UNITED NATIONS UNIVERSITY
UNU-GTP
Geothermal Training Programme

Orkustofnun, Grensasvegur 9,
IS-108 Reykjavik, Iceland

Reports 2015
Number 35

# ASSESSMENT OF THE URBAN DEZHOU SANDSTONE GEOTHERMAL RESERVOIR IN NORTH CHINA

**Zheng Tingting**
Shandong Provincial Institute of Geology and Mineral Resources
No.13632 Jingshi Road, Lixia District
Jinan 250014, Shandong Province
CHINA
*zttshandong@126.com*

## ABSTRACT

Sedimentary geothermal reservoirs are one of the two main types of low-temperature reservoirs in China, with productive wells. The reservoirs are characterized by infinite extent, homogeneous aquifers and are heated by heat conduction. This report presents the results of reservoir assessment of the Urban Dezhou Guantao formation sandstone geothermal reservoir in Shandong Province of North China.

As a consequence of large-scale production, water level decline problems have occurred in the Urban Dezhou reservoir. Therefore, reinjection tests were undertaken and the results show that 100% of the production water can be reinjected during a space heating period (120 days) without significant cooling in the reservoir. A tracer test model was set up to predict the geothermal temperature changes, they predict the temperature to remain stable for 50 years. Thermal breakthrough is calculated by another simple model to give an idea of the safe distance between reinjection wells and production wells. Monte Carlo volumetric assessment is undertaken to estimate the total recoverable energy in the Urban Dezhou reservoir. The lifetime of the Urban Dezhou reservoir is estimated based on the current production rate and the recoverable energy. Using the long-term monitoring water level depth data, the sustainable yield of the Urban Dezhou reservoir is estimated based on a two-tank closed lumped parameter model. The prerequisite is a maximum allowable water level depth of 150 m in 50 years' time. The estimated sustainable yield without reinjection is 25% of the current production rate, which cannot meet the demands of the city. To keep the current production rate, the reinjection rate should be more than 75% of the production rate. By keeping the maximum reinjection rate, which is 80% of the production, the sustainable yield becomes 25% more than the current production rate. Therefore, the sustainable yield with reinjection cannot only meet the demands of the city but also gives potential for more development of the reservoir. Further study of temperature and chemistry changes in the Urban Dezhou reservoir should be undertaken to complete the reservoir assessment.

## 1. INTRODUCTION

Sedimentary geothermal reservoirs are one of the two main types of low-temperature reservoirs in China. They are mostly of high potential with quite productive wells, heated by heat conduction from depth and are characterized by infinite extent and homogeneous aquifers. The geothermal resources contained in the major sedimentary basins of China are estimated to be about $2.5\times10^{22}$ J (Zheng et al., 2015). The North China sedimentary basin is one of the most important sedimentary basins in China. There are numerous urban areas in the basin, including Beijing, Tianjin, the Hebei Province and the Shandong Province. In Beijing, about 400 geothermal wells had been drilled by 2008, and the annual geothermal water production has been 7-9 million $m^3$. The temperature is in the range of 38-103°C, mostly 40-70°C (Huang, 2012). In Hebei, there are about 1000 geothermal wells in the sedimentary basin area and the annual geothermal water production has been around 50 million $m^3$ (Zhang et al., 2013).

This report presents the results of an assessment of the Urban Dezhou reservoir in the Shandong Province of North China. The report gives an overview of the reservoir properties and status and different methods are used to assess its properties and potential for utilization and development. The Urban Dezhou reservoir has a long production history. Water level decline became the main problem for the reservoir for which reinjection is the most effective solution. Reinjection is considered an important part of comprehensive geothermal resource management as well as an essential part of sustainable and environmentally friendly geothermal utilisation (Axelsson, 2012). The first reinjection test in Dezhou City took place in 2006. After 8-years of experiments, substantial improvements in injection, drilling and well construction have been achieved. In 2012, a reinjection test without artificial pressure successfully took place in Pingyuan County, Dezhou City. The first tracer test in the Urban Dezhou reservoir was undertaken in 2015 to predict the cooling in the reservoir and to get more information about reservoir properties.

## 2. THE URBAN DEZHOU SANDSTONE GEOTHERMAL RESERVOIR

Dezhou is a city in the north-western part of Shandong Province, 400 km from Beijing, in northeast China (Figure 1). The Urban Dezhou sandstone geothermal reservoir is in the north-western Shandong Depression which is part of the North China sedimentary basin located in the Yellow River alluvial plain (Figure 2). It is a low-temperature sedimentary reservoir, where 83 production wells have been successfully drilled since 1997, yielding water with temperatures between 52 and 59°C. The main geothermal development has been in the area of direct-utilization, such as for space heating, swimming pools and balneology (Kang, 2000).


FIGURE 1: Location of Dezhou city, Shandong, China (Kang, 2000)

### 2.1 Geological setting and hydrogeological conditions

The north-western Shandong Guantao formation sandstone geothermal reservoir is located in a large and continuous sedimentary basin and there are no obvious impermeable boundaries between different parts of the Guantao formation reservoir. For the purposes of this assessment, the reservoir studied is

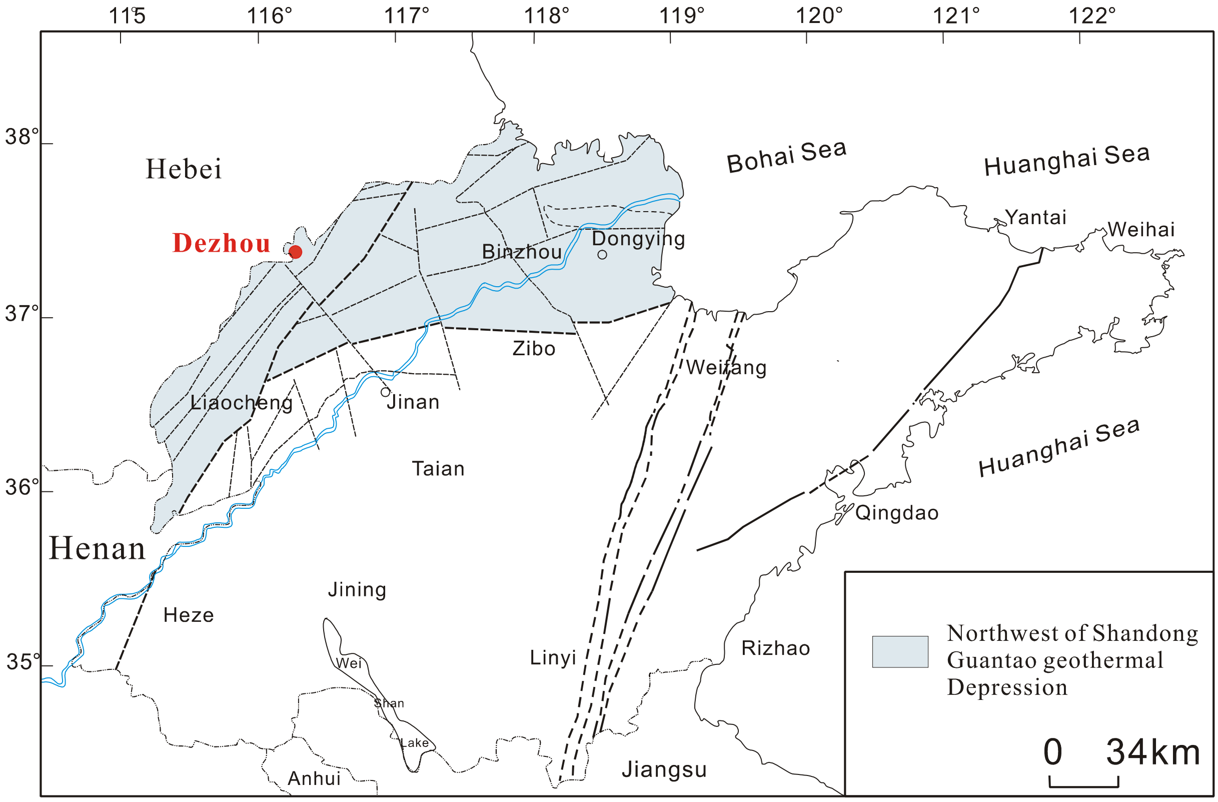


FIGURE 2: Location of the Dezhou geothermal field in the north-western Shandong Guantao geothermal depression

the Guantao formation sandstone aquifer from the Neogene age in the urban area of Dezhou City. The full name of the reservoir should be the Urban Dezhou Guantao formation sandstone geothermal reservoir. Later in this report, the term "the Urban Dezhou reservoir" will be used as an abbreviation for this specific reservoir.

The Dezhou depression area (Figure 3) is considered to correspond to the Urban Dezhou reservoir, with an area of about 169 km$^2$. The boundaries of the reservoir are permeable faults and tectonic zones, named the Bianlinzhen fault on the east side, the Cangdong fault on the west side, the Xiaoyuzhuang tectonic zone on the south side, and the Xisongmen tectonic zone on the north side. As a low-temperature water-dominated conduction controlled reservoir, the reservoir

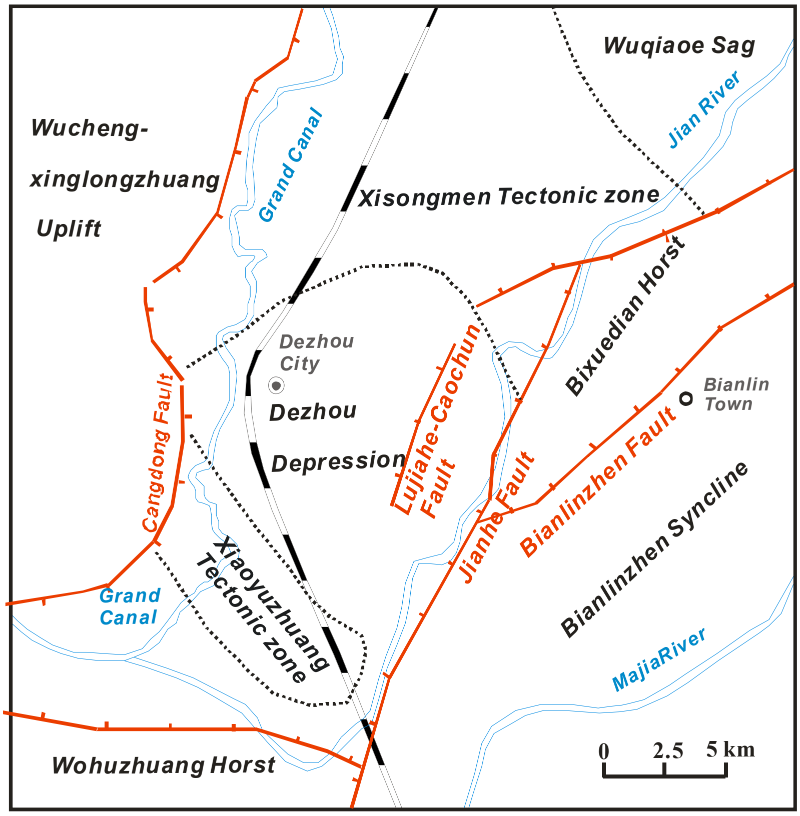


FIGURE 3: Tectonic settings of the Urban Dezhou reservoir (Zhang et al., 2015a)

exists because of the formation of fracture-controlled highly permeable sedimentary layers with an above average geothermal gradient. When it reaches great depth, below 1300 m approximately, the water is heated by thermal conduction. As shown in Figure 4, the depth of the Guantao Formation sandstone of the reservoir ranges from 1350 to 1650 m and thicknesses varies from 300 to 480 m.

The cap rock of the reservoir is upper Minghuazhen formation from the Neogene age, with a thickness of 900 m. It is composed of argillite and sandy argillite with interbedded sandstone. The main production aquifers of the reservoir are comprised of sandstone and conglomerate with high porosity, 24-35%. In the natural state, most of the wells in the Urban Dezhou reservoir are artesian, with an artesian water level height of 7-8 m above the ground surface and a free-flow rate of 8.3-11.1 l/s (Kang, 2000).

Layers below the Guantao formation in the Urban Dezhou reservoir are formations of Eogene age, such as Dongying formation, Shahejie formation and Kongdian formation (Figure 4). The aquifers of these formations are mainly sandstone. Because they are much deeper and the water-abundance is much less than in the Guantao sandstone in Dezhou area, they are not considered reservoirs for development yet. In the future, if the water level of the Guantao Formation aquifer decreases too much, the development of the reservoirs below might be considered. The reservoirs in formations of Eogene age are not considered in this report on the Urban Dezhou reservoir, however.

