



PRODUCTION CAPACITY OF GEOTHERMAL SYSTEMS

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ABSTRACT

Geothermal systems are classified on the basis of reservoir temperature, reservoir enthalpy, their physical state or their nature and geological setting. They are often classified as either high-temperature (reservoir temperature a 1 km depth above 200°C) or low-temperature (reservoir temperature a 1 km depth below 150°C). Geothermal systems are also classified as (a) volcanic systems with the heat sources being hot intrusions or magma, (b) convective systems with deep water circulation in tectonically active areas, (c) sedimentary systems with permeable layers at great depth, (d) geo-pressured systems, (e) hot dry rock or enhanced geothermal systems and (f) shallow resources utilized through ground-source heat pump application. Low-temperature resources are distributed throughout the world; they are not restricted to volcanic regions. They are suitable for various direct applications, in particular space-heating. Even though geothermal resources are considered renewable their production capacity is not unlimited. It is predominantly controlled by the reservoir pressure decline caused by the hot water production. This is in turn determined by the size of a geothermal reservoir, its permeability, reservoir storage capacity, water recharge and geological structure. Geothermal systems can in most cases be classified as either closed, with limited or no recharge, or open, where recharge equilibrates with the mass extraction. Volumetric assessment and dynamic modelling are the main methods of estimating the production capacity of geothermal reservoirs. Simple analytical models, lumped parameter models and detailed numerical models are used to simulate the nature and production response of geothermal systems as well as to calculate future predictions.

1. INTRODUCTION

Geothermal energy stems from the Earth's outward heat-flux and geothermal systems are regions in the Earth's crust where this flux, and the associate energy storage, are abnormally great. In the majority of cases the energy transport medium is water and such systems are, therefore, called hydro-thermal systems. Geothermal springs have been used for bathing, washing and cooking for thousands of years in a number of countries worldwide (Cataldi *et al.*, 1999). China and Japan are good examples and ruins of baths from the days of the Roman Empire can be found from England in the north to Syria in the south. Yet commercial utilisation of geothermal resources for energy production only started in

the early 1900's. Electricity production was initiated in Larderello, Italy, in 1904 and operation of the largest geothermal district heating system in the world in Reykjavik, Iceland, started in 1930. At about the same time extensive greenhouse heating with geothermal energy started in Hungary. Since this time, utilisation of geothermal resources has increased steadily.

Geothermal resources have been identified in some 90 countries, with systematic utilisation in more than 70 countries (Fridleifsson, 2003). In 2004, the worldwide direct use of geothermal energy amounted to about 76 TWh/a, and the electricity production equalled 57 TWh/a (Lund *et al.*, 2005; Bertani, 2005). The direct use increased by 43% from 1999 to 2004 (annual growth rate of 7.5%). The top five countries in geothermal direct use in the world in 2004 were China, Sweden, USA, Turkey and Iceland, utilizing from 6800 to 12600 GWh/a. Geothermal electricity is produced in 23 countries, and electricity production increased by 16% from 1999 to 2004 (annual growth rate of 3%). Stefánsson (2005) estimated identified geothermal resources worldwide to amount to 4.4 and 0.2 TW (39,000 and 1800 TWh/a) for direct use and electricity generation, respectively. The total potential (identified and unidentified) is expected to be up to an order of magnitude greater. The present geothermal use is a very small fraction of the identified potential. There is, therefore, ample space for accelerated use of geothermal resources worldwide in the near future.

The understanding of geothermal resources has grown concurrently with the rapid development of the last decades. Old ideas on the origin of the heat and the fluid supply of the geothermal resources and its nature, based on limited knowledge, have been challenged with extensive new data from exploration, drilling and production monitoring of numerous geothermal fields throughout the world. 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.

This paper discusses briefly the production capacity of geothermal systems. This capacity is highly variable depending on the size, characteristics and nature of the various systems. The different types of geothermal systems are discussed as well as the factors that control their capacity. The different aspects of the production response of geothermal systems are discussed, with the support of some real examples (case histories). Finally the different methods of resource capacity assessment and modelling are reviewed. In two follow-up papers by the current author the management of geothermal resources during utilization is discussed (Axelsson, 2008b) as well as the importance of waste- and return-water reinjection in geothermal resource management (Axelsson, 2008c).

2. NATURE AND CLASSIFICATION OF GEOTHERMAL SYSTEMS

Geothermal resources are distributed throughout the world. Even though most geothermal systems and the greatest concentration of geothermal energy are associated with the Earth's plate boundaries, geothermal energy may be found in most countries. It is highly concentrated in volcanic regions, but may also be found as warm ground water in sedimentary formations world-wide. In many cases geothermal energy is found in populated, or easily accessible, areas. But geothermal activity is also found at great depth on the ocean floor, in mountainous regions and under glaciers and ice caps. Numerous geothermal systems probably still remain to be discovered, since many systems have no surface activity. Some of these are, however, slowly being discovered. The following definitions are used here:

- *Geothermal Field* is a geographical definition, usually indicating an area of geothermal activity at the earth's surface. In cases without surface activity this term may be used to indicate the area at the surface corresponding to the geothermal reservoir below.
- *Geothermal System* refers to all parts of the hydrological system involved, including the recharge zone, all subsurface parts and the outflow of the system.

- *Geothermal Reservoir* indicates the hot and permeable part of a geothermal system that may be directly exploited. For spontaneous discharge to be possible geothermal reservoirs must also be pressurised.

Geothermal systems and reservoirs are classified on the basis of different aspects, such as reservoir temperature or enthalpy, physical state, their nature and geological setting. Table 1 summarizes classifications based on the first three aspects.

TABLE 1: Classifications of geothermal systems on the basis of temperature, enthalpy and physical state (Bodvarsson, 1964; Axelsson and Gunnlaugsson, 2000).

