

Sustainable Development of Geothermal Resources in China

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ABSTRACT

China is rich in, especially low-medium temperature geothermal resources. There are more than 3000 natural geothermal springs and 3500 geothermal wells distributed in the country. The direct use of geothermal energy reached 18,900 GWh in 2007, with an annual increase rate of 13%, which ranked first in the world. The space heating area in China has reached 30 million m² by using geothermal water, and 40 million m² by using geothermal heat pumps. Due to the heavy exploitation of geothermal water and irrational layout of exploitation, overdevelopment of geothermal resources has occurred in China, and induced some corresponding environmental geothermal issues, including water level (pressure) declining continuously, cold water intrusion and temperature and TDS drop, waste water pollution, etc.

Aiming sustainable development of geothermal resources, this paper explores the concept of sustainable yield of geothermal wells and reservoirs. The prerequisite of calculating sustainable yield is to determine a rational maximum allowable drawdown of the production wells in the geothermal reservoir, within a time frame. For a new discovered reservoir, which has not been heavily extracted, it is essential to build a conceptual and numerical model to carry out sustainable yield evaluation based on interference pumping test and water level response observation. Whereas for a developed geothermal reservoir, it is essential to evaluate sustainable yield in view of long-term water level response and the constraints of unacceptable environmental geothermal issues. It is believed that the sustainable development of geothermal resources can be achieved, i.e. the water level and temperature will be maintained in the allowable limits at the end of time frame, if the production is based on sustainable yield. Three case studies have been presented in this paper, one is for a heavily developed sedimentary geothermal reservoir with continuous water level decline, the second is for a new discovered sedimentary geothermal reservoir, and the third is for an overexploited fractured geothermal reservoir with temperature and TDS drop.

1. GEOTHERMAL DEVELOPMENT IN CHINA

High temperature geothermal resources in China are distributed in the zone from Tibet to West Yunnan, which have been used for power generation in Yangbajain, Tibet, with an operating installed capacity of 25.18 MWe. Geothermal power satisfied 50% electricity demand in Lhasa, the capital of Tibet, even 60% in winter (Figure1).

China is rich in, especially low-medium temperature geothermal resources. There are more than 3000 natural

geothermal springs and 3500 geothermal wells distributed in the country. Low-medium temperature geothermal resources are directly used in various aspects in China: space heating, bathing, balneology, fish farming, sanatorium, swimming pool and greenhouse, etc.



Figure 1: Geothermal power generation in Yangbajain

The direct use of geothermal energy reached 18,900 GWh in 2007, with an annual increase rate of 13%, which ranked first in the world. The geothermal water production reached 470 million m³. The space heating area in China has reached 30 million m² by using geothermal water, and 40 million m² by using geothermal heat pumps.

2. ENVIRONMENTAL GEOTHERMAL ISSUES

Due to the heavy exploitation of geothermal water and irrational layout of exploitation, overdevelopment of geothermal resources has occurred in China, and induced some corresponding environmental geothermal issues, including water level (pressure) declining continuously, cold water intrusion and temperature and TDS drop, waste water pollution, etc.

2.1 Continuous Geothermal Water Level (Pressure) Declining

Corresponding to the overdevelopment of geothermal water, the water level (pressure) in the reservoir has been decreasing dramatically. Figure 2 shows the water level variations along with monthly production in southeast urban geothermal field of Beijing, with an annual water level decrease of 1-2.5 m.