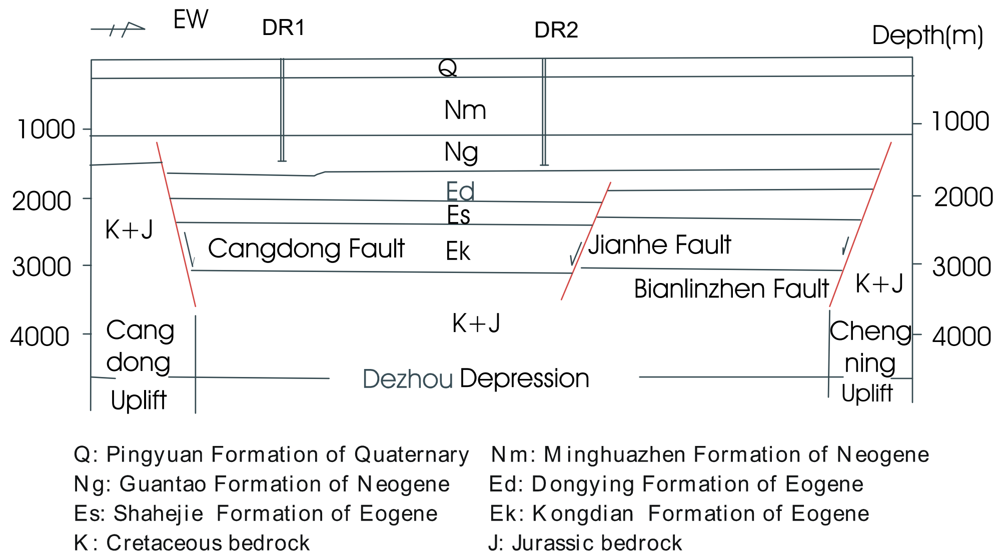


FIGURE 4: Tectonic cross-section of the Dezhou depression (Kang, 2000)

## 2.2 Geothermal reservoir properties

Figure 5 shows the thickness and the contours of the bottom depth of the Guantao formation in the Urban Dezhou reservoir, in which the depth ranges from 1350 to 1650 m and the thickness from 300 to 480 m. The main sandstone production aquifer of the reservoir has a thickness of 150-210 m, about 43-50% of the total reservoir thickness (Figure 6).

Figure 7 shows that the formation temperature increases quickly from 43 to 50°C below 1351 m depth. The main aquifer zone in well R34 is from 1400 to 1500 m depth with a stable temperature of 50°C. The average thermal gradient of the well is 3.05°C/100 m. It should be pointed out that this temperature log was taken during drilling when the well was cooler than later during production when temperature reached 52-55°C.

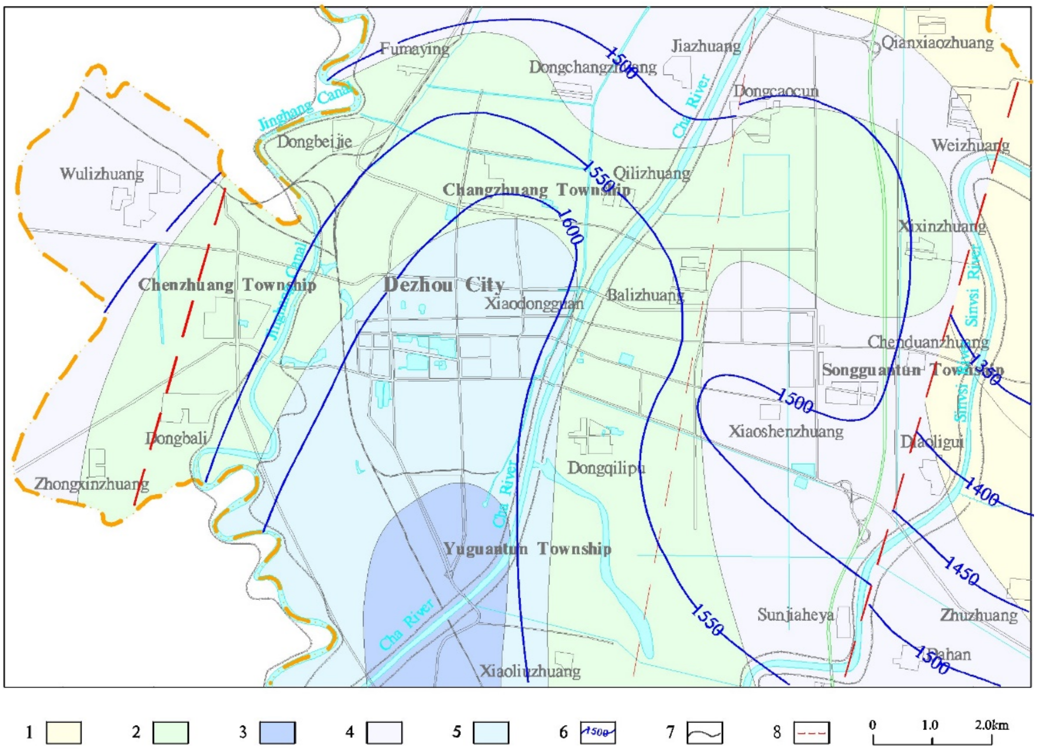


FIGURE 5: Thickness and contours of the bottom of the Guantao formation (Zhang et al., 2011)
(1: Thickness < 350 m, 2: Thickness 350-400 m, 3: Thickness 400-450 m, 4: Thickness 450-500 m, 5: Thickness > 500 m, 6: Bottom depth contour of the Guantao Formation, 7: Boundary of thickness zonation, 8: Main fault)

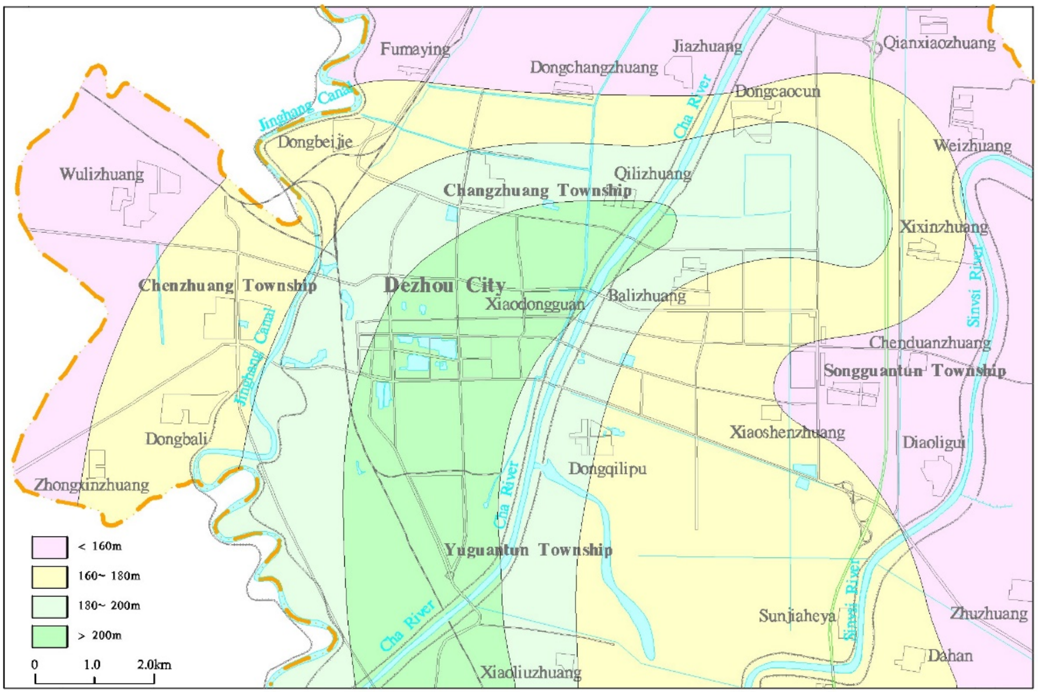


FIGURE 6: The thickness of the sandstone aquifer in the Guantao formation reservoir (Zhang et al., 2011)

In the Urban Dezhou reservoir, thermal gradient ranges from 3.0 to 3.1°C/100 m (Figure 8). The production temperature of the reservoir ranges from 52 to 59°C (Figure 9).

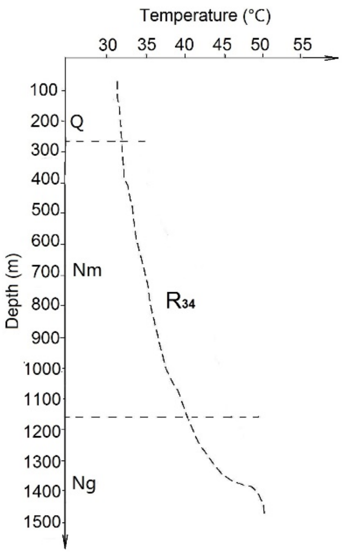


FIGURE 7: Temperature log in well R34 measured during drilling (Zhang et al., 2011)

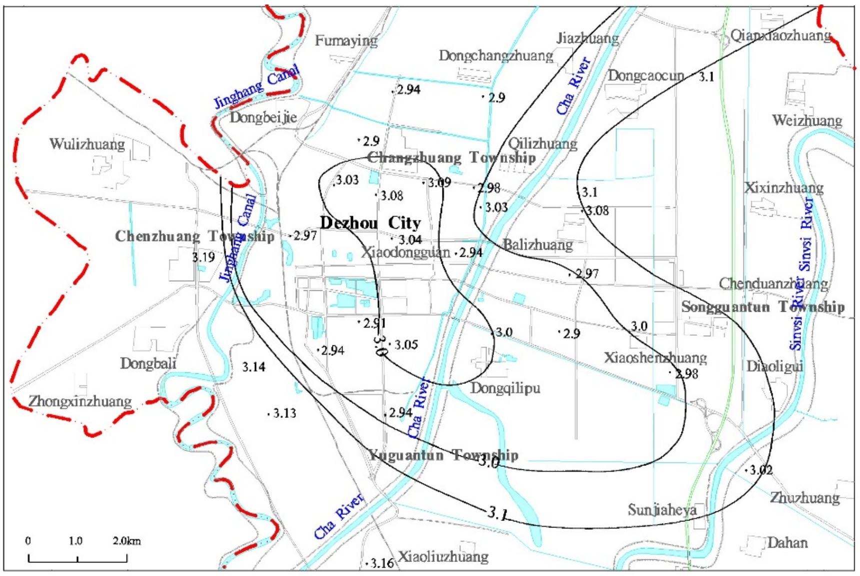


FIGURE 8: The geothermal gradient contour of the Guantao formation reservoir (°C/100 m) (Zhang et al., 2015b)

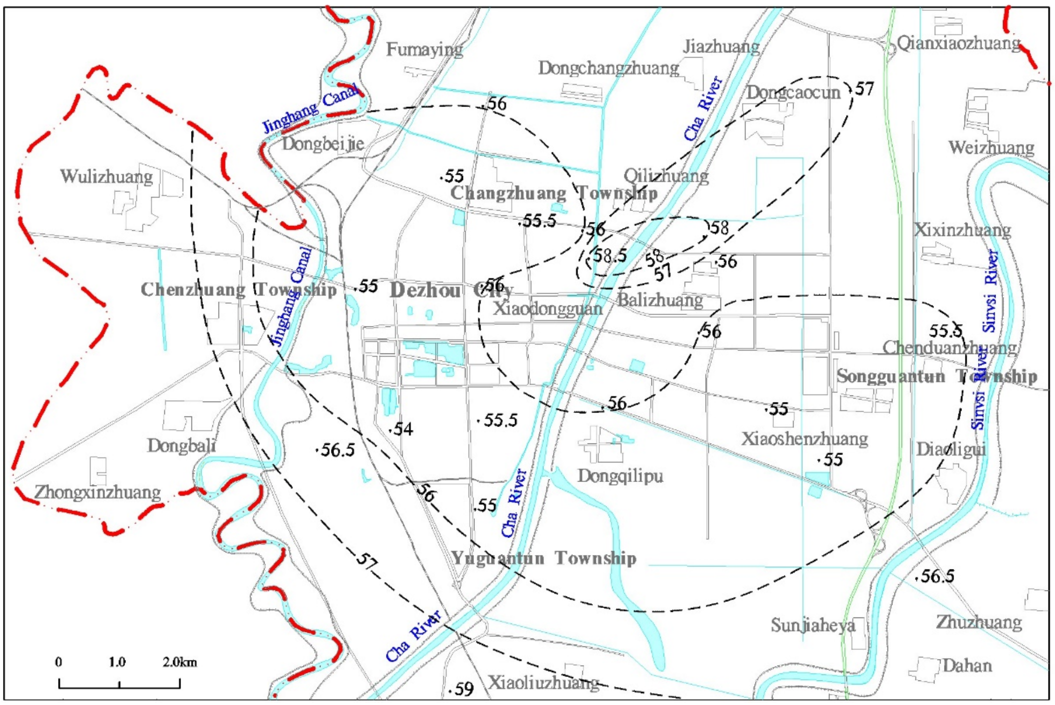


FIGURE 9: Geothermal temperature contours of the Urban Dezhou reservoir (°C) (Zhang et al., 2011)

### 2.3 Exploration and development history of the Urban Dezhou reservoir

The first geothermal well in the area (well R14) was drilled in 1997 and the second in 1998 (Kang, 2000). Nowadays there are 256 geothermal wells in Dezhou city, about 82 of which are located in the Urban Dezhou reservoir (Figure 10). The other wells are in outer parts of Guantao formation sandstone reservoirs in the outer areas of the Dezhou city. The total production rate of the Urban Dezhou reservoir was 18.3 million m$^3$ in 2014, the depth of the wells ranges from 1400 to 2010 m and the production rate changes seasonally; 90% of the production is for the space heating demand from middle November until middle March. The main utilization of the geothermal fluid is for space heating, about 89.5% of the total. Bathing and entertainment use about 9% of the total. The other 1.5% is used in greenhouses. It should be kept in mind that large-scale production of geothermal fluid and geothermal energy used with low efficiency and without reinjection may produce environmental problems.

