. Methods for analysing gravity changes in geothermal fields are presented by Allis and Hunt (1986). Figure 4 presents an example of the results of gravity and subsidence monitoring in the Svartsengi high-temperature geothermal field in SW-Iceland. Nishijima *et al.* (2000 and 2005) also provide good examples from Japanese high-temperature fields of the application of repeated micro-gravity monitoring for reservoir monitoring.

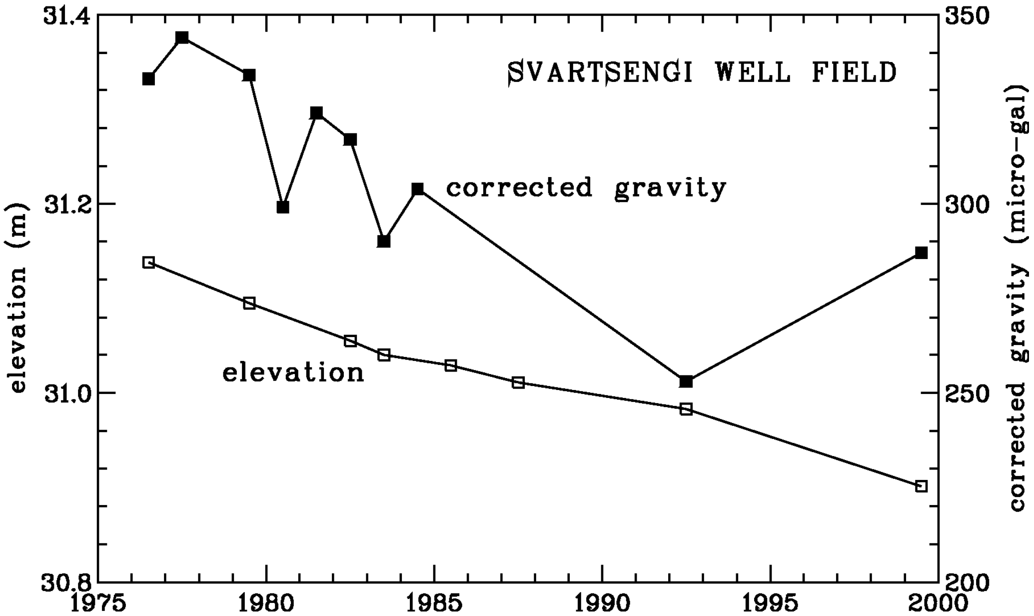

FIGURE 4: Results of gravity and subsidence monitoring in the Svartsengi high-temperature geothermal field in SW-Iceland. These data were used to infer that about 70% of the mass extracted from the reservoir had been restored through natural recharge (Eysteinsson, 2000).

Repeated *electrical resistivity surveys* have not been conducted in many geothermal fields, but might help delineate cold, fresh-water inflow into geothermal reservoirs, induced by production. Such surveys may also be helpful in locating reservoir volumes affected by re-injection.

Surface activity and heat flow may either decrease or increase during production from a geothermal field. Monitoring of these changes is, however, more often associated with monitoring of the environmental effects of geothermal exploitation. These may be monitored through repeated (a) ground temperature measurements, (b) airborne infrared measurements, and (c) observations of thermal features (hot springs, fumaroles, mud pools, etc.).

The purpose of *monitoring seismic activity* may be two-fold. Firstly, to monitor changes in seismic activity in an already active area. This may be considered environmental rather than reservoir monitoring (see later). Secondly, to delineate the regions in a geothermal reservoir affected by exploitation or re-injection, because in some cases the pressure and thermal changes associated with geothermal exploitation and re-injection may be sufficient to generate some micro-seismic activity.

Water level changes in shallow ground water systems above geothermal reservoirs are monitored in some geothermal fields. *Self-potential monitoring* has been proposed as a tool to study the changes in geothermal reservoirs due to mass extraction and re-injection.