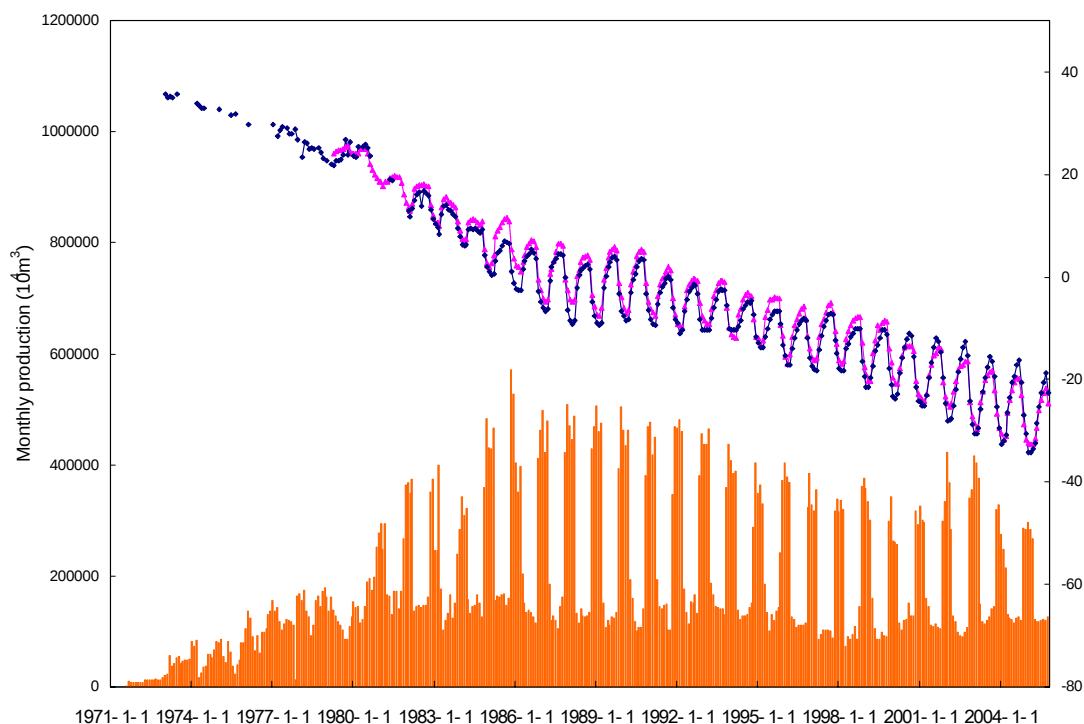


Figure 2: Water level variations along with monthly production in SE urban geothermal field of Beijing (From Liu Jiurong, (2008))

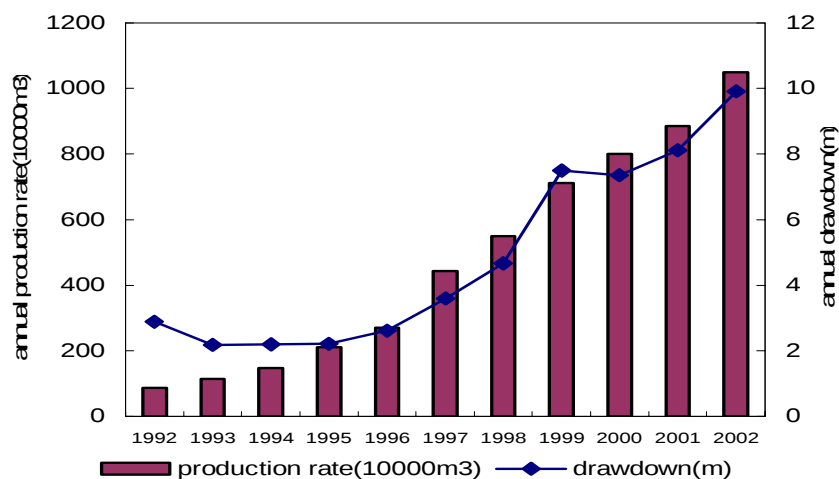


Figure 3: History curve of water level drawdown and geothermal water production of the dolomite reservoir in Tianjin urban area

Figure 3 illustrates the history curve of water level drawdown and geothermal water production of the dolomite reservoir in Tianjin urban area from 1992 to 2002. Since 1997, the annual water level drawdown has been over 3 m, and even got to 10 m in 2002. At present, the depth to the water level varies between 40 m and 120 m in different areas. The area of water level deeper than 90 m has reached 554 km² in 2007 (Figure 4). Now, the geothermal water level is still decreasing 6-9 m annually.

2.2 Temperature and TDS Drop

Corresponding to the water level drawdown, obvious temperature and TDS decrease occurred in some geothermal reservoirs, especially in natural warm spring areas due to shallow colder groundwater or surface water inflow.