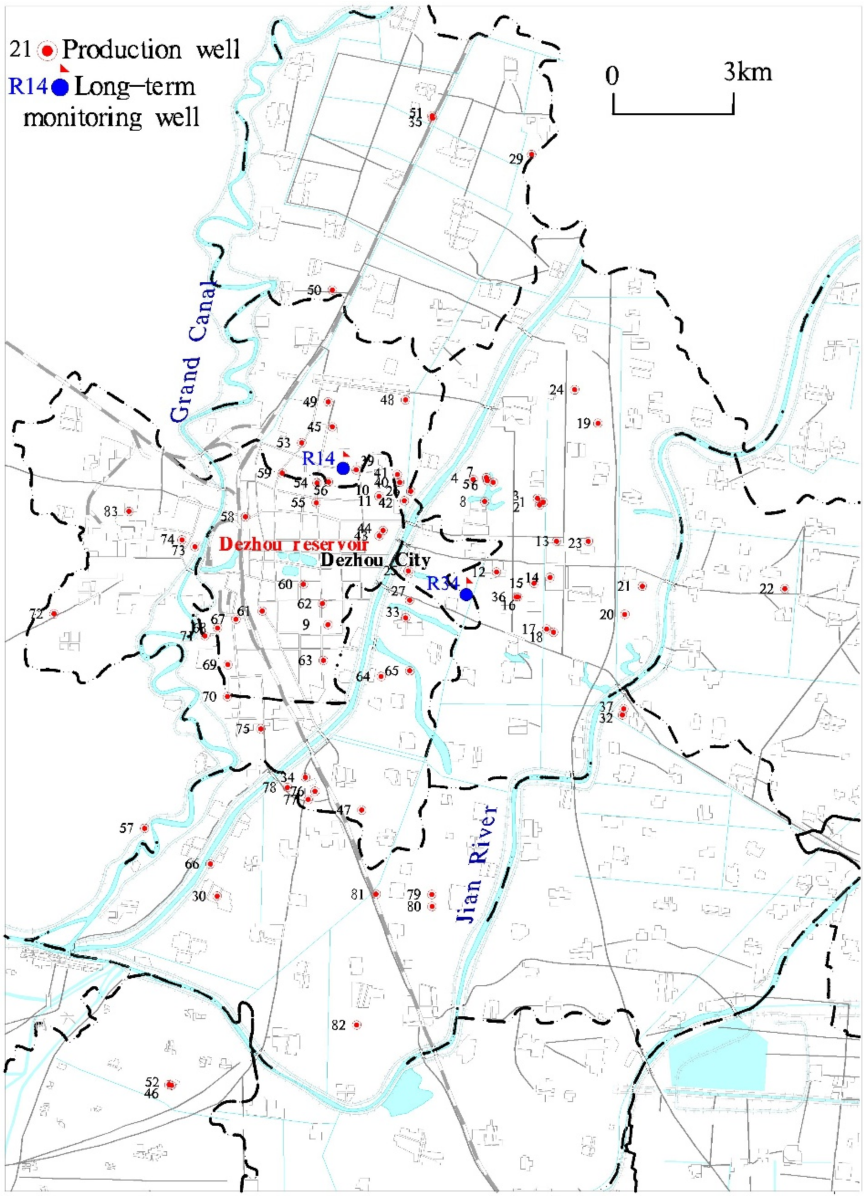


FIGURE 10: Distribution of production and monitoring wells in the Urban Dezhou reservoir (Zhang et al., 2015a)

### 2.3.1 Water level decline

Owing to its very low actual production, 2.9 l/s in 1999 (Kang, 2000), the Urban Dezhou reservoir, overall, was still in its natural state. However, after nearly 10-years of large scale of production, the water level of the whole Guantao sandstone geothermal aquifer has decreased significantly.

Figure 11 shows the initial water level of the complete north-western Shandong Guantao geothermal depression, before large scale production, and water level depth in 2015. It can be seen that the water level drawdown increases significantly after large-scale production started and that several water level depression cones have emerged. The water level depression cone in the Urban Dezhou reservoir can be seen in Figure 12 with the maximum water level depth of 70 m.

Wells R14 and R34 are located in the centre of the depression cone of the water level and are used for long term monitoring (Figures 10, 12 and 13). The water level depth in Dezhou reservoir has been decreasing from 8.3 m artesian height before 1997 to 70 m below ground surface in 2015, which corresponds to an annual decrease of 3.6 m (Figure 12).

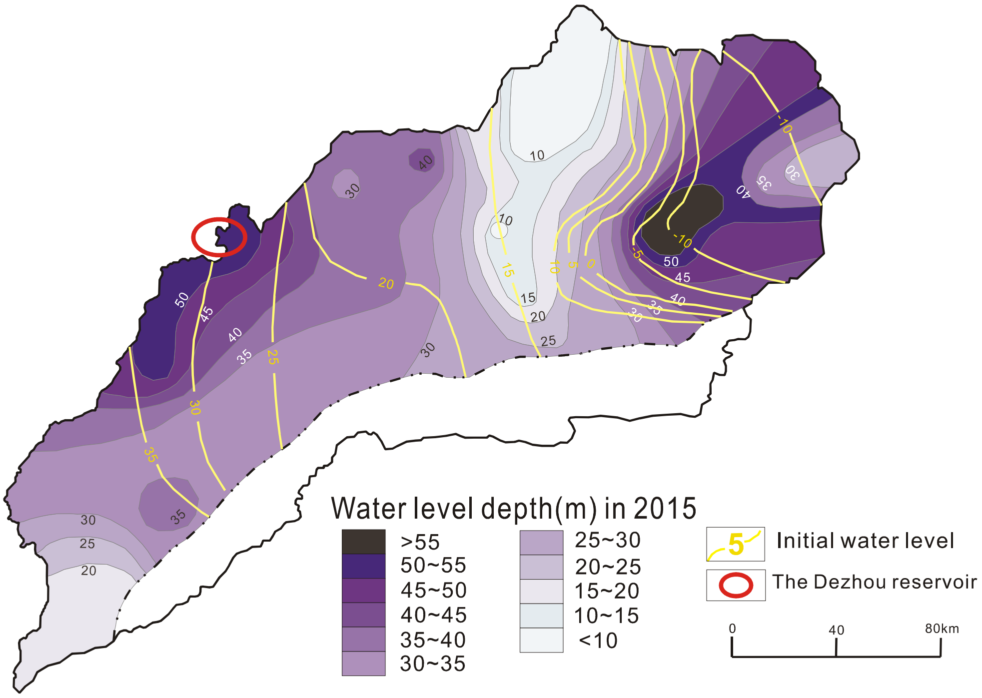


FIGURE 11: Observed water level changes in the north-western Shandong Guantao geothermal depression. Water level depth is measured in 2015 after large-scale production. The initial water level is measured before large-scale production. (Zhang et al., 2015b)

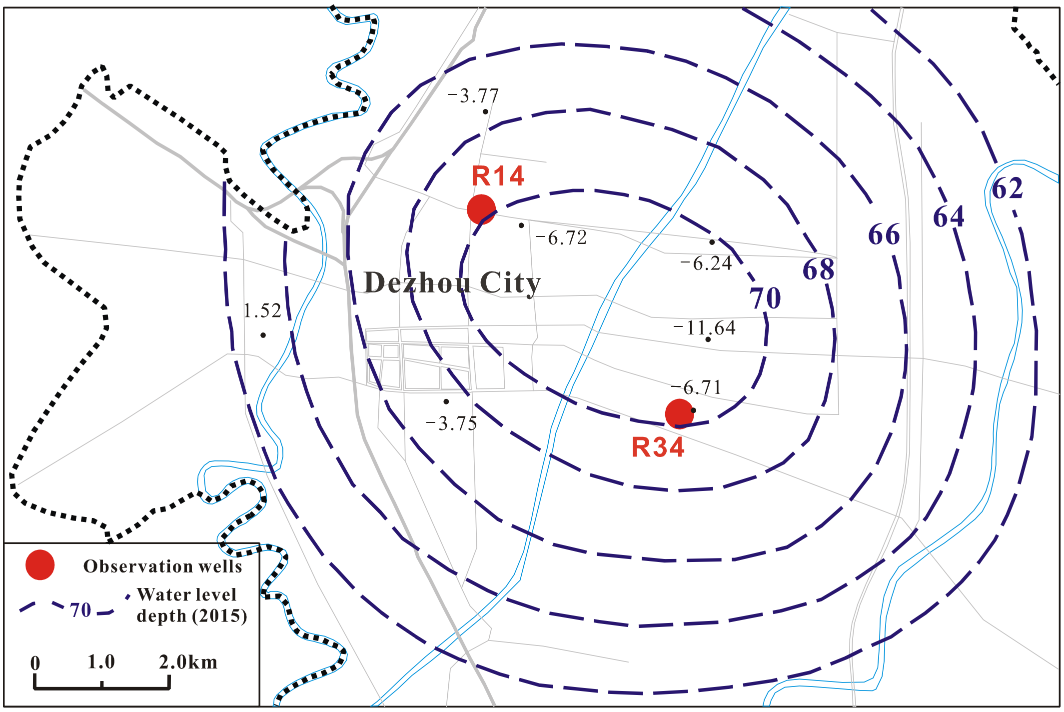


FIGURE 12: The water level depth of the Urban Dezhou reservoir, 2015

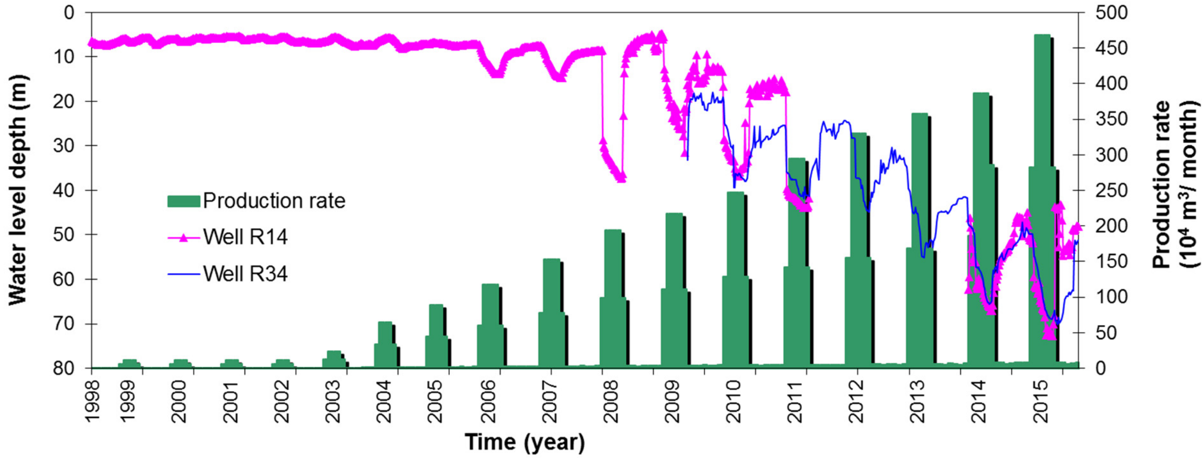


FIGURE 13: Measured long-term variations in water level depth with increasing production rate in wells in the Urban Dezhou reservoir (1998-2015) (Zhang et al., 2015b)

### 2.3.2 Cooling in reservoir

Temperature monitoring in well R14 from 1998 to 2015 (Figure 14) shows that the geothermal water temperature of the Urban Dezhou reservoir didn't changed significantly from 1998 to 2011. The temperature is between 52 and 55°C. From 2014 to 2015, the temperature in the well changed but this was because the well was closed and the water column in the well cooled down. When pumping was reinitiated in the well, the colder water was pumped out and the water temperature rose back to near 55°C, the same before the production break. From this it can be deduced that there appear to be no cooling problems due to large-scale production of geothermal water in the Urban Dezhou reservoir.