Finally, it may be pointed out that a combination of indirect monitoring with numerical reservoir simulation should enhance the reliability of such models, as wells as aiding in the correct understanding of the nature of the geothermal system involved.

4. MANAGEMENT CHALLENGES

A multitude of challenges and issues face those responsible for the management of geothermal resources. A few of these are listed below, some interlinked in one way or another:

(1) Lack of monitoring results in insufficient knowledge on the geothermal reservoir in question. Thus unexpected and detrimental changes may occur, such as reservoir cooling or drastic pressure drop. Lack of monitoring is one of the factors, which can cause overexploitation (item (3) below).
(2) Overexploitation mostly occurs because of lack of monitoring (item (1)) and/or when many users utilize the same resource without common management (item (5)).
(3) Common monitoring is important in situations when many production/reinjection wells have been drilled in the same geothermal area, can be computerized as well as centralized (using a local phone-system or other communication network).
(4) Management of geothermal systems with large surface areas, and many users, needs special attention. This is because each user cannot operate as if he is utilizing his own isolated geothermal system. Therefore, some kind of common management (item (5)) is essential, in particular to prevent overexploitation (item (2)). Common monitoring (item (3)) may aid common management significantly.
(5) Common management is essential when more than one user utilizes a single geothermal resource.
(6) Reinjection has become an essential part of sustainable and energy-efficient geothermal utilization. Is used to counteract pressure draw-down (i.e. provide additional recharge), to dispose of waste-water, to counteract surface subsidence and to maintain valuable surface activity (Axelsson, 2008c).
(7) A variety of operational aspects and problems requires a multitude of technical solutions, both to general operational aspects and problems as well as to more site specific ones. These aspects may be classified as: (i) related to hardware such as wells and pipeline, (ii) related to chemical content (corrosion and scaling) and (iii) related to reservoir conditions.

The best known example of over-exploitation due to lack of common management is the Geysers field in California (Figure 5). Another more recent example is the Xi'an field in China (Axelsson, 2008a). A good example of the opposite, i.e. common management with centralized monitoring is the Paris Basin (Boisdet *et al.*, 1990; Axelsson, 2008c). Utilization of the geothermal resources in Tianjin, China, is also increasingly along these lines (Wang *et al.*, 2006).

5. SUSTAINABLE GEOTHERMAL UTILIZATION

The term *sustainable development* has been defined as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (World Commission on Environment and Development, 1987). This definition is inherently rather vague and sustainability of geothermal energy production is a topic that has received limited attention. The following discussion is based on Axelsson and Stefánsson (2003) and Axelsson *et al.* (*2005*) and the reader is referred to those papers for more details.

Several decades of experience have in many cases shown that by maintaining the production level below a certain limit, a geothermal system reaches a kind of balance, which may be maintained for a long time. Good examples are the Laugarnes system in SW-Iceland (see Figure 3 in Axelsson, 2008a) and the Matsukawa geothermal system in Japan (Axelsson and Stefánsson, 2003). Other examples are available where production has been so great that equilibrium was not attained. Cases in point are the Geysers geothermal field in California, where steam production had to be dramatically curtailed in the late 1980's because of over-exploitation (see Figure 5 below) and the Tiwi system in the Philippines (Barker *et al.*, 1990).