Low-temperature (LT) systems with reservoir temperature at 1 km depth below 150°C. Often characterised by hot or boiling springs.	Low-enthalpy geothermal systems with reservoir fluid enthalpy less than 800 kJ/kg, corresponding to temperatures less than about 190°C.	Liquid-dominated geothermal reservoirs with the water temperature at, or below, the boiling point at the prevailing pressure and the water phase controls the pressure in the reservoir. Some steam may be present.
Medium-temperature (MT) systems.		Two-phase geothermal reservoirs where steam and water co-exist and the temperature and pressure follow the boiling point curve.
High-temperature (HT) systems with reservoir temperature at 1 km depth above 200°C. Characterised by fumaroles, steam vents, mud pools and highly altered ground.	High-enthalpy geothermal systems with reservoir fluid enthalpy greater than 800 kJ/kg.	Vapour-dominated geothermal where temperature is at, or above, the boiling point at the prevailing pressure and the steam phase controls the pressure in the reservoir. Some liquid water may be present.

It should be pointed out that hardly any geothermal systems in Iceland fall in-between 150 and 200°C reservoir temperature, i.e. in the MT range. Also that a common classification is not to be found in the geothermal literature, even though one based on enthalpy is often used. Different parts of geothermal systems may be in different physical states and geothermal reservoirs may also evolve from one state to another. As an example a liquid-dominated reservoir may evolve into a two-phase reservoir when pressure declines in the system as a result of production. Steam caps may also evolve in geothermal systems as a result of lowered pressure. Low-temperature systems are always liquid-dominated, but high-temperature systems can either be liquid-dominated, two-phase or vapour-dominated.

Geothermal systems may also be classified based on their nature and geological setting (see Figure 1):

- Volcanic systems* are in one way or another associated with volcanic activity. The heat sources for such systems are hot intrusions or magma. They are most often situated inside, or close to, volcanic complexes such as calderas and/or spreading centres. Permeable fractures and fault zones mostly control the flow of water in volcanic systems.
- In *convective systems* the heat source is the hot crust at depth in tectonically active areas, with above average heat-flow. Here the geothermal water has circulated to considerable depth (> 1 km), through mostly vertical fractures, to mine the heat from the rocks.
- Sedimentary systems* are found in many of the major sedimentary basins of the world. These systems owe their existence to the occurrence of permeable sedimentary layers at great depths (> 1 km) and above average geothermal gradients (> 30°C/km). These systems are conductive

in nature rather than convective, even though fractures and faults play a role in some cases. Some convective systems (B) may, however, be embedded in sedimentary rocks.

- D. *Geo-pressured systems* are analogous to geo-pressured oil and gas reservoirs where fluid caught in stratigraphic traps may have pressures close to lithostatic values. Such systems are generally fairly deep; hence, they are categorised as geothermal.
- E. *Hot dry rock (HDR) or enhanced (engineered) geothermal systems (EGS)* consist of volumes of rock that have been heated to useful temperatures by volcanism or abnormally high heat flow, but have low permeability or are virtually impermeable. Therefore, they cannot be exploited in a conventional way. However, experiments have been conducted in a number of locations to use hydro-fracturing to try to create artificial reservoirs in such systems, or to enhance already existent fracture networks. Such systems will mostly be used through production/reinjection doublets.
- F. *Shallow resources* refer to the thermal energy stored near the surface of the Earth's crust. Recent developments in the application of ground source heat pumps have opened up a new dimension in utilizing these resources.