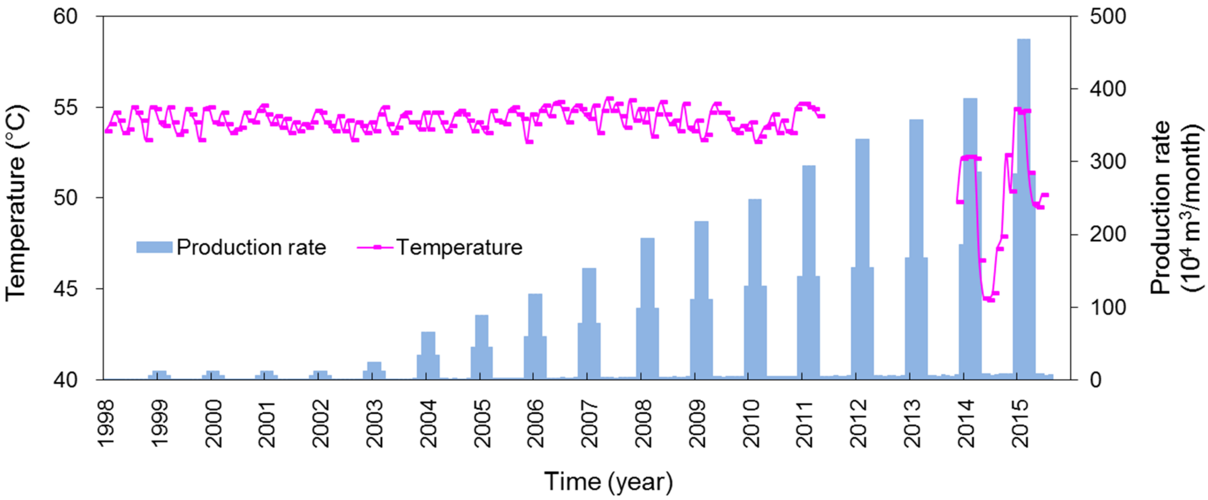


FIGURE 14: Measured long-term variations of water temperature for well R14 with the increase in production rate in the Urban Dezhou reservoir (1998-2015) (Zhang et al., 2015a)

### 2.3.3 Subsidence

Declining water level usually leads to other problems. Ground subsidence is one of the most common problems in the north-west part of the Shandong Province. Unfortunately, there is no data available measuring the subsidence caused by production of geothermal water in Dezhou. However, it is possible to infer some idea from the subsidence caused by cold groundwater production.

There is a colder groundwater aquifer in the Minghuazhen formation, above the geothermal aquifer, at a depth of 190-250 m. It is the main water supply of the city of Dezhou. This aquifer has been producing since 1965. The groundwater level has been declining at a rate of 3 to 4 m per year and has fallen from 2 to 140 m depth in response to extensive production of up to $7.0\times10^4$ $m^3$ per day. The cause of the subsidence is considered compression of high-porosity, low-permeability mudstone at 90-150 m depth (Kang et al., 2015).

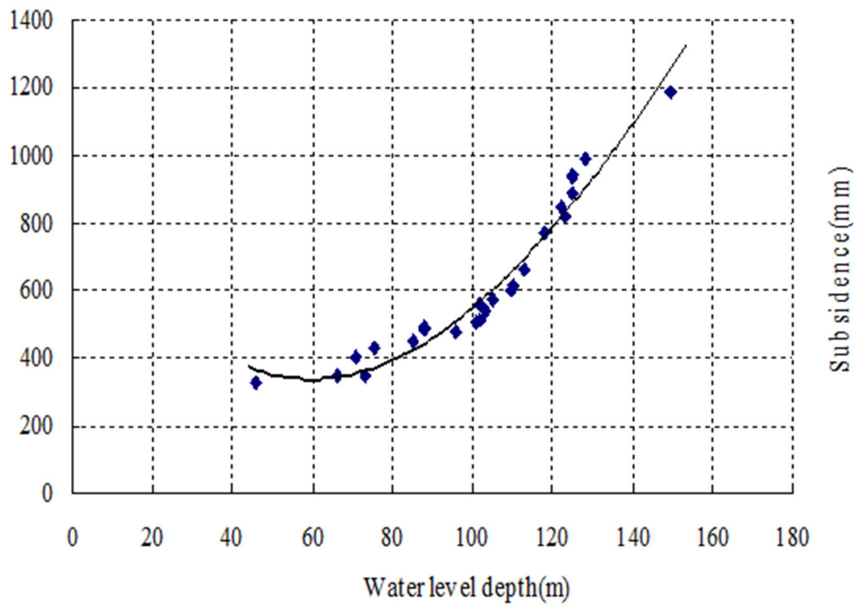


FIGURE 15: Relation between groundwater level depth and subsidence in Urban Dezhou (Kang et al., 2015)

Figure 15 shows the relationship between water level depth in the ground-water system and subsidence in Urban Dezhou. When the water level depth is between 100 and 150 m depth, the rate of subsidence increases to 14 mm for every metre of water level decrease. This is much higher than above the 100 m water level depth. From this conclusion, it is important to consider water level depth as a factor constraining conditions of both colder groundwater and geothermal water productions. To avoid subsidence caused by geothermal water level decline in Dezhou city in the future, it would be best to maintain the water level above 100 m depth. However, considering the demand of the city, the maximum allowable water level depth can be somewhat lower, or above 150 m depth. With this depth limit, further subsidence can be avoided and the demands of the city met. The relationship between water-level decline in the geothermal reservoir and land subsidence needs to be studied further, however.

The above emphasises the fact that reasonable assessment of production potential is a prerequisite for developing the geothermal resource perennially; and comprehensive management countermeasures should be adopted to assure sustainable development of the geothermal reservoir (Kang et al., 2015).

### 2.3.4 Thermal and chemical pollution

After its use for district heating, the waste geothermal water in Dezhou drains into surface water directly without reutilization or reinjection. The wastewater temperatures are around 30-35°C and the environment air temperature of -10-5°C (during heating season). The temperature difference between the geothermal wastewater and the environment may cause ecological unbalance in surface water. The total dissolved solids (TDS) of the Dezhou geothermal water is around 4000-5000 mg/l. The draining of wastewater into surface irrigation water may cause hardening and salinization problems in the soil. The fundamental countermeasure for solving these problems is reinjection, which can not only reduce the wastewater draining but also improve the efficiency of the geothermal exploitation.

## 3. REINJECTION TESTS AND ANALYSIS

Reinjection is the most effective solution to solve the water level decline problem in the Urban Dezhou reservoir. Geothermal reinjection involves returning some, or even all, of the water produced from a geothermal reservoir back into the geothermal system, after energy has been extracted from the water (Axelsson, 2013).

For the purpose of sustainable development of geothermal resources, especially for the Chinese sedimentary aquifers with very little geothermal water recharge, including sandstone aquifers, reinjection is increasingly becoming the means for sustainable and environmentally friendly geothermal utilization. It is efficient for wastewater disposal as well as to provide additional recharge to geothermal aquifers (Kang et al., 2015). Thus, reinjection counteracts pressure (water level) drawdown induced by heavy development and extracts more thermal energy from reservoir rocks (Axelsson, 2008), ideally maintaining the production capacity of the geothermal aquifers. Meanwhile, reinjection can also mitigate land subsidence and be used to maintain geothermal manifestations (artesian wells, natural hot springs) (Kang, 2015).

In China, the earliest geothermal reinjection experiments were successfully implemented in the urban area of Beijing in 1974 and 1975 in a dolomite aquifer. However, during the reinjection, the injectivity decreased quickly (Liu, 2008).

Three reinjection tests have been undertaken in Pingyuan Country, Dezhou City. The Pingyuan County is about 30 km south-east from Urban Dezhou, and is in the same sedimentary basin as the Urban Dezhou reservoir (Figure 16). Thus, the tests can be taken to represent the reinjection properties of the Urban Dezhou reservoir. There is one production well and one reinjection well, with 231 m distance between them. The static water level depth in the reinjection well was 30.7 m, and 31.8 m in the production well. The aquifers of the two wells are in the same sandstone formation, the Neogene Guantao formation at a depth at around 1130 mm (Figure 17).

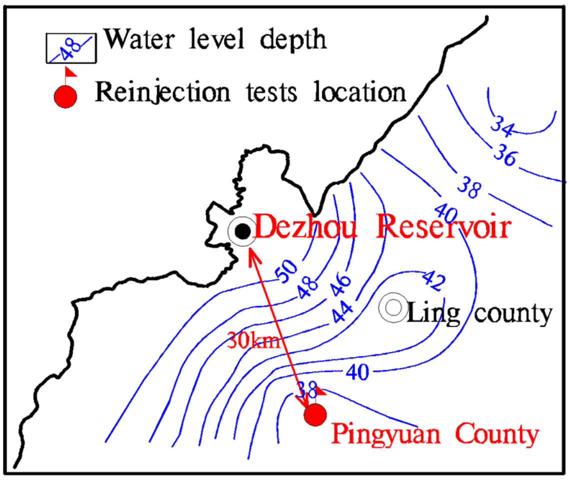


FIGURE 16: Location of reinjection tests in Pingyuan County, Dezhou

### 3.1 Reinjection test 1

The first reinjection test took place from October 13th to December 15th, 2012. The main purpose of this reinjection test was to assess how much water could be injected into the sandstone reservoir in natural condition, without artificial pressure. The geothermal water for reinjection in this test was taken directly from the production well with the same temperature, 50-52°C, without any utilization.

The methodology of this test is presented in Figure 18. After production and reinjection, a depression cone is observed around the production well and the water level inside the well is at a minimum, while there is a water level uplift cone around the reinjection well and water level inside the well is at a maximum. Artificial water level difference is created between the two wells and the reinjection water gets more potential energy to flow between them.

Figure 19 shows that the highest injection rate is about 70 $m^3/h$ along with the maximum water level increase in the reinjection well of 28.7 m. The maximal stable water level increase in the production well is 3.6 m.

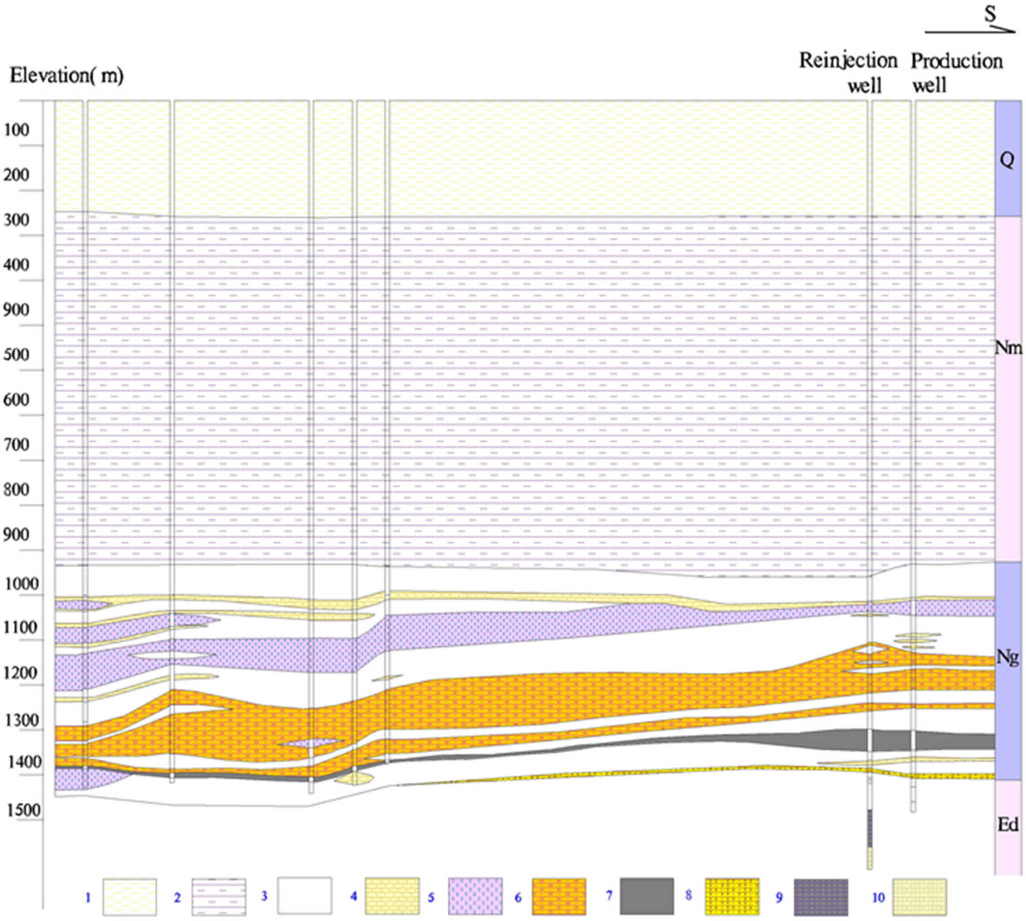


FIGURE 17: A borehole cross-section in the Dezhou geothermal field (Q-Pingyuan formation of Quaternary: 1-clay and sandy clay; Nm-Minghuazhen formation of Neogene: 2-upper section: mudstone, silt and fine sand, low diagenesis, lower section: argillite, silt and fine sand, high diagenesis; Ng-Guantao formation of Neogene: 3-argillite, 4-fine sandstone, 5-medium sandstone, 6-coarse sandstone, 7-intrusive rock, 8-conglomerate; Ed-Dongying formation of Eogene: 9-sandy argillite, 10-argillaceous sandstone) (Kang et al., 2015)