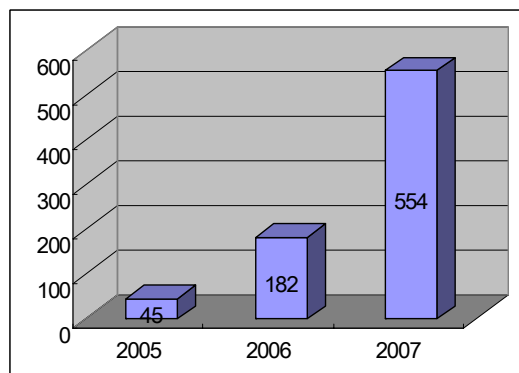


Figure 4: The area of water level deeper than 90 m in Tianjin

Tangtuo, one of the 18 natural geothermal springs in Shandong province of Eastern China, its temperature and TDS have decreased since 1970's due to large scale development (Figure 5). Before 1960's, the free flow rate was 388 m³/d, with temperatures ranging around 70°C and TDS around 4.5 g/l. In 2000, the total production from geothermal wells reached 955 m³/d, its temperature dropped to 48°C, and TDS to 1.9 g/l.

2.3 Waste Water Pollution

Generally speaking, geothermal is renewable and clean energy, but the geothermal waste waters have higher salinity and contain pollutants as Fluorine (F), Boron (B), Mercury (Hg), Arsenic (As). Parts of the pollutant contents exceed the national disposal water quality standards for drinking, irrigation and aquaculture water. Meanwhile, cascaded and comprehensive use of geothermal water in China is not so common. As a result, the discharged water usually has higher temperature with higher thermal energy.

3. SUSTAINABLE DEVELOPMENT OF GEOTHERMAL ENERGY

The prerequisite for sustainable geothermal extraction is to determine the sustainable yields of the production wells in the geothermal reservoir. The sustainable yield can be defined as geothermal exploitation over a specified timeframe without causing:

- (1) decrease water level (pressure) below the designed,
- (2) impact the normal exploitation of existed geothermal extraction wells,
- (3) water quality and temperature exceed allowable limits,
- (4) induce harmful environmental issues.

Based on the behaviors of geothermal development, particularly focused on the environmental geothermal issues, the author believes that the most fundamental indicator for sustainable yield of geothermal is maximum allowable yield of geothermal is maximum allowable water level (pressure) drawdown. The reason for this is that

most of the environmental geothermal issues are induced by too deep drawdown of water level (pressure). To be brief, the sustainable yield of geothermal is the maximum allowable yield when the actual drawdown doesn't exceed the maximum allowable drawdown within a time frame. Accordingly, the prerequisite to determine the sustainable yield is to determine the maximum allowable drawdown.

For a new discovered reservoir, which has not been heavily extracted, it is essential to build a conceptual and numerical model to carry out sustainable yield evaluation based on interference pumping test and water level response observation, as well as response predicting for the long-term behaviors of wells and reservoirs, including water level changes and its side effects. Detailed numerical modeling is an effective method for production potential calculation and evaluation by calculating and predicting water level behaviors for different future production scenarios. It can take interference of different wells into account, also consider the reservoir boundary conditions-open or close or in between, which has drastically different long-term behaviors individually.

To fulfill this aim, the maximum allowable water level drawdown should be determined carefully as the precondition of the sustainable yield evaluation. In other words, sustainable yield is drawdown dependent.

Whereas for a developed geothermal reservoir, it is essential to evaluate sustainable yield in view of long-term water level (pressure) response and the constraints of unacceptable environmental geothermal issues. So, the importance of long-term measurements of geothermal water level (pressure) should be highlighted.

It is believed that the sustainable development of geothermal resources can be achieved, i.e. the water level and temperature will be maintained in the allowable limits at the end of time frame.