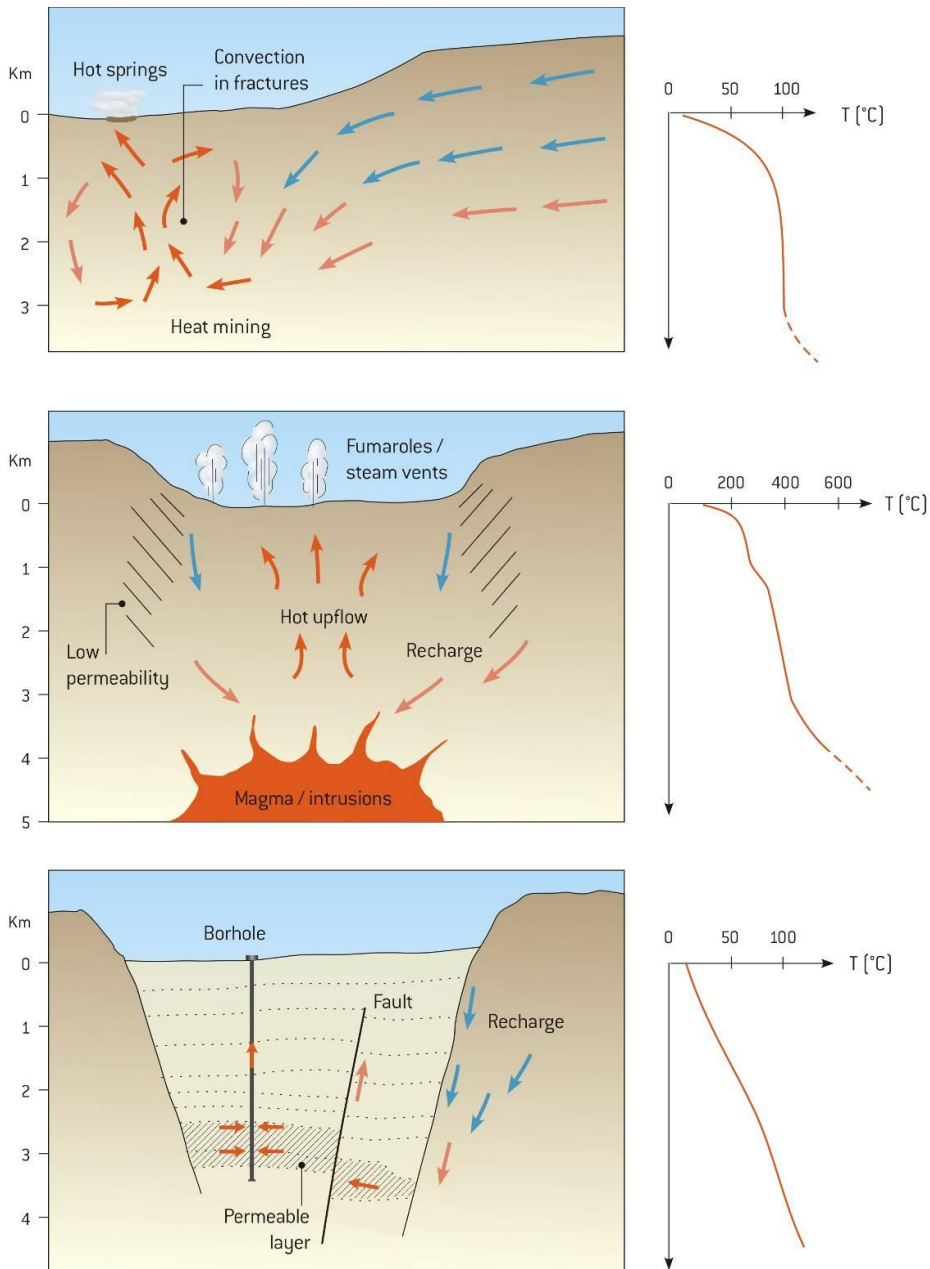


FIGURE 1: Schematic figures of the three main types of geothermal systems (A, B and C). Numerous volcanic geothermal systems (A) are found for example in The Pacific Ring of Fire, in countries like New Zealand, The Philippines, Japan and in Central America. Geothermal systems of the convective type (B) exist outside the volcanic zone in Iceland, in the SW United States and in SE China, to name a few countries. Sedimentary geothermal systems (C) are for example found in France, Central Eastern Europe and throughout China. Typical examples of geopressured systems (D) are found in the Northern Gulf of Mexico Basin in the U.S.A., both offshore and onshore. The Fenton Hill project in New Mexico in The United States and the Soultz project in NE-France are well known HDR and EGS projects (E) while shallow resources (F) can be found all over the globe.

3. WHAT CONTROLS PRODUCTION CAPACITY OF GEOTHERMAL SYSTEMS

Geothermal resources are normally classified as renewable energy sources, because they are maintained by a continuous energy current. This is in accordance with the definition that the energy extracted from a renewable energy source is always replaced in a natural way by an additional amount of energy with the replacement taking place on a time-scale comparable to that of the extraction time-scale (Stefánsson, 2000). Such a classification may be an oversimplification because geothermal resources are in essence of a double nature, i.e. a combination of an energy current (through heat convection and conduction) and stored energy (Axelsson *et al.*, 2005). The renewability of these two aspects is quite different as the energy current is steady (fully renewable) while the stored energy is renewed relatively slowly, in particular the part renewed by heat conduction. During production the renewable component (the energy current) is greater than the recharge to the systems in the natural state, however, because production induces in most cases an additional inflow of mass and energy into the systems (Stefánsson, 2000).

Even though geothermal resources are considered renewable their production capacity is not unlimited. Their utilisation involves extracting mass and heat from a given geothermal reservoir, most often through deep boreholes. In low-temperature areas this is most often done by pumping water from the boreholes while in high-temperature areas the mass extraction is mostly through spontaneous discharge of the wells. The processes dominating this are, of course, mass and heat transport in the geothermal system and through the boreholes. Mass and heat transfer are also the predominant processes during the undisturbed natural state of a geothermal system. In the natural state, this transport is driven by global pressure variations in the geothermal system. During production, the mass and heat transport forced upon the system causes spatial as well as transient changes in the pressure state of a reservoir. Mass extraction causes e.g. a reservoir pressure decline. Therefore, it may be stated that *reservoir pressure* is one of the most important parameters involved in geothermal exploitation.

Energy content, either represented as internal energy or enthalpy, is the other crucial parameter of geothermal exploitation. In single-phase situations, this depends on temperature only, and pressure and temperature define the state of the reservoir. In two-phase situations pressure and temperature are related and an additional parameter is needed, such as water saturation or enthalpy.

The energy production potential of a geothermal system is predominantly determined by pressure decline due to production. This is because there are technical limits to how great a pressure decline in a well is allowable, because of e.g. pump depth. The production potential is also determined by the available energy content of the system, i.e. by the temperature or enthalpy of the extracted mass. The pressure decline is determined by the rate of production, on one hand, and the nature and characteristics of the geothermal system, on the other hand, such as:

- The size of the geothermal reservoir,
- permeability of the reservoir rocks,

- reservoir storage capacity (depending on porosity and reservoir nature/processes),
- water recharge (i.e. boundary conditions) and
- geological structure of the system (e.g. fracture networks and permeable volumes).

The nature of the geothermal reservoirs 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.

Geothermal reservoirs can be classified as either *open* or *closed*, with drastically different long-term behaviour, depending on their boundary conditions:

- Pressure declines continuously with time, at constant production, in systems that are *closed* or with small recharge. In such systems the production potential is limited by lack of water rather than lack of thermal energy. Such systems are ideal for reinjection, which provides man-made recharge. Examples are many sedimentary geothermal systems, systems in areas with limited tectonic activity or systems that have been sealed off from surrounding hydrological systems by chemical precipitation.
- Pressure stabilizes in *open* systems because recharge eventually equilibrates with the mass extraction. The recharge may be both hot deep recharge and colder shallow recharge. The latter will eventually cause the reservoir temperature to decline and production wells to cool down. In such systems the production potential is limited by the reservoir energy content (temperature and size) as the energy stored in the reservoir rocks will heat up the colder recharge as long as it is available/accessible.