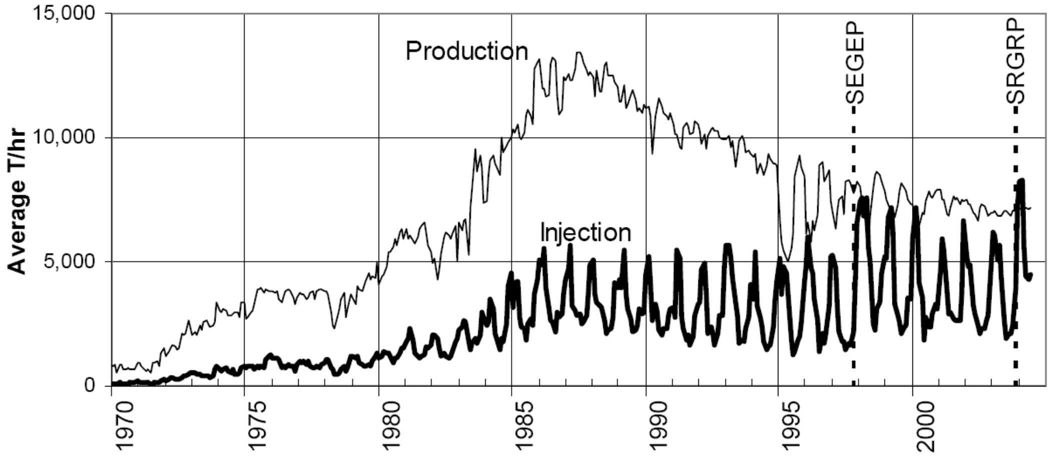

FIGURE 5: Production and water injection history of the Geysers geothermal field in California (Stark *et al.*, 2005). The figure shows how the production peak in the late 1980's could not be sustained and had to be reduced to nearly half of the peak production. Ever increasing water injection has helped maintain production at a semi-stable level in recent years.

Axelsson *et al.*, (2001) attempt to define the term sustainable production of geothermal energy, based on the assumption that for each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, E_0, below which it is possible to maintain constant energy production from the system for a long time or 100–300 years. It applies to the total extractable energy, and depends, in principle, on the nature of the system in question and the mode of production, but not on load-factors or utilization efficiency. It does not consider economical aspects, environmental issues, or technological advances, all of which may be expected to fluctuate over time. The value of E_0 is not known a priori, but it may be estimated by modelling on basis of available data.

Axelsson *et al.* (2005) present the results of modelling studies for three geothermal systems that were performed to assess the sustainable production potential of the systems, or provide answers to questions related to the issue. These are the Hamar geothermal system in N-Iceland, the Urban geothermal system below the city of Beijing in China and the Nesjavellir geothermal system in the Hengill region in SW-Iceland, all of which are listed in Table 2 of Axelsson (2008a). The results for Hamar (see Figure 8 in Axelsson (2008a) and Figure 6 below) indicate that the sustainable production potential of the Hamar reservoir is controlled by the energy content of the small system rather than pressure decline. Results for the Urban system (see Figure 5 in Axelsson (2008a) and Figure 7 below) indicate that the sustainable potential of the system is limited by lack of fluid recharge rather than lack of thermal energy. Because of this the Urban system requires full re-injection for sustainable utilization.

Finally the modelling results for the Nesjavellir high-temperature system (see Axelsson *et al.*, 2005) demonstrate that the present rate of utilization of the system (400 MW_{th} and 120 MW_e) can clearly not be sustained for the next 100 – 300 years. The model calculations indicate, however, that the effects of the present intense production should mostly be reversible, and that the reservoir pressure should recover at approximately the same time-scale as the period of intense production. This result, which is also believed to apply to other comparable geothermal systems, is relevant for the possible modes of sustainable utilization that are reviewed below.