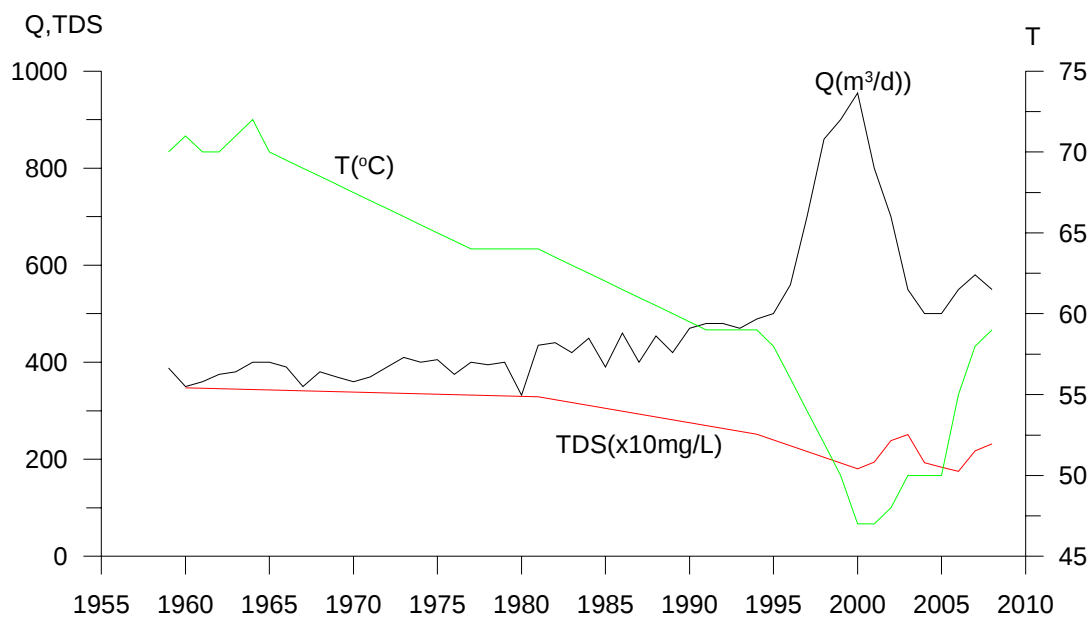


Figure 5: Relationship among production(Q), temperature(T) and water quality(TDS) of Tangtuo natural geothermal spring, Shandong, China

4. CASE STUDIES

4.1 Sedimentary Geothermal Reservoirs

Sedimentary geothermal reservoirs, which are widely distributed in the plain and basin areas of China, are characterized by large areal extent, rather homogeneous aquifers, quite productive wells and great energy potential.

Considering constraints in the sedimentary geothermal reservoir, including

- (1) setting depths of submersible pumps,
- (2) design of the production wells,
- (3) risk of colder water inflow,
- (4) subsidence,

the maximum allowable drawdown is determined as 300 m within 100 years.

Linqing, one of the sedimentary geothermal reservoirs in Northern China Plain, is located in Shandong Province, with heat-flow dominated by conduction. It is believed that the reservoir exists because of the occurrence of highly permeable sedimentary layers at great depth, and an above average geothermal gradient; as well as because of the faults and fractures. The cap rock is upper Minghuazhen formation of Neogene age. The upper Minghuazhen formation, with a thickness of 900 m, is composed of argillite and sandy argillite with interbedded sandstone.

The Linqing geothermal reservoir is located within the Guantao formation of Neogene age, with a depth ranging from 1130 to 1200 m. The main production aquifer of the reservoir is comprised of sandstone and conglomerate, covers an area of 519 km² and has a thickness of 160-220 m.

On the basis of the establishment of conceptual model of the Linqing Geothermal reservoir, a three-dimensional finite-difference model has been formulated as:

$$\left\{ \begin{array}{l} S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) + \varepsilon \\ x, y, z \in \Omega, t \geq 0 \\ \mu \frac{\partial h}{\partial t} = K_x \left(\frac{\partial h}{\partial x} \right)^2 + K_y \left(\frac{\partial h}{\partial y} \right)^2 + K_z \left(\frac{\partial h}{\partial z} \right)^2 - \frac{\partial h}{\partial z} (K_z + p) \\ x, y, z \in \Gamma_0, t \geq 0 \\ h(x, y, z, t)_{t=0} = h_0 \quad x, y, z \in \Omega, t \geq 0 \\ K_n \frac{\partial h}{\partial n} \Big|_{r_2} = q(x, y, t) \quad x, y, z \in \Gamma_1, t \geq 0 \end{array} \right.$$

After calibration, sensitivity analysis, and verification, the model can be used to evaluate the sustainable yield by calculating and predicting water level performance for different future production scenarios. Considering the constraint of maximum allowable drawdown-300m in the Linqing geothermal reservoir, the sustainable yield is evaluated to be 71,000 m³/d on the average for the next 100 years (Figure 6).