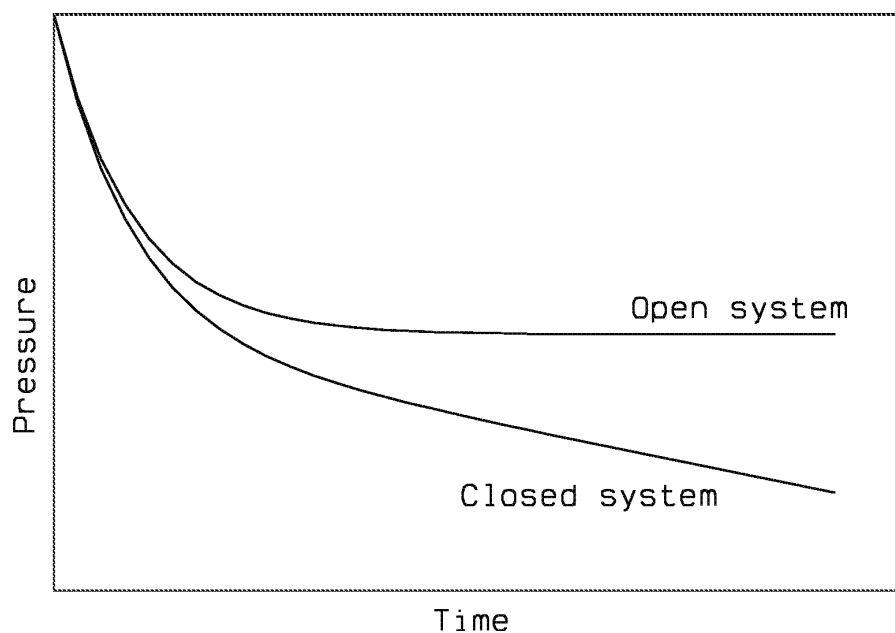


FIGURE 2: Schematic comparison of pressure decline in open (with recharge) or closed (with limited or no recharge) geothermal systems at a constant rate of production.

4. PRODUCTION RESPONSE

Water or steam extraction from a geothermal reservoir causes, in all cases, some decline in reservoir pressure, as already discussed. The only exception is when production from a reservoir is less than its natural recharge and discharge. Consequently, the pressure decline manifests itself in further changes, which may be summarised in a somewhat simplified manner as follows:

- A. Direct changes caused by **lowered reservoir pressure**, such as changes in surface activity, decreasing well discharge, lowered water level in wells, increased boiling in high-enthalpy reservoirs and changes in non-condensable gas concentration.
- B. Indirect changes caused by **increased recharge** to the reservoir, such as changes in chemical composition of the reservoir fluid, changes in scaling/corrosion potential, changes in reservoir temperature conditions (observed through temperature profiles of wells) and changes in temperature/enthalpy of reservoir fluid.
- C. **Surface subsidence**, which may result in damage to surface installations.

Table 2 presents examples of the effect of long-term, large-scale production in several geothermal systems, both in Iceland and other parts of the world. These are both high- and low-enthalpy systems, of quite contrasting nature. Some exhibit a drastic pressure draw-down for limited production while others experience very limited draw-down for substantial mass extraction. The table also shows examples of reservoir cooling due to long-term production. Figures 3 – 6 show the production and response histories of four of the fields in the table, as examples.

TABLE 2: Information on the effect of large-scale production on selected geothermal systems e.g. in Iceland, China (Urban Area), The Philippines (Palinpinion-1) and El Salvador (Ahuachapan). Note that the data are approximate, but representative, values based on information from 2000–2006.

System (location)	Production initiated	Number of prod. wells	Average prod. (kg/s)	Reservoir temp. (°C)	Draw-down	Temp. decline (°C)
Svartsengi (SW-Icel.)	1976	10	380	240	275 m	0
Laugarnes (SW-Icel.)	1930	10	160	127	110 m	0
Reykir (SW-Icel.)	1944	34	850	70-97	100 m	0-13*
Nesjavellir (SW-Icel.)	1975	11	390	280-340	7 bar	0
Hamar (N-Icel.)	1970	2	30	64	30 m	0
Laugaland (N.-Icel)	1976	3	40	95	370 m	0
Krafla (N-Icel.)	1978	21	300	210-340	10-15 bar	0
Urridavatn (E-Icel.)	1980	3	25	75	40 m	2-15**
Gata (S-Icel.)	1980	2	17	100	250 m	1-2
Urban Area (China)	late 1970's	90-100	~100	~40-90	45 m	0
Xi'an (China)***	1994	~80	~240	~40-105	150 m	0
Palinpinion-1 (Philip.)	1983	23	710	240	55 bar	-
Ahuachapan (El Sal.)	1976	~16	~700	240-260	14 bar	-

* Only 3 of the 34 production wells have experienced some cooling.

** Two older production wells, not used after 1983, experienced up to 15°C cooling.

*** Inaccurate data.

It should be mentioned that reinjection affects the production response of geothermal systems, primarily by providing pressure support and thus reducing pressure decline. This is discussed in detail by Axelsson (2008c).

5. ESTIMATING PRODUCTION CAPACITY

Various methods have been used the last several decades to assess geothermal resources during both exploration and exploitation phases of development. These range from methods used to estimate resource temperature and size to complex numerical modelling aimed at predicting the production response of systems and estimating their production potential. Being able to assess a given resource

during different stages of its development, as accurately as possible, is essential for its successful development. The main methods used are:

- (a) Deep temperature estimates (based on chemical content of surface manifestations).
- (b) Surface thermal flux.
- (c) Volumetric methods (adapted from mineral exploration and oil industry).
- (d) Decline curve analysis (adapted from oil/gas industry).
- (e) Simple mathematical modelling (often analytical).
- (f) Lumped parameter modelling.
- (g) Detailed numerical modelling of natural state and/or exploitation state (often called distributed parameter models).