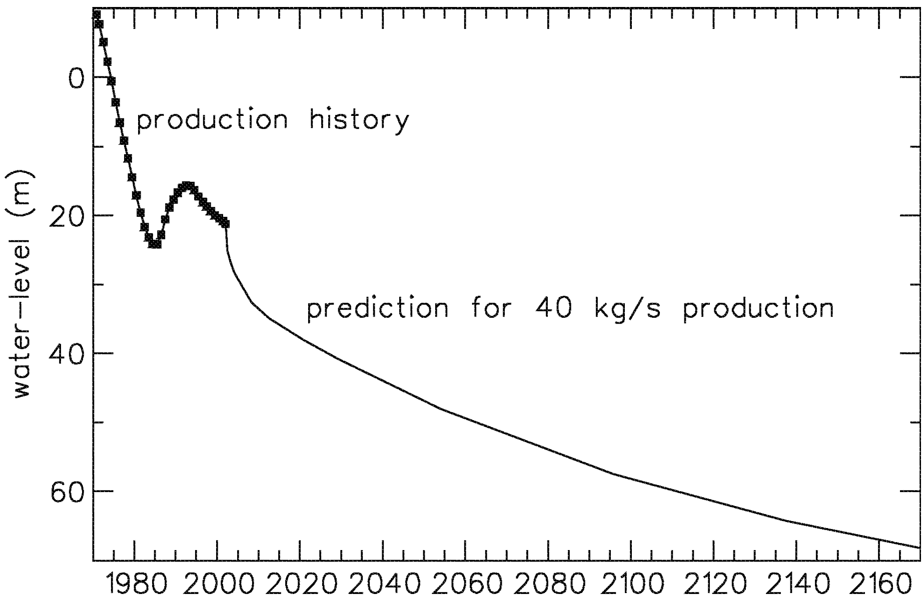

FIGURE 6: Long-term water level prediction for the Hamar system, as it was calculated by a lumped parameter model. Prediction calculated for a constant rate of production up to 2170 for a sustainability study for the system (Axelsson *et al.*, 2005)

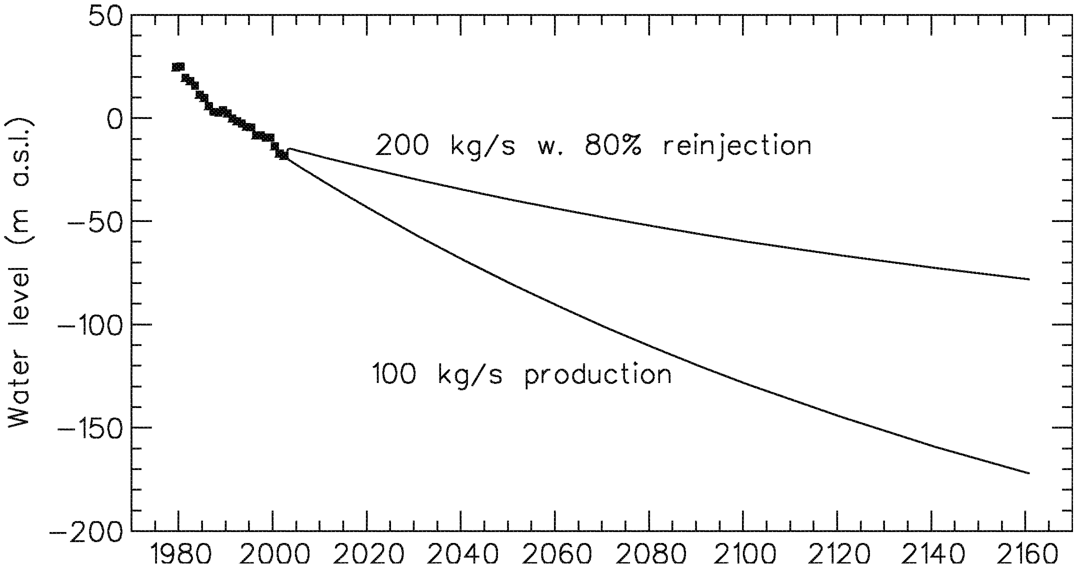

FIGURE 7: Predicted water level changes (pressure changes) in the Urban geothermal system under Beijing-city in China until 2160 for production scenarios with and without reinjection (Axelsson *et al.*, 2005).

The principal methods/modes of sustainable geothermal utilization that may be envisioned are the following (also presented by a schematic diagram in Figure 8):

(1) Constant production (aside from variations due to temporary demand such as annual variations) for 100 – 300 years. This is hardly a realistic option because the sustainable production capacity of geothermal systems is unknown beforehand.
(2) Production increased in a few steps until the sustainable potential has been assessed and the sustainable limit attained.

(3) Excessive production (not sustainable) for a few decades (about 30–50 years) with total breaks in-between (about 30–50 years), wherein a geothermal system is able to recover almost fully (see above).