4.2 Fractured Geothermal Reservoir

Fractured geothermal reservoirs in China are mainly distributed in the eastern and southeastern coastal zones of China, which are controlled by neotectonisms and large- and deep faults, with convective heat flow. Their main aquifers are granite and metamorphic rocks, and the natural hot springs are the major geothermal manifestations, with temperatures varying from 40 to 120 °C

Considering main restrictions in the fractured geothermal reservoir, including

- (1) risk of colder water inflow (surface water, ground water, and sea water),
- (2) temperature and TDS decrease,

the maximum allowable drawdown is defined as 5-50 m in Shandong Peninsula, based on the critical water level when harmful water temperature and TDS drop appear for different geothermal reservoirs.

For Tangtou fractured geothermal reservoir, the maximum allowable drawdown is defined as 10 m, which means that when the water level is deeper than 10 m, obvious water temperature and TDS drop will occur in the reservoir-temperature below 60°C and TDS below 2.5 g/l (Figure 5). Corresponding to the maximum allowable drawdown, the sustainable yield is determined as 500 m³/d. That is to say, when the production in the Tangtou geothermal reservoir is less or equal 500 m³/d, the water temperature will be higher or equal 60°C and TDS will be higher or equal 2.5 g/l.

Yujiatang fractured geothermal reservoir is located in Shandong Peninsula. Based on the long-term observation, the relationship between water level and temperature has been obviously shown in Figure 7. When the water level is deeper than 12 m, the water temperature is lower than 40 °C, which decrease the utilization value remarkably. Accordingly, the maximum allowable drawdown is determined to be 12 m, and the corresponding sustainable yield is evaluated to be 633 m³/d.

5. CONCLUSIONS

The prerequisite for sustainable geothermal extraction is to determine the sustainable yields of the production wells in the geothermal reservoir. The sustainable yield can be defined as geothermal exploitation over a specified timeframe without causing harmful environmental geothermal issues.

The most fundamental indicator for sustainable yield of geothermal is maximum allowable water level (pressure) drawdown, and the sustainable yield is the maximum allowable yield when the actual drawdown doesn't exceed the maximum allowable drawdown within a time frame.

For a new discovered reservoir, which has not been heavily extracted, it is essential to build a conceptual and numerical model to carry out sustainable yield evaluation based on interference pumping test and water level response observation, as well as response predicting for the long-term behaviors of wells in the reservoir, including water level changes and its side effects.

For a developed geothermal reservoir, it is essential to evaluate sustainable yield in view of long-term water level (pressure) response and the constraints of unacceptable

environmental geothermal issues. So, the importance of long-term measurements of geothermal water level (pressure) should be highlighted.

If the actual production is based on the sustainable yield, it is believed that the sustainable development of geothermal energy can be achieved, i.e. the water level, temperature and water quality will be maintained in the allowable limit at the end of the time frame.