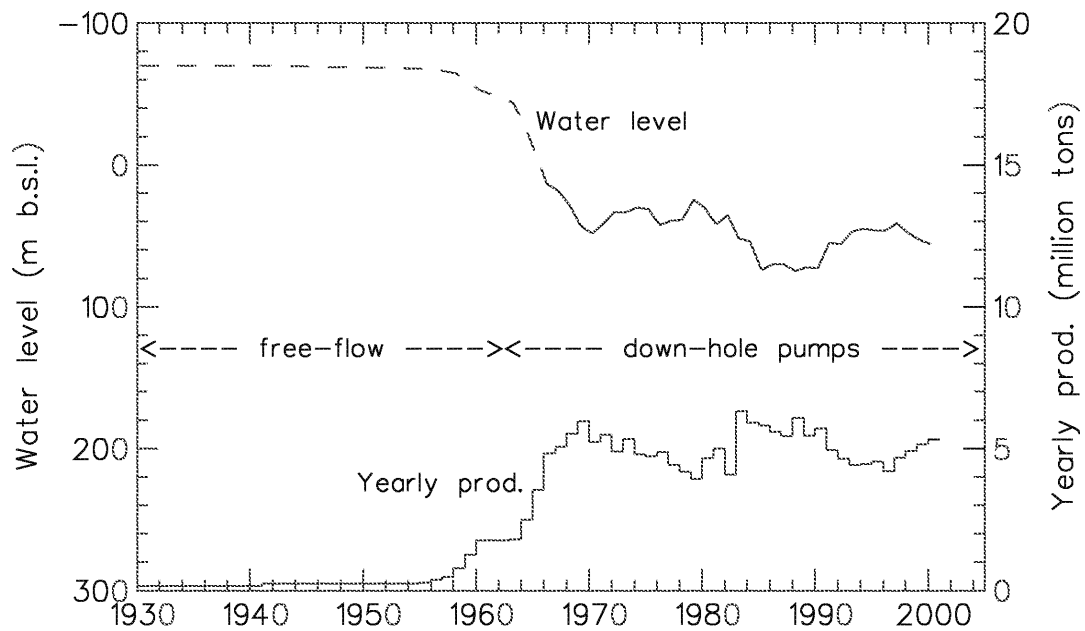


FIGURE 3: History of production and water level response of the Laugarnes geothermal field in SW-Iceland from 1930.

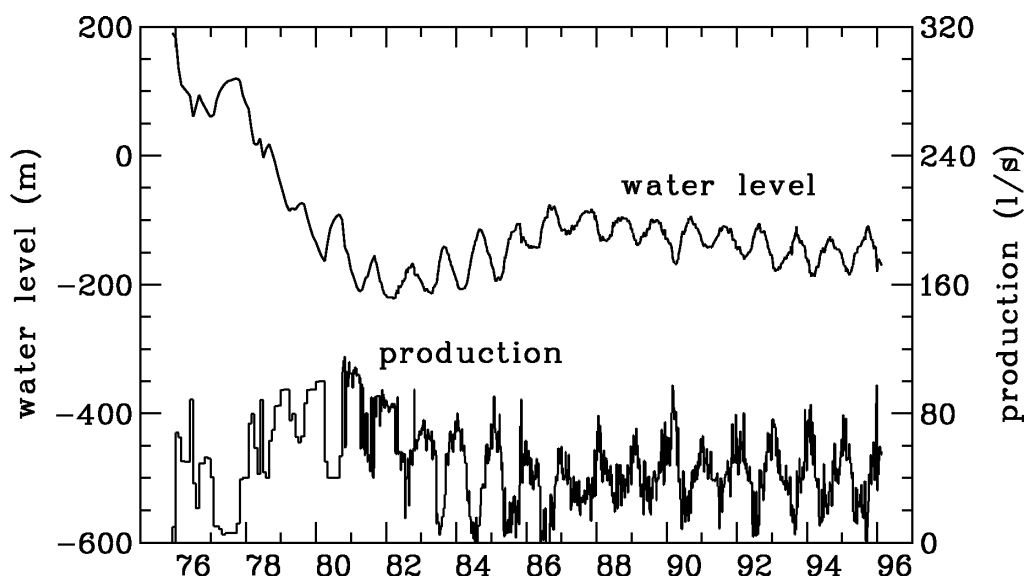


FIGURE 4: Production and water-level response history of the Laugaland geothermal field in N-Iceland.

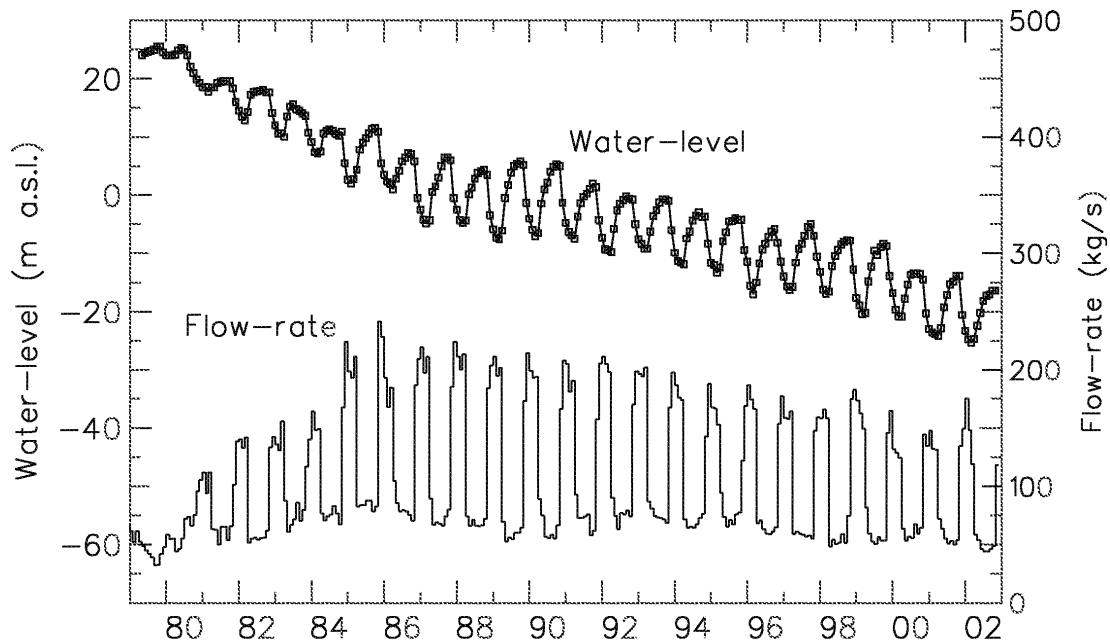


FIGURE 5: Production and water-level response history of the Urban Area in Beijing, China since the late 1970's (Liu *et al.*, 2002).