(4) Excessive production for 30–50 years followed by a steady, but much reduced production for the next 150–170 years. The production following the excessive period would thus be much less than the sustainable potential at constant production (mode (1)).

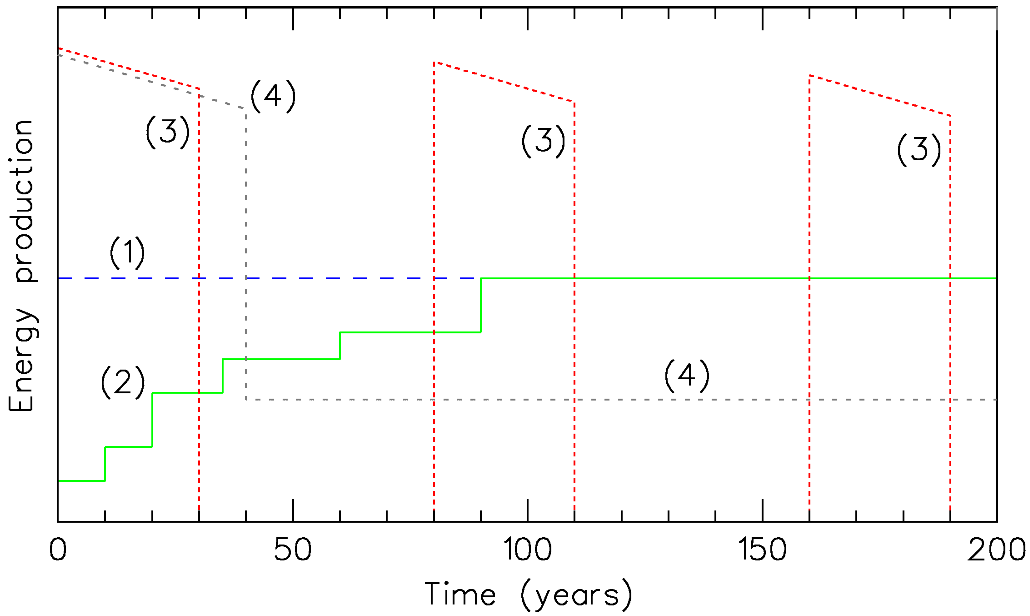

FIGURE 8: A schematic diagram showing examples of possible different methods/modes of sustainable geothermal system utilization. The numbers refer to the production methods/modes discussed in the paper.

6. ENVIRONMENTAL AND SOCIAL ISSUES

Even though geothermal energy can be considered a clean and renewable source of energy its development has both environmental and social impacts, which are receiving ever increasing attention. These are not the main focus of this paper, but will be reviewed briefly here. For further information the reader is referred to e.g. Kristmannsdóttir and Ármannsson (2003) and Bromley *et al*. (2006).

The main environmental issues associated with geothermal developments are (based on Kristmannsdóttir and Ármannsson, 2003):

- Surface disturbances such as due to drilling, road construction, pipelines and power plants as well as general untidiness. Here the local scenery also needs attention and often protection. In some instances landslides are liable to occur, if care is not exercised.
- Physical effects of fluid withdrawal and re-injection such as changes in surface manifestations, i.e. fading of hot springs and geysers or increased steam discharge from fumaroles, land subsidence, lowering of ground-water tables and induced seismicity.
- Noise such as that associated with drilling, discharging of wells and power plant operation.
- Thermal effects of excess energy contained in waste water and steam discharge.
- Chemical pollution in the water phase, particularly from arsenic (As) and mercury (Hg), and through the discharge of geothermal gases such as carbon dioxide (CO_2) and hydrogen sulphide (H_2S).
- Impact on local biology, i.e. fauna and flora.

- Protection of natural features that are of scientific or historical interest as well as being tourist attractions.

Various solutions to these issues have been proposed, tested and implemented, with re-injection being one of the most widely beneficial. Bromley *et al*. (2006) discusses practical environmental enhancement strategies that may include improved discharges from surface thermal features through targeted injection or extraction, creation of enhanced thermal habitats and treatment or injection of toxic chemicals and gases.