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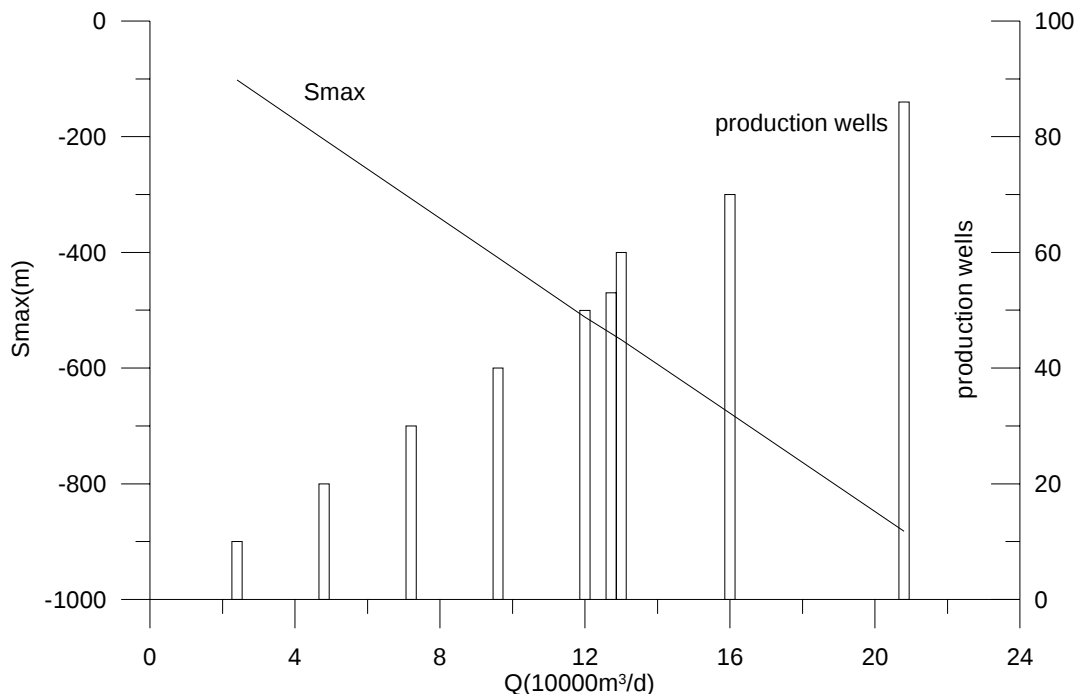


Figure 6: Relationship among production(Q), production wells and maximum water level drawdown (Smax) within 100 years in Linqing sedimentary geothermal reservoir, Shandong, China

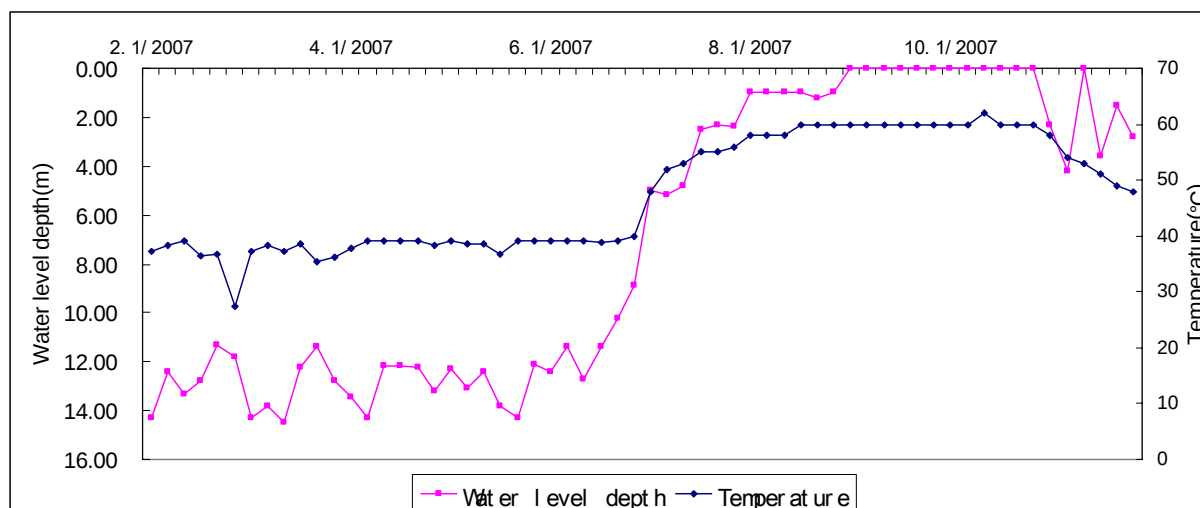


Figure 7: Relationship between water level and temperature in Yujiatang geothermal reservoir, Shandong Peninsula