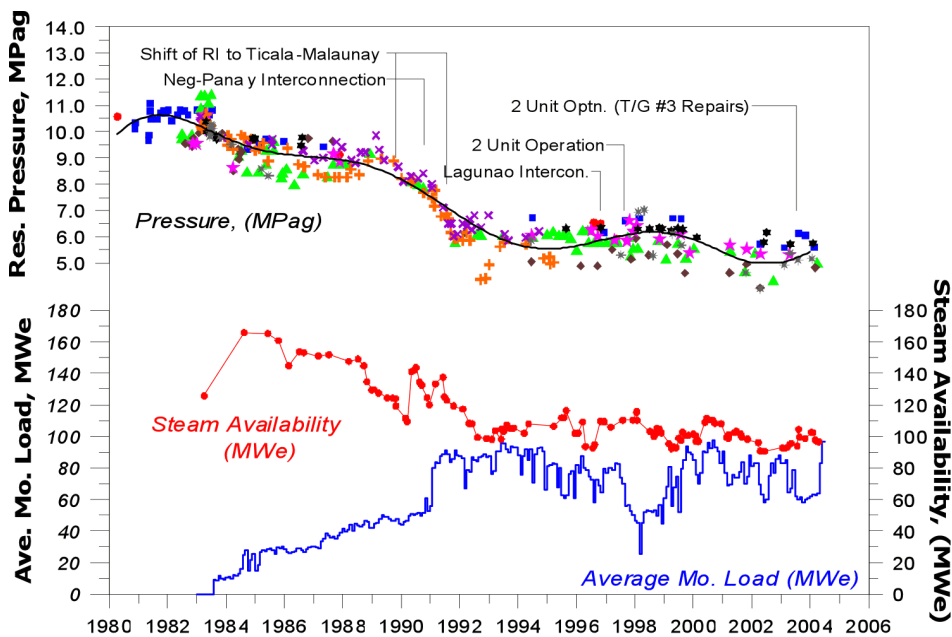


FIGURE 6: The production and pressure response history of the Palinpinon-1 geothermal field in The Philippines (Aqui *et al.*, 2005).

Modelling plays an essential role in geothermal resource development and management. This ranges from basic volumetric resource assessment and simple analytical modelling of the results of a short well test to detailed numerical modelling of a complex geothermal system, simulating an intricate pattern of changes resulting from long-term production. The purpose of geothermal modelling is firstly to obtain information on the conditions in a geothermal system as well as on the nature and properties of the system. This leads to proper understanding of its nature and successful development of the

resource. Secondly, the purpose of modelling is to predict the response of the reservoir to future production and estimate the production potential of the system as well as to estimate the outcome of different management actions.

The diverse information, which is the foundation for all reservoir-modelling, needs to be continuously gathered throughout the exploration and exploitation history of a geothermal reservoir. Information on reservoir properties is obtained by disturbing the state of the reservoir (fluid-flow, pressure) and by observing the resulting response, and is done through well and reservoir testing and data collection. Different methods of testing geothermal reservoirs are available, but it should be emphasised that the data collected does not give the reservoir properties directly. Instead, the data are interpreted, or analysed, on the basis of appropriate models yielding estimates of reservoir properties. It is important to keep in mind that the resulting values are *model-dependent*, i.e. different models give different estimates. It is also very important to keep in mind that the longer, and more extensive the tests are, the more information is obtained on the system in question. Therefore, the most important data on a geothermal reservoir is obtained through careful monitoring during long-term exploitation, which can be looked upon as prolonged and extensive reservoir testing.

The modelling methods may be classified as either *volumetric assessment methods* or *dynamic modelling methods*. Both involve development of some kind of a mathematical model that *simulates* some, or most, of the data available on the system involved. The volumetric method is based on estimating the total heat stored in a volume of rock (referred to some base temperature), both thermal energy in rock matrix and in water/steam in pores.

The volumetric method is often used for first stage assessment, when data are limited and was more commonly used in the past (Rybach and Muffler, 1981), but is still the main assessment method in some countries, e.g. for Chinese low-temperature resources. The main drawback of this method is that the dynamic response of a reservoir to production is not considered, such as the pressure response and the effect of fluid recharge. Reservoirs with the same heat content may have different permeabilities and recharge and, hence, very different production potentials.

In the volumetric method the likely surface area and thickness of a resource are estimated from geophysical and geological data. Consequently likely temperature conditions are assumed. Based on these, estimates of reservoir porosity and thermal properties of water and rock involved, the total energy content is estimated. Subsequently the surface accessibility is incorporated, i.e. what proportion of the reservoir volume can be accessed through drilling from the surface. Finally a recovery factor (R) is incorporated, a factor which indicates how much of accessible energy may be technically recovered, often assumed in the range of 0.05–0.20. For electrical generation the resource potential is often assessed using a likely conversion-efficiency above a given reference temperature.

The volumetric method can be applied to individual geothermal systems or on a regional scale. For individual systems the Monte Carlo method is often applied (see Figure 7). It involves assigning probability distributions to different parameters and estimating the system potential with probability.

The models used for dynamic modelling can be (1) simple analytical models, (2) lumped parameter models and (3) detailed numerical models. The model provides information on conditions in, and properties of the actual geothermal system. This information is, however, not unique but model-dependent. Consequently the model is used to predict future changes in the reservoir involved and estimate its production potential. Reservoir models are also helpful in estimating the outcome of different management actions.