Social acceptance, in particular by local communities, is an important prerequisite for a successful implementation of geothermal projects. This applies, especially, to projects aimed at electrical generation because of their size and overall impact. Direct geothermal applications have not encountered significant social constraints, or opposition, because of their obvious social benefits, a case in point being Iceland where almost 90% of the space heating market utilizes geothermal energy. Social acceptance of direct geothermal development should not be neglected, however. According to Cataldi (1999) the three main conditions for gaining social acceptance are minimisation of environmental impact, prevention of adverse effects on people's health, and creation of tangible benefits for the local population. Milos and Nisyros in Greece, Mt. Amiata in Italy, Ohaaki in New Zealand, and Puna (Hawaii) in the USA are examples where opposition by local populations, concerned with the possible impacts of project activities on environment, economy, tourism, and cultural or religious traditions, has hindered geothermal power developments (Cataldi, 1999). In situations where local knowledge on the nature of geothermal resources is available and cooperation with local communities is maintained, such opposition has been largely avoided.

Social issues of geothermal developments have been decisively addressed in the Philippines during the last decade or two (de Jesus, 2005). The following have been the main issues:

a) lack of consultation,
b) physical and economic dislocation of settlements,
c) lack of benefits,
d) encroachment of ancestral domain and
e) privatization of the people's forest heritage.

The measures that have been developed to successfully address these concerns include:

a) awareness and acceptance campaigns,
b) opening up communication,
c) translating commitments into action,
d) third party multi stakeholder monitoring,
e) installation of environmental guarantee fund,
f) resettlement,
g) provision of benefits,
h) protection of prior and ancestral rights and
i) protection of heritage and advocacy for appropriate public policies.

The relationship between the existence and development of conventional geothermal systems, in tectonically active regions, and seismic activity is well known. On one hand seismic activity is simply a signature of the tectonic movements needed to create and maintain the flow-paths of geothermal systems. On the other hand geothermal development and utilization, i.e. drilling, production and injection, can cause changes in the natural seismic activity. Majer *et al*. (2007) review present knowledge on seismicity induced in enhanced geothermal systems and conclude that induced seismicity does not pose any threat to the development of geothermal resources. In fact, induced seismicity provides a direct benefit because it can be used as a monitoring tool and the effects of induced seismicity have been dealt with in a successful manner. They point out that open communication between geothermal developer and local inhabitants must be ensured. It is, perhaps, important not to view induced seismicity as "earthquakes" but rather focus on the resulting surface movement (acceleration and frequency). By proper management it should be possible to maintain these parameters within limits set by local building regulations, as is successfully done both in the mining- and petroleum industry.

7. CONCLUSIONS

In conclusion the following should be emphasized: Comprehensive management is essential for successful long-term geothermal exploitation, both for direct applications and for electrical production, in particular to prevent overexploitation and general operational problems. This requires extensive, continuous and careful monitoring of various physical and chemical parameters. Such monitoring data provides the basis for geothermal reservoir modelling, which is used to estimate the production potential of geothermal reservoirs as well as for other reservoir management purposes. In addition indirect monitoring; such as surface elevation measurements, micro-gravity observations and micro-seismic monitoring, can help in understanding as well as in quantifying reservoir changes caused by production. Such indirect monitoring has mostly been limited to high-temperature systems, but has also the potential of providing added insight to the nature of many low-temperature systems being utilized.

Geothermal resources can be utilized in a sustainable manner based on the definition that sustainable utilization involves utilization according to a scenario that can be operated/maintained for 100 – 300 years. The sustainable potential of a geothermal resource is either controlled by the pressure decline caused by production or by the energy content of the system in question, depending on the nature of the resource. Various sustainable utilization scenarios can be envisioned, such as through constant production below a sustainable limit, step-wise increase in production, intermittent excessive production with breaks or reduced production after a shorter period of excessive production.

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