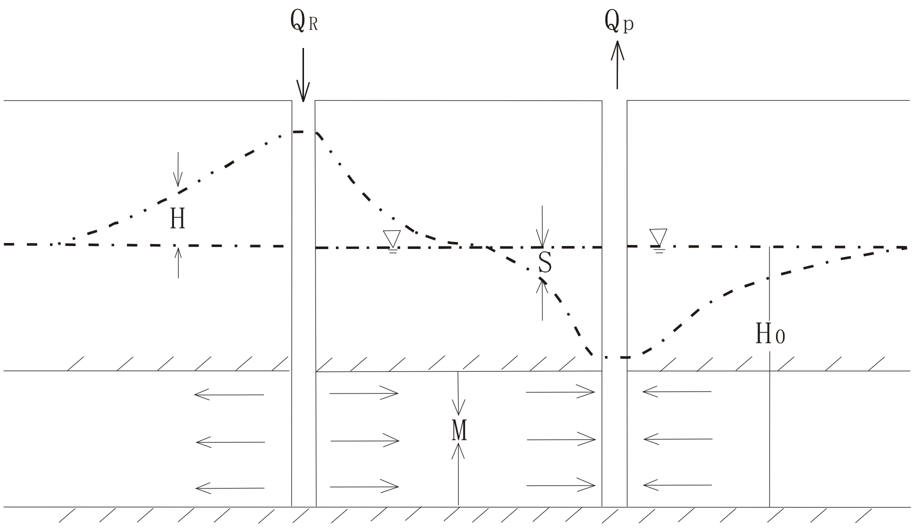


FIGURE 18 Methodology of reinjection under natural condition ($Q_R$- Reinjection rate, $Q_P$- Production rate, H- Water level increase, S- Water level drawdown, $H_0$- Initial water level, M- Aquifer thickness)

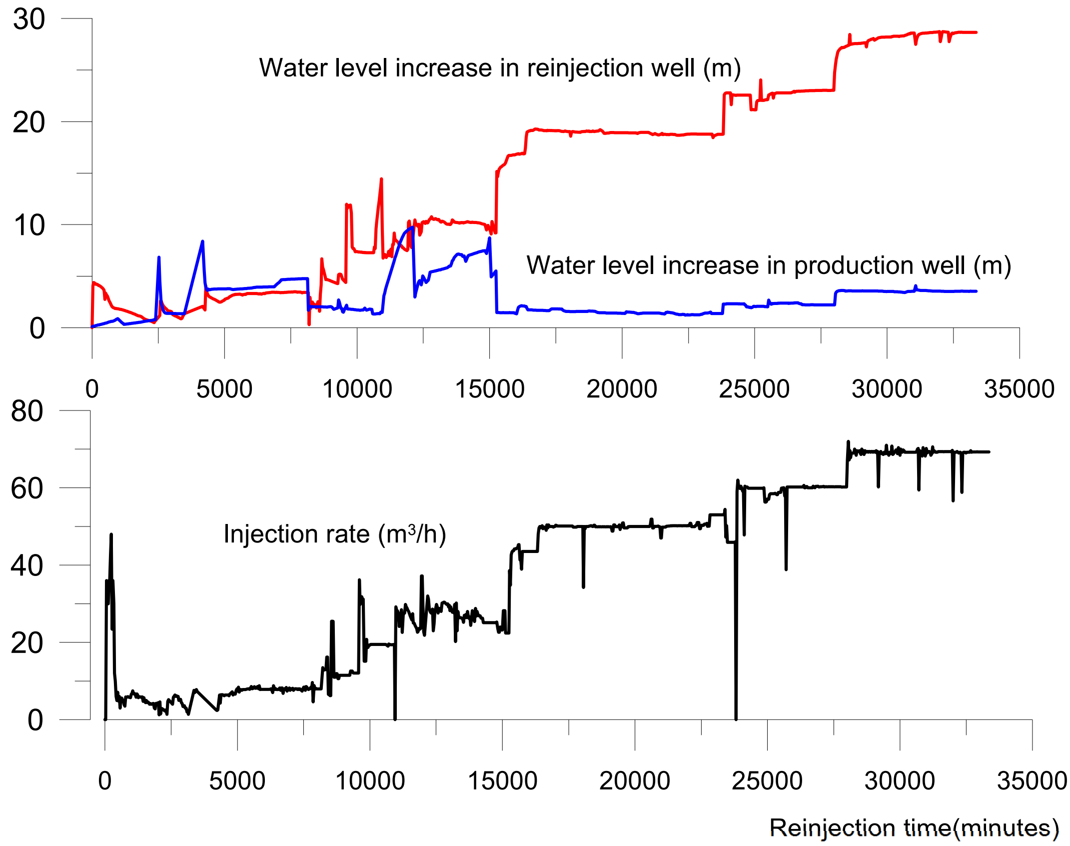


FIGURE 19: The reinjection rate changes and water level increase in production and reinjection wells during the period of October 13th - December 15th, 2012 (Kang et al., 2015)

Figure 20 shows the correlation between the reinjection rate and the water level increase in the reinjection well. It can be seen that the reinjection rate is positively correlated with water level increase. The linear equation of correlation as given in Figure 20 is:

$$y = 0.396x - 0.0856 \quad (R^2 = 0.99) \qquad (1)$$

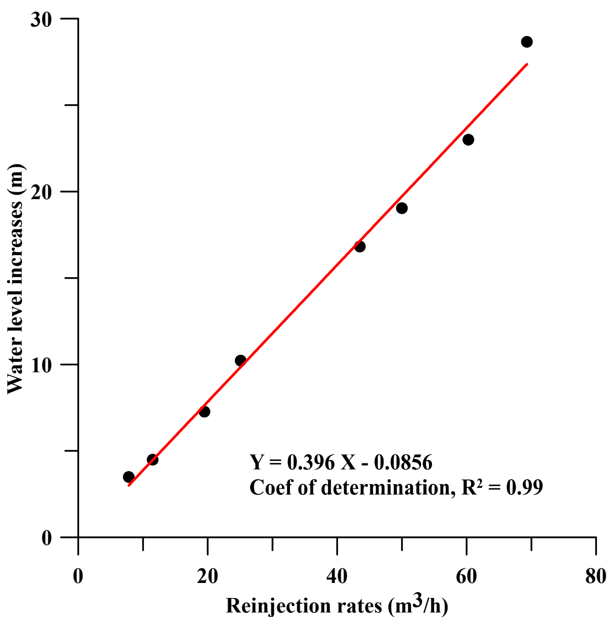


FIGURE 20: The relationship between reinjection rate and water level increase (dots: measured data, line: fitted line)

### 3.2 Reinjection test 2

The second test took place from November 14th, 2013 to March 14th, 2014. The reinjection test was implemented in the same wells also under natural condition, with the main purpose of assessing the temperature response of the reservoir to the test.

Figure 21 shows that the reinjection water, of temperatures about 30-32°C, does not influence temperature in the production well, which remains at 53°C during the whole space heating period of 120 days.

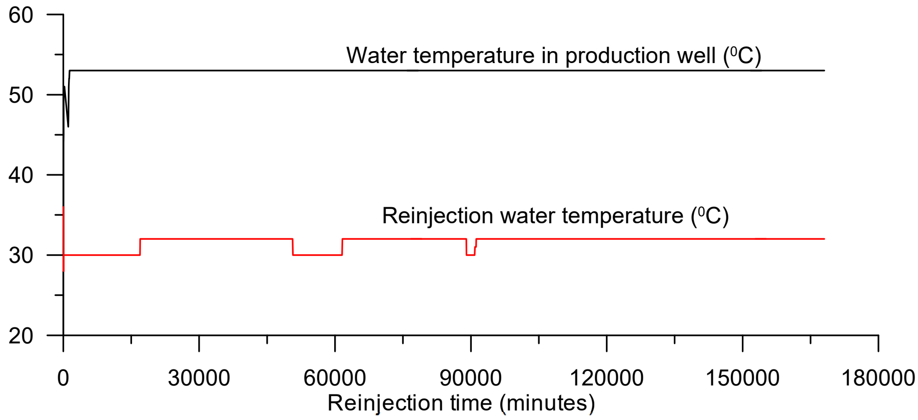


FIGURE 21: Comparison of reinjection water temperature to those in the production well during the period from Nov. 14, 2013 to Mar. 14, 2014 (Kang et al., 2015)

## 3.3 Reinjection test 3 with tracer test

### 3.3.1 Result of the tracer test

Tracer testing is an important tool for reinjection studies because tracer tests actually have a predictive power since tracer transport is orders of magnitude faster than cold-front advancement around reinjection boreholes. A simple and efficient method of tracer test interpretation, assuming specific flow channels connecting reinjection and production boreholes, is used here (Axelsson, 2013). The third reinjection test in the same place also implemented in the same wells. A tracer test was taken with the reinjection test.

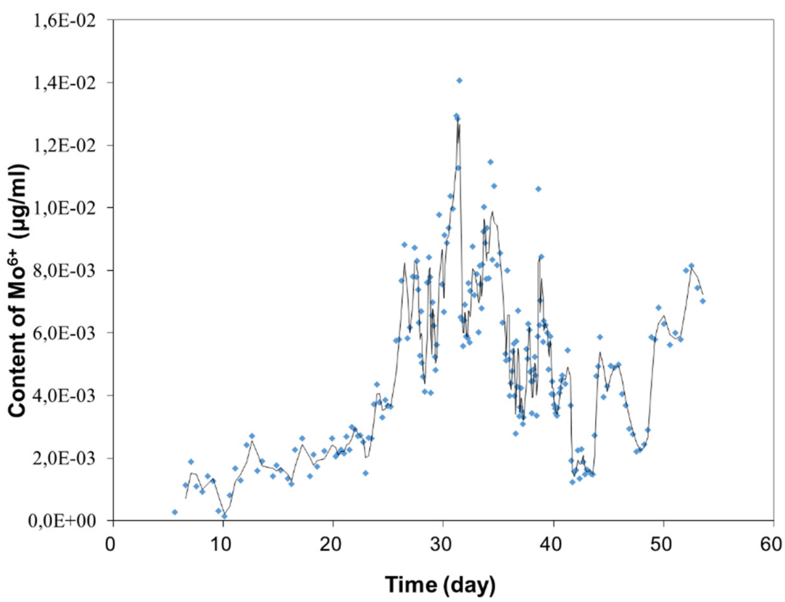


FIGURE 22: Changes of content of $Mo^{6+}$ in the production well, during the test period

The tracer test started on January 20th, 2015 and concluded on March 16th, 2015 along with the third reinjection test. The reinjection also took place under natural conditions with an average production rate of 18.1 kg/s and reinjection rate of 4.5 kg/s. The water temperature in the production well was 53°C and the reinjection temperature was 32.8°C. The tracer chosen was ammonium molybdate, 50 kg of which were injected into the reinjection well. Comparing the content of $Mo^{6+}$ in water samples taken before the tracer test and in the beginning of the test and considering the error in the analysis, the background content of $Mo^{6+}$ is estimated to be 0.014 µg/ml. Figure 22 shows the changes in the content of the $Mo^{6+}$ tracer in the water produced during the test period, after background value correction. The peak of the tracer concentration occurred about 32 days (755 hours) after tracer injection and the tracer recovery lasted 42 days (1000 hours). After this time, the tracer is considered to re-enter the production well through recirculation.

### 3.3.2 Tracer recovery modelling

The main purpose of tracer testing in geothermal studies and management is to predict possible cooling of production wells due to long-term reinjection of colder fluid (Axelsson et al., 2005). In order to quantify this cooling, interpretation of tracer data is needed and numerous models have been developed for that.

The method of tracer test interpretation used here is conveniently based on the assumption of specific flow channels connecting injection and production boreholes. These flow-channels may, in fact, be parts of near-vertical fracture-zones or parts of horizontal interbeds or layers. The channels may be envisioned as being delineated by the boundaries of these structures, on one hand, and flow-field streamlines, on the other hand. In other cases, these channels may be larger volumes involved in the flow between boreholes. In some cases, more than one channel may be assumed to connect an injection and a production borehole, for example connecting different feed-zones in the boreholes involved. In the case of one-dimensional tracer transport, the relevant differential equation simplifies to (Axelsson et al., 2005):

$$D\frac{\partial^2 C}{\partial x^2} = u\frac{\partial C}{\partial x} + \frac{\partial C}{\partial t} \tag{2}$$

where $D$ = Dispersion coefficient of the material in the flow channel (m2/s);
$C$ = Tracer concentration in the channel (kg/m3);
$x$ = Distance along the channel (m);
$u$ = Average transport velocity, $q/\rho A\emptyset$;
$q$ = Injection rate (kg/s);
$\rho$ = Water density (kg/m$^3$);
$A$ = Average cross-sectional area of the flow-cannel (m$^2$);
$\emptyset$ = Flow-channel porosity.

Molecular diffusion is neglected in this simple model such that $D = \alpha_L u$ with $\alpha_L$ the longitudinal dispersivity of the channel (m). Assuming instantaneous injection of a mass $M$ (kg) of tracer at time $t$ = 0, the solution is given by Axelsson et al., (2005) as:

$$c(t) = \frac{uM\rho}{Q}\frac{1}{2\sqrt{\pi D t}}e^{-(x-ut)^2/4Dt} \tag{3}$$

where $c(t)$ = Tracer concentration in the production borehole fluid;
$Q$ = Production rate (kg/s);
$x$ = Distance between the boreholes involved (m).

Conservation of the tracer according to $c \cdot Q = C \cdot q$, has been assumed. Such a simulation yields information on the flow channel cross-section area, actually $A\emptyset$, the dispersivity $\alpha_L$ as well as the mass of tracer recovered through the channel (Axelsson et al., 2005).

This one dimensional flow-channel model for the Urban Dezhou reservoir tracer test can be applied by using the ICEBOX software package form UNU-GTP (Arason et al., 2004), including several programs which can be used for inversion of tracer test data and to predict cooling of production wells during long-term reinjection.

For the Urban Dezhou reservoir, it is assumed that there is one flow channel in the aquifer between the reinjection well and production well. Figure 23 shows the simulation curve of the model and Table 1 below shows the settings and parameters of the model.

Now, the result of one flow-channel obtained by the TRINV tracer programme is used to predict the production temperature during long-term production and injection. The surface area is assumed to have

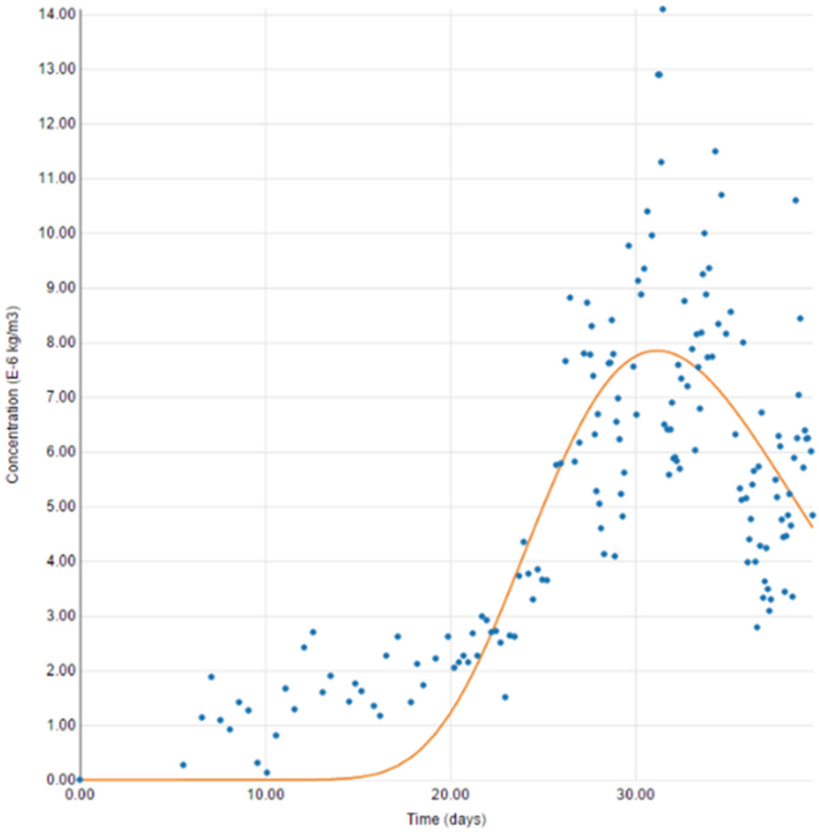


FIGURE 23: Simulation curve of the tracer model

equal width and height and porosity is assumed to be 32%. Because the calculated cross-section (area × porosity) is 0.25 $m^2$, the width and the height can be calculated, both of them are about 0.86 m. The result calculated by the programme shows there is no temperature change in the production well in 50 years, which remains constant at 53°C.

The predicted cooling of the production well is very little due to the low mass fraction recovered (0.46%). This low mass fraction may be caused by the fact that the tracer is added to the water level uplift cone of the reinjection well (Figure 18) and is thus diffused to all directions, with only a limited amount of the tracer received by the production well.

TABLE 1: The settings and parameters of the one dimensional flow-channel model of the connection between the injection well and production well

| Setting | One channel | Parameter | One channel |
|---|---|---|---|
| Tracer mass (kg) | 50.0 | Velocity (m/s) | $8.36\times10^{-5} \pm 9.1\times10^{-7}$ |
| Production rate (kg/s) | 18.1 | Dispersivity (m) | 6.22 ± 0.76 |
| Reinjection rate (kg/s) | 4.5 | Mass (kg) | 0.23 ± 0.01 |
| Reservoir temperature (°C) | 53.0 | Mass fraction (%) | 0.46 |
| Reinjection temperature (°C) | 32.8 | Cross-section ($m^2$) | 0.25 |
| Distance between 2 wells (m) | 231 | | |

### 3.4 Advancement of the reinjection tests

Poor injection performance for sandstone geothermal reservoirs has become an issue for many countries in the world (Liu, 2003; Axelsson, 2008). Known problems of reinjection in sandstone aquifers include the reinjection rates decreasing significantly with time due to problems in the wells or the equipment, such as scaling, clogging and corrosion. Many tests have e.g. been performed in different Guantao formation geothermal fields in China. To improve the reinjection performance in Guantao formation sandstone reservoirs, well completion is a key factor. Nowadays, the traditional option for well completion is perforation, which is adopted in many projects, such as in the Binhai and Wuqing reservoirs in Tianjin (Zhao et al., 2015). But these kind of methods are limited to actual industrial reinjection because they are expensive.

However, the reinjection tests in Pingyuan County provide possible new solution to overcome rapid clogging of aquifers next to reinjection wells in porous sandstone aquifers. The following measures may be adopted: Large diameter reaming and gravel packing to enlarge the flow surface area and increase the permeability around the reinjection well, coarse filtering, fine filtering with 3-5 μm precision, gas escaping, back flushing when the pressure difference between the two sides of filtering equipment reaches 50-60 kPa, re-pumping for the reinjection well at an interval of reinjection for 7 days (Kang et al., 2015).

Three reinjection tests have been successfully implemented during different space heating periods from November to March, about 120 days, in three years. During these periods no obvious aquifer clogging occurred according to observed data. Similarly, the reinjection rates and water level increases in the reinjection well have been stable.

Because this method is not as costly as the perforation one, it has a potential to be used in actual reinjection projects in the future.

## 4. THERMAL BREAKTHROUGH

The thermal breakthrough is the most serious issue in long-term reinjection. Although there is no cooling of the Urban Dezhou reservoir during the reinjection tests, thermal diffusion is much slower than pressure diffusion, so cooling effect may occur in the long term. For this reason, it is necessary to predict the overall long-term thermal breakthrough time for the Urban Dezhou reservoir, in addition to the specific cooling prediction based on the tracer test results.

A porous model with cold recharge can be used for a simple estimate of the reinjection breakthrough time. This model involves an infinite, homogeneous, isotropic, fluid-saturated, hot (at temperature $T_r$), horizontal layer of porous material with porosity $\varnothing$ and thickness $H$. At time $t$= 0, injection of cold (at temperature $T_0$, cold relative to the initially hot layer) water at a rate $Q$ (kg/s) is initiated at the location $r$ = 0 (location of the injection well).

By assuming that heat transport by conduction is negligible compared to the advective heat transport, one can show that a cold front travels radially away from the reinjection well (two-dimensional flow). On the inside of the front, the temperature is $T_0$, while on the outside, the temperature is undisturbed at $T_r$. The distance to the cold front is then given by (Bödvarsson, 1972):

$$r_T = \sqrt{\frac{\beta_w Q t}{\pi H < \rho\beta >}} \tag{4}$$

So, the cold-front breakthrough time is given by:

$$t = \frac{R^2 \pi H < \rho\beta >}{\beta_w Q} \tag{5}$$

where $t$ = Thermal breakthrough time (s);
$R$ = Radial distance from reinjection well (m);
$r_T$ = Radial distance of cold front (m);
$H$ = Reservoir thickness (m);
$<\rho\beta>$ = Average volumetric heat capacity of reservoir, i.e. = $\varnothing \beta_w \rho_w$+(1-$\varnothing$) $\beta_r \rho_r$ (J/m$^3$/°C);
$\beta_w$ = Heat capacity of water (J/kg/°C);
$\rho_w$ = Water density (kg/m$^3$);
$\varnothing$ = Rock porosity;
$\beta_r$ = Heat capacity of rock (J/kg/°C);
$\rho_r$ = Rock density (kg/m$^3$);
$Q$ = Injection rate (kg/s).

The geothermal production wells in the Urban Dezhou reservoir have different production rates. Here the 4 most common injection rates and corresponding production rates (including the maximum rate) are chosen for the calculation. It should be pointed out that these injection rates are based on the space-heating period (120 days). The annual average injection rate for calculation is shown in Table 2.

TABLE 2: Injection rate scenarios for the thermal breakthrough calculations of the Urban Dezhou reservoir

| No. | Space heating time (kg/s) | Annual average (kg/s) |
|---|---|---|
| 1 | 11.0 | 3.6 |
| 2 | 13.7 | 4.5 |
| 3 | 16.4 | 5.4 |
| 4 | 19.2 | 6.3 |

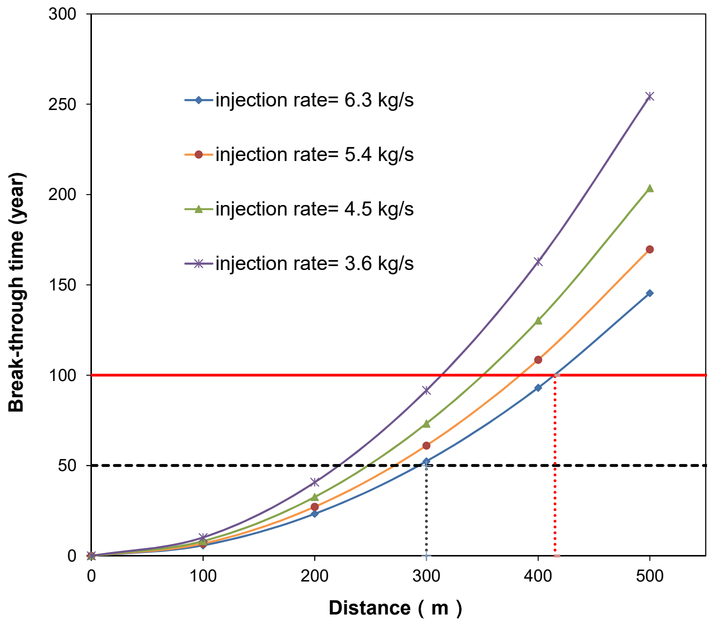


FIGURE 24: Estimated cold front breakthrough time as a function of distance between reinjection well and production well with different reinjection rates in Urban Dezhou reservoir

The breakthrough time is calculated as a function of the distance between reinjection and production wells. Here the annual average injection rates in Table 2 are used.

The results are presented in Figure 24. It should be pointed out that for the safety of the reservoir to avoid colder water intrusion through flow channels in feed-zones, the thickness of the reservoir used in the above equation is 50 m, approximately 33% of the actual thickness of the reservoir considering the porosity. To avoid thermal breakthrough in 50 years, the estimated safe distance between the reinjection well and the production well should be more than 300 m. To avoid thermal breakthrough in 100 years, the estimated safe distance should be more than 420 m.

The result of this model may, however, be too optimistic. Because, it considers the system to be homogeneous and isotropic. In reality, the aquifer may be influenced by fractures, which cause flow velocity variations in different directions.

## 5. VOLUMETRIC ASSESSMENT OF THE URBAN DEZHOU SANDSTONE GEOTHERMAL RESERVOIR

After avoiding cooling in the reservoir an assessment of the energy in reservoir should be made. A simple but useful method is volumetric assessment.

### 5.1 Methodology background

The volumetric method refers to the calculation of thermal energy in the rock and the fluid, which could be extracted, based on specified reservoir volume, reservoir temperature and reference or final temperature.

The volumetric method is patterned from the work applied by the USGS (United States Geological Survey) to the Assessment of Geothermal Resources of the United States (Muffler, 1979). It is often used for first stage assessment, when data are limited. The main drawback of this method is that the dynamic response of a reservoir to production is not considered, such as pressure response, permeability, recharge, etc.

For a liquid-dominated reservoir, the equations used for calculating the thermal energy are as follows:

$$Q_T = Q_r + Q_w \tag{6}$$

in which

$$Q_r = A \cdot h \cdot (1 - \emptyset) \cdot \beta_r \cdot \rho_r \cdot (T - T_0) \tag{7}$$

$$Q_w = A \cdot h \cdot \emptyset \cdot \beta_w \cdot \rho_w \cdot (T - T_0) \tag{8}$$

where $Q_T$ = Total thermal energy (kJ/kg);
$Q_r$ = Heat in rock (kJ/kg);
$Q_w$ = Heat in water (kJ/kg);
$A$ = Area of the reservoir ($m^2$);
$h$ = Average thickness of the reservoir (m);
$\emptyset$ = Rock porosity;
$\beta_r$ = Specific heat of rock at reservoir (kJ/(kg°C));
$\beta_w$ = Specific heat of water (kJ/(kg°C));
$\rho_r$ = Rock density ($kg/m^3$);
$\rho_w$ = Water density ($kg/m^3$);
$T$ = Average temperature of the reservoir (°C);
$T_0$ = Cut-off temperature (°C).

Not all the energy can be extracted from the reservoir, so the recovery factor is defined to help estimate the energy that can be extracted. The thermal energy recoverable from the system can be calculated as follows:

$$Q_R = R \cdot Q_T \tag{9}$$

where $Q_R$ = Recoverable thermal energy (kJ/kg);
$R$ = Recovery factor.

The recovery factor represents how easily the heat contained in the reservoir can be extracted which mostly depends on the reservoir permeability. Muffler proposed a linear connection between the porosity and the recovery (Muffler, 1979) and Williams (2007) introduced models for fractured reservoir and proposed recovery in the range of 2-25%.

### 5.2 Monte Carlo volumetric assessment calculation

The parameters used in the Monte Carlo volumetric assessment calculation for the Urban Dezhou reservoir are presented in Table 3.

*Area ($km^2$):* The distribution of sedimentary reservoir aquifer is continuous. It is considered that the area is the same as the surface area of 169 $km^2$.

*Thickness (m):* The thickness of the sandstone aquifer in Guantao formation ranges from 100 to 300 m. For Monte Carlo calculations, use the most likely: 200 m; minimum: 100 m; maximum: 300 m.

*Rock density (kg/m³):* The main type of rock is sandstone, which has a density of around 2800 kg/m³. Therefore, the most likely estimate is 2800 kg/m³; minimum: 2700 kg/m³; maximum: 2900 kg/m³.

*Porosity (%):* The average porosity of the sandstone aquifer is around 32%. In the Monte Carlo input cell, use the most likely: 32%; minimum: 24%; maximum: 35%.

*Rock specific heat (J/(kg°C)):* Usually this is about 950 J/(kg°C). For the Monte Carlo calculations use the most likely: 950 J/(kg°C); minimum: 910 J/(kg°C); maximum: 980 J/(kg°C).

*Reservoir temperature (°C):* The formation temperature of the conduction reservoir is not easy to obtain. The geothermal water temperature in wells is around 53°C. For the Monte Carlo calculations, it is assumed that the most likely value is 60°C; minimum: 53°C; maximum: 70°C.

*Fluid density (kg/m³):* Water density is 983.2 (most likely), 977.8 (minimum) and 988.1 kg/m³(maximum) at 60, 70 and 50°C, respectively.

*Fluid specific heat (J/(kg°C)):* It is about 4200 J/(kg°C) for pure water.

*Recovery factor (%):* The porosity of sandstone in Dezhou reservoir ranges from 24 to 35% with the average of 32%. Muffler (1979) proposed a linear correlation between porosity and recovery factor. However, it seems too optimistic for this reservoir. For a conservative estimate and referring to other sedimentary reservoirs in China (Huang, 2012), the estimated most likely recovery factor of Dezhou reservoir is 23%. For Monte Carlo calculations use the most likely: 23%, minimum: 20%, maximum: 25%.

*Cut-off temperature (°C):* One of the main reasons for cooling of reservoir is reinjection. Here the average reinjection temperature of 32.8°C is taken as the cut-off temperature.

TABLE 3: Parameters used for Monte Carlo volumetric assessment of the Urban Dezhou reservoir

| Input Variables | Units | Minimum | Most likely | Maximum |
|---|---|---|---|---|
| Surface area | km² | - | 169 | - |
| Thickness | M | 100 | 200 | 300 |
| Rock density | kg/m³ | 2700 | 2800 | 2900 |
| Porosity | % | 24% | 32% | 35% |
| Rock specific heat | J/(kg°C) | 910 | 950 | 980 |
| Temperature | °C | 52 | 55 | 59 |
| Fluid density | kg/m³ | 977.8 | 983.2 | 988.1 |
| Fluid specific heat | J/(kg°C) | - | 4200 | - |
| Recovery factor | % | 20% | 23% | 25% |
| Cut-off temperature | °C | - | 32.8 | - |

The most likely estimate of the total energy of the reservoir is 2340 PJ ($10^{15}$ J), and the most likely estimate for recoverable energy is 540 PJ.

To estimate for how long the energy of reservoir can be used, the following equation is used：

$$Q_0 = q \cdot \beta_w \cdot (T - T_0) \tag{10}$$

where $Q_0$ = Thermal heat taken by production annually (kJ/s or kWth);
$q$ = Production rate of geothermal wells annually (kg/s);
$\beta_w$ = Specific heat of water (kJ/(kg°C));
$T$ = Average temperature of the reservoir (°C);
$T_0$ = Cut-off temperature (°C).

The current annual production rate of Dezhou reservoir is about 600 kg/s (q). The thermal heat of one year taken by production ($Q_0$) is $5.6\times10^4$ kWth. Based on the calculation, it will take about 300 years to extract all the recoverable energy (540 PJ) from the reservoir.

The thermal energy is usually plotted using the relative frequency distribution and the cumulative frequency distribution. The relative frequency of a value or a group of numbers is calculated as a percentage of the total number of data points.

For the 300-year lifetime of the reservoir, the relative frequency distribution and the cumulative frequency of the thermal power calculated by the Monte Carlo model are presented in Figure 25. The mean thermal power, the median thermal power, the standard deviation, 90% upper limit, and 90% lower limit could also be extracted from the results, shown in Table 4.

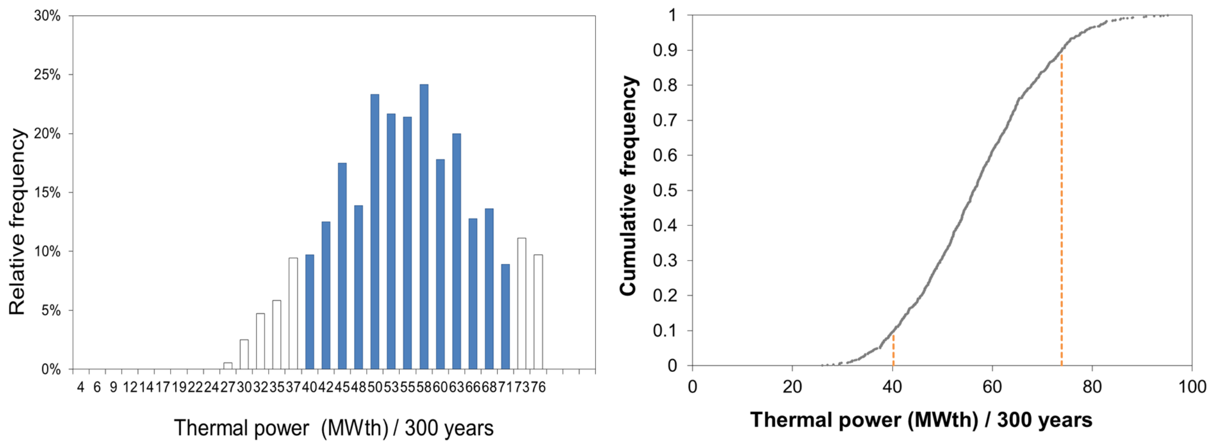


FIGURE 25: The relative and cumulative frequency distributions of thermal power for a 300-year utilization; the darker columns on the left indicate the 90% probability range while the dotted lines on the right indicate the 90% upper and lower limit of the cumulative distribution

TABLE 4: The results of the thermal power estimation for the Urban Dezhou reservoir by the Monte Carlo volumetric assessment

| **Results** | **Thermal power / 300 years** |
|---|---|
| Most likely thermal power ($MW_{th}$) | 57 |
| 90% above ($MW_{th}$) | 41 |
| 90% below ($MW_{th}$) | 72 |

The result shows that the most likely thermal power for the direct use is 57 $MW_{th}$ for a reservoir lifetime of 300 years. From the 90% acceptance range, the results of the simulations are that the estimated thermal power will range between 41 and 72 MWth, for 300 years. That means the resource capacity will be at least 41 MWth for 300 years. However, as mentioned before, the volumetric assessment can only build a static model. It cannot give a dynamic view. Also, it is not environmentally friendly to extract the total recoverable energy from the Urban Dezhou reservoir without sustainable development.

## 6. SUSTAINABLE YIELD OF THE URBAN DEZHOU SANDSTONE GEOTHERMAL RESERVOIR

### 6.1 Reservoir modelling

The main objective when modelling a geothermal system is to simulate the response of the reservoir to long-term and large-scale production. The reservoir model can be used to assess the production potential by predicting the water level response to different production scenarios.

#### 6.1.1 Conceptual model

The conceptual model is the foundation of the reservoir model. The conceptual model of the Urban Dezhou reservoir can be described briefly as follows:

1) *Reservoir type:* Low-temperature sedimentary reservoir, water-dominated, heated by conduction of the thermal flow (with the average thermal gradient of 3.05°C/100m) (see Figures 7-9);
2) *Boundary and area:* Permeable fault boundaries, 169 $km^2$ (see Figure 3);
3) *Production aquifer:* Horizontal, homogeneous, and confined sandstone, with a thickness from 150 to 210 m at a depth between 1350 and 1650 m (Figures 4-7);
4) *Cap rock:* Upper Minghuazhen formation of Neogene period, composed of argillite and sandy mudstone (Figures 4 and 17);
5) *Underlying rock:* Eogene Dongying Formation composed of argillite, fine sandstone, and siltstone (Figures 4 and 17);
6) *Recharge*: Meteoric origin.

### 6.1.2 Lumped parameter modelling

The Urban Dezhou reservoir has a large area and about 82 production wells. The changes in water level and temperature of these wells show similar trends (Figure 13). Compared to numerical models, which requires large amounts of field data, lumped parameter modelling has the advantage of needing only production history and water level data. In addition, it is simpler and thus can give an estimate of the nature of the geothermal reservoir in a relatively short time. Thus in conclusion, lumped parameter model is a good choice for modelling the Urban Dezhou reservoir.

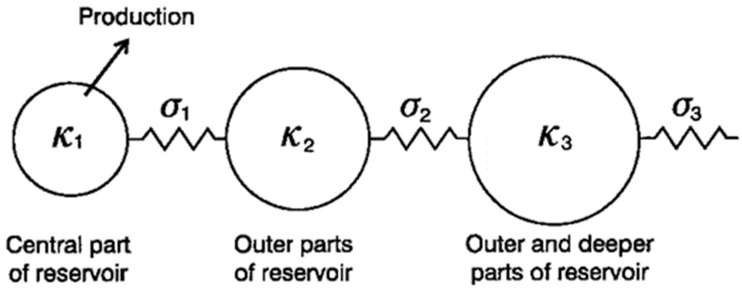


FIGURE 26: Schematic diagram of lumped parameter model (Axelsson et al., 2005)

Lumped parameter models can simply be considered as distributed parameter models with a very coarse spatial discretization (Axelsson, 1989). A general lumped model consists of a few tanks and flow resistors as is shown in Figure 26. The resistors, controlled by permeability of rocks, simulate the flow resistance in a reservoir. The first tank simulates the innermost part of a geothermal reservoir, i.e. it represents the active well field; while the second and third tanks simulate outer and deeper parts of a system, i.e., they act as recharge parts from either deeper or outside parts of the main reservoir. If the third tank is connected by a resistor to a constant pressure source, which supplies recharge to a geothermal system, the model is open. Otherwise, without the connection to a constant pressure source the model would be closed (Axelsson, 1985).

The water level or pressure in the tanks simulates the water level or pressure in different parts of a geothermal system. The pressure response ($p$) of a general open lumped model with $N$ tanks, to a constant production ($Q$) since time $t$=0, is given by the equation (Axelsson, 1985):

$$p(t) = p_0 - \sum_{j=1}^{N} Q \frac{A_j}{L_j} [1 - e^{-L_j t}] \tag{11}$$

The pressure response of an equivalent $N$ tank closed model is given by the equation:

$$p(t) = p_0 - \sum_{j=1}^{N} Q \frac{A_j}{L_j} [1 - e^{-L_j t}] - QBt \tag{12}$$

The coefficients $A_j$, $L_j$ and $B$ are functions of the storage coefficients of the tanks ($\kappa_j$) and the conductance coefficients of resistors ($\sigma_j$) in the model.

The main problem when performing lumped parameter modelling is the estimation of the tank and conductor parameters. To tackle the simulation as an automatic inverse problem, a powerful and effective computer code LUMPFIT has been developed (Axelsson, 1985). Here the LUMPFIT programme is used to model the Urban Dezhou reservoir.

As mentioned previously, there are no obvious temperature changes in the reservoir and the main response of the reservoir for production is water level decreases. In order to predict future water level changes and to be able to suggest solutions to problems such as land subsidence caused by it, long term monitoring data is used as a basis for reservoir modelling using lumped parameter modelling. Two different models are compared: a two-tank closed and a two-tank open lumped parameter model.

The long term monitoring data used for the modelling is water level depth in wells R14 and R34 and the corresponding total production data of the reservoir (both shown in Figure 13) from 1998 to 2015. Figure 27 shows the simulated water level depth, the measured water level depth and the production. Both models present good agreements with the same coefficient of determination of 0.95.

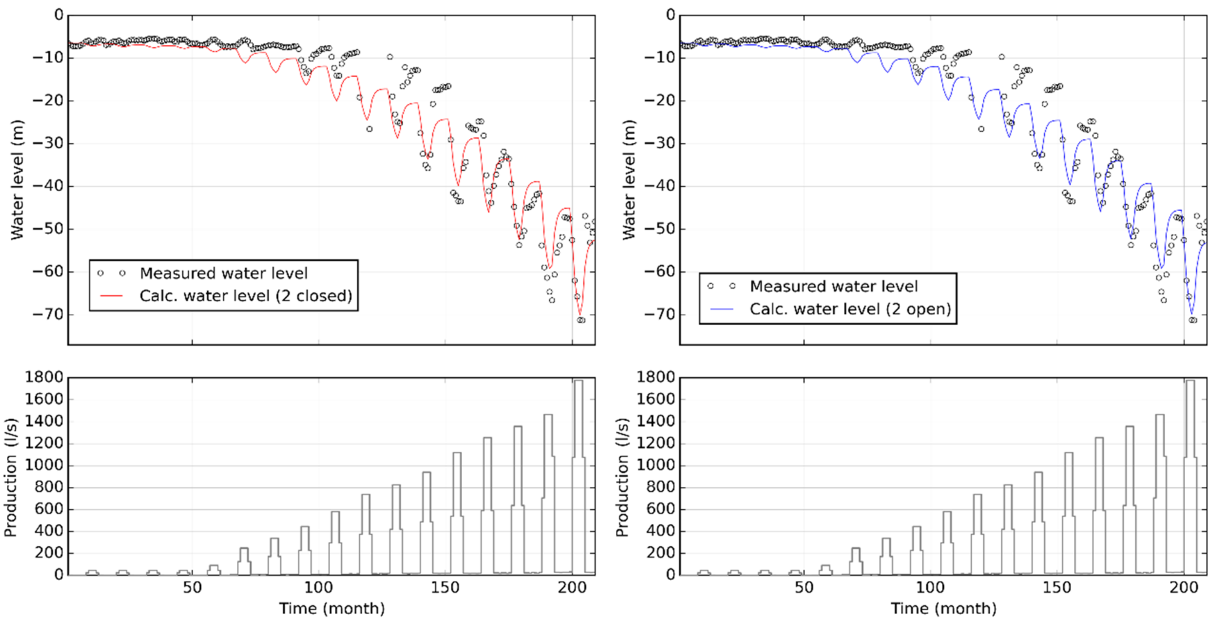


FIGURE 27: The results of the two-tank closed and open lumped parameter model of the Urban Dezhou reservoir

The reservoir properties calculated by the two models are presented in Table 5. The $\sigma_2$ represents the conductance of the second tank to the recharge from the boundary. It has very small number, which shows that the flow between the second tank and the open boundary is very limited. The monitoring data in Figure 13 shows that when production is halted, the water level rises and remains stable without recovering to the initial water level, which indicates that the recharge source is limited. These results indicate that the Urban Dezhou reservoir data fits better using a closed two-tank model than an open one. The closed two-tank model can thus be used to predict pressure changes in the reservoir for given production scenarios.

Before extensive exploitation of the Urban Dezhou reservoir, around the year 2000 the same method was used to model the reservoir. The result was different from the results presented here since a closed three-tank model fitted the data best. The data used for the modelling was from a pumping test during the period from Mar. 28 to Apr. 4, 1997 (Kang, 2000). Table 6 compares the parameters of the older model to the model presented here. The two-tank closed model shows larger storage ($\kappa$) and higher

TABLE 5: Parameters of the two types of lumped model of Dezhou

| Parameter | Two-tanks closed | Two-tanks open |
|---|---|---|
| $A_1(10^{-3})$ | 9.4 | 9.2 |
| $L_1(10^{-1})$ | 8.1 | 8.3 |
| $A_2(10^{-4})$ | - | 9.7 |
| $L_2(10^{-9})$ | - | 2.3 |
| $B$ | $9.6\times10^{-4}$ | - |
| $\kappa_1$ (ms$^2$) | 25700 | 26200 |
| $\kappa_2$ (ms$^2$) | 252000 | 247000 |
| $\sigma_1$ ($10^{-5}$ ms) | 720 | 750 |
| $\sigma_2$ ($10^{-10}$ ms) | - | 2.4 |
| Coefficient of determination: 0.95<br>κ: Capacitance (storage)<br>σ: Conductivity | | |

permeability (σ) between the inner part and the outer part of reservoir based on long term monitoring data. The older model is based on data from the only production well at the time, R14. The model can thus be estimated to represent the properties of the reservoir in a near natural state. The two-tanks model presented in this report is based on long-term monitoring data, which better represents the large-scale production situation and can be used to predict the development of the reservoir under exploitation. It can be deduced that as the development of the reservoir increases, more storage is consumed by the reservoir and a larger area is influenced, which is a typical property of closed sedimentary reservoirs.

TABLE 6: Parameters of the lumped model of the Urban Dezhou reservoir during different periods

| Parameter | Model 1 (two-tank closed) | Model 2 (Kang, 2000) |
|---|---|---|
| $\kappa_1$ (ms$^2$) | 25700 | 0.023 |
| $\kappa_2$ (ms$^2$) | 252000 | 4.4 |
| $\kappa_3$ (ms$^2$) | - | 9520 |
| $\sigma_1$ ($10^{-4}$ms) | 72 | 6.2 |
| $\sigma_2$ ($10^{-4}$ms) | - | 54.4 |
| κ: Capacitance (storage)<br>σ: Conductivity | | |

### 6.2 Sustainable yield estimated by lumped parameter model

The prerequisite of calculating sustainable yield is to determine a reasonable maximum allowable drawdown of the production wells in the geothermal reservoir, within a given time frame (Kang, 2010). The constraints in the Urban Dezhou reservoir include the risk of cold-water inflow, the setting depths of production well pumps and especially the land subsidence caused by the water level decrease. Thus, the maximum allowable water level depth is defined as 150 m.

Using the maximum allowable drawdown and the lumped parameter model, water level predictions were calculated for 50 years for two different production scenarios.

#### 6.2.1 Sustainable yield without reinjection

The water level predictions calculated by the lumped parameter model, are presented in Figure 28, which shows the water level depth changes for the next 50 years.

For the current production situation (Table 7) the water level depth will be below the 150 m limit in 10 years' time. The sustainable yield without reinjection is 25% of the current production rate (Table 7). That means the production of the reservoir cannot meet the demands of the city.

TABLE 7: Comparison of current and sustainable production rate without reinjection

| Period | Current production rate (l/s) | Sustainable production rate (l/s) |
|---|---|---|
| Dec.-Feb. | 1770 | 440 |
| Mar. | 1070 | 260 |
| Apr.-Oct. | 30 | 7.5 |
| Nov. | 1070 | 260 |
| Space heating period | 1490 | 370 |
| The whole year | 630 | 150 |

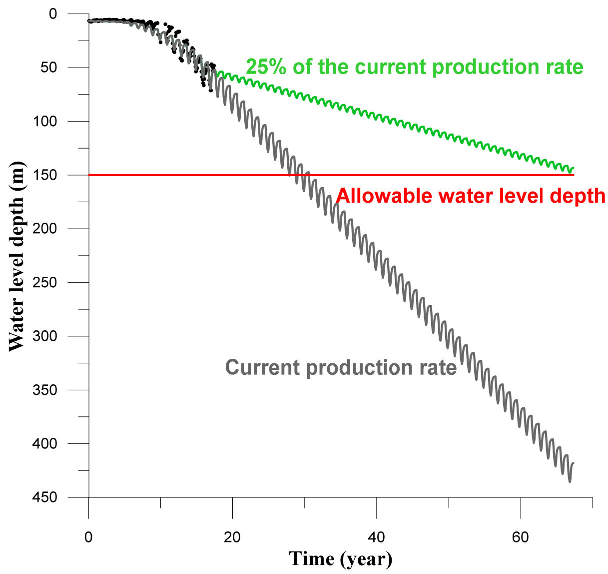


FIGURE 28: The water level depth predictions without reinjection, calculated with the lumped parameter model

### 6.2.2 Sustainable yield with reinjection

As discussed before, reinjection is an effective method for sustainable development of geothermal resources and according to the results of the reinjection tests with a 100% injection rate mentioned above, reinjection in the Urban Dezhou reservoir is feasible.

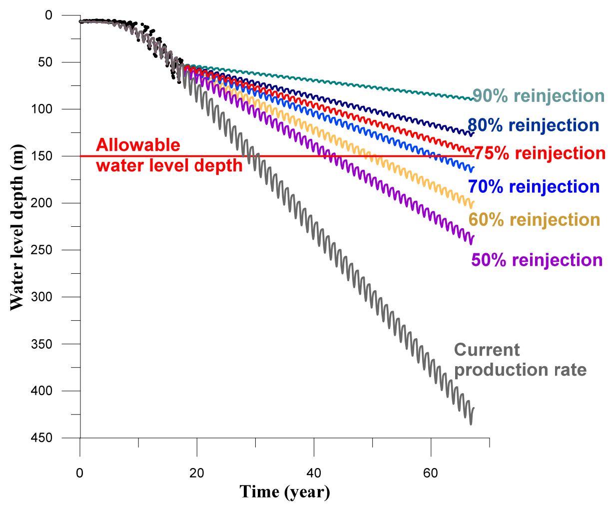


FIGURE 29