The initial step in model development should be the development of a good conceptual model (Bodvarsson *et al.*, 1986; Pruess, 2002). This is a qualitative or descriptive model incorporating all the essential features of a geothermal system revealed by analysis of all available data. Quantitative natural state model is thus developed that should simulate the physical state of a geothermal system

prior to production. Finally, an exploitation model is developed to simulate changes in the physical state of a system during long-term production, and to calculate predictions as well as for other management purposes.

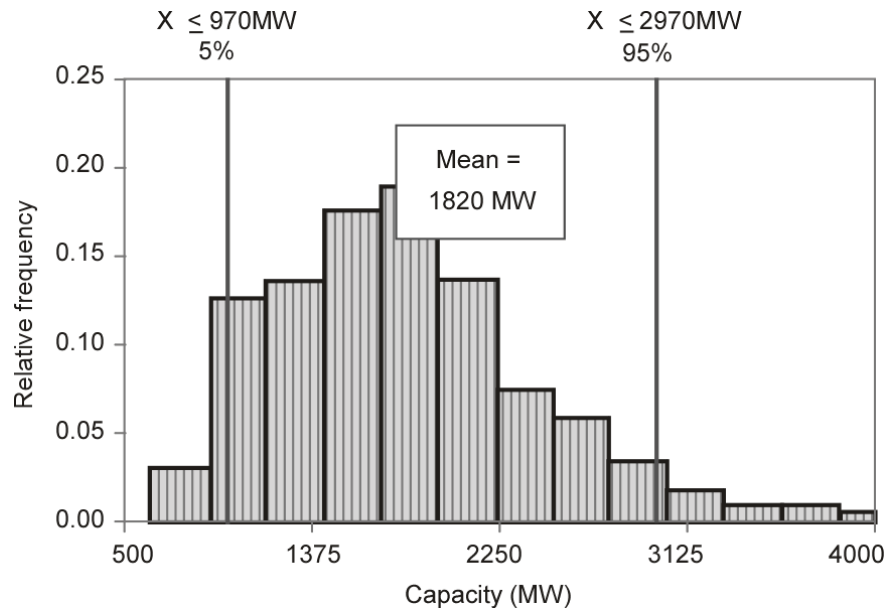


FIGURE 7: An example of the results of a volumetric resource assessment for the greater Hengill geothermal region in SW-Iceland. The Monte Carlo method was applied in the assessment (Sarmiento and Björnsson, 2007)

Numerous examples are available on the successful role of modelling in geothermal resource management (Axelsson and Gunnlaugsson, 2000; O'Sullivan *et al.*, 2001). These involve the use of simple analytical models as well as complex numerical models. In simple models, the real structure and spatially variable properties of a geothermal system are greatly simplified, in order that analytical mathematical equations, describing the response of the model to hot water production may be derived. These models, in fact, often only simulate one aspect of a geothermal system's response. Detailed and complex numerical models, on the other hand, can accurately simulate most aspects of a geothermal system's structure, conditions and response to production. Simple modelling takes relatively little time and only requires limited data on a geothermal system and its response, whereas numerical modelling takes a long time and requires powerful computers as well as comprehensive and detailed data on the system in question. The complexity of a model should be determined by the purpose of a study, the data available and its relative cost.

Numerical modelling, which is increasingly being used to simulate geothermal systems in different parts of the world, will not be discussed here. Instead the reader is referred to a comprehensive review by O'Sullivan *et al.*, (2001). Simple modelling, on the other hand, has been used extensively to study and manage the low-temperature geothermal systems utilised in Iceland, in particular to model their long-term response to production. Lumped parameter modelling, which is used to simulate data on water level and pressure changes, has been the principal tool for this purpose (Axelsson *et al.*, 2005a). Lumped models can simulate such data very accurately, even very long data sets (several decades). Today, lumped models have been developed by this method for more than 20 low-temperature and 3 high-temperature geothermal systems in Iceland, as well as geothermal systems in China, Turkey, Eastern Europe, Central America and The Philippines, as examples.

Figures 8 – 10 show examples from modelling studies of two geothermal fields, one in Iceland and the other one in China.

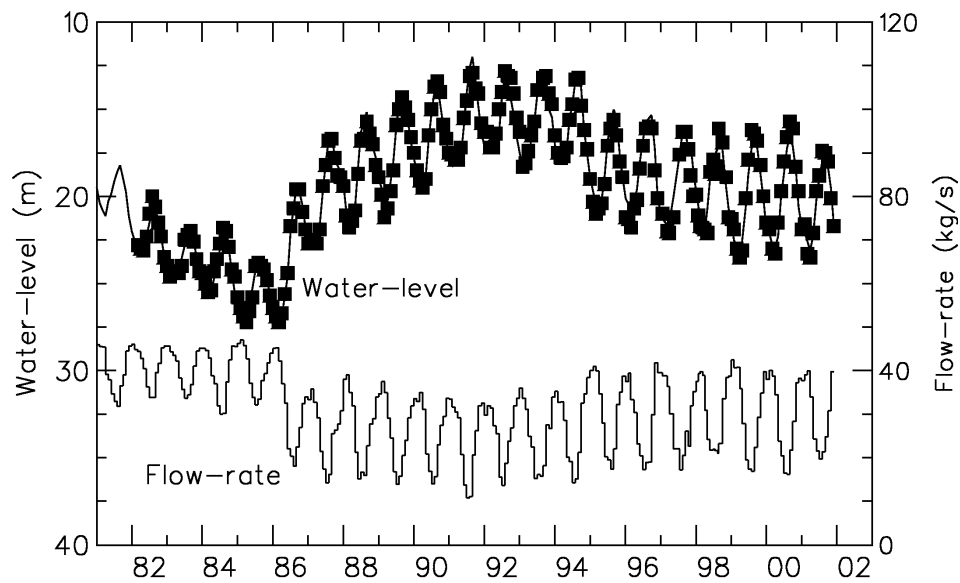


FIGURE 8: Water level changes in the Hamar low-temperature system in N-Iceland (see Table 2) simulated by a simple lumped-parameter model. The model was consequently used to calculate water-level predictions not presented here (Axelsson *et al.*, 2005b).

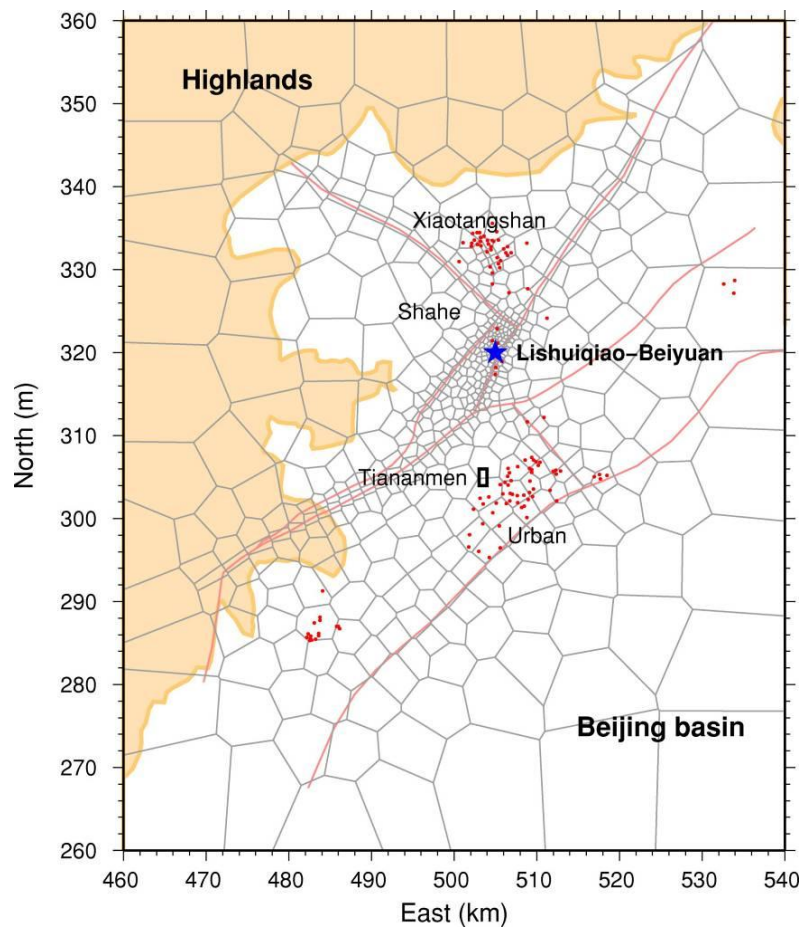


FIGURE 9: The model grid layout of a complex numerical model set up for the sedimentary geothermal resources under Beijing, China, by Hjartarson *et al.* (2005). The model is also divided into 8 layers with identical grid layout.

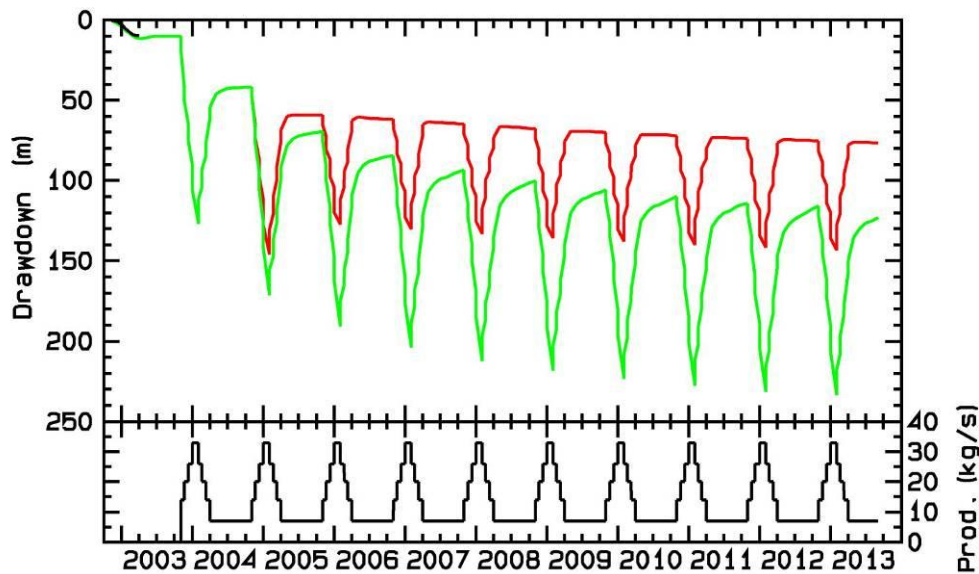


FIGURE 10: Water level predictions for well BY-1 in the Lishuiqiao area of Beijing, calculated by the model of Figure 9 for two production scenarios, one with 50% reinjection (red line) and the other without any reinjection (green line).

6. CONCLUSIONS

In conclusion the following should be emphasized: Even though energy content (mainly depending on temperature and size) controls the energy production potential of a geothermal system the pressure decline caused by hot water production is really the determining factor in this regard. This has been revealed by numerous geothermal production case histories. The pressure response is controlled by the nature and properties of a geothermal system, which can be classified as being of approximately two main types. (A) Closed systems where pressure declines continuously with time, at constant production, because of small or no recharge. In such systems the production potential is limited by lack of water rather than lack of thermal energy. (B) Open systems where recharge eventually equilibrates with the mass extraction. The colder shallow part of the recharge will eventually cause the reservoir temperature to decline and production wells to cool down. In such systems the production potential is limited by the reservoir energy content.

The nature of the geothermal system must, therefore, be kept in mind when planning exploitation and during management. This requires full-scale geothermal research continuing from the initial stages of exploration throughout the long-term utilization phase. Modelling plays a key role in understanding the nature of geothermal systems and is the most powerful tool for predicting their response to future production. The nature of a system also determines how beneficial reinjection can be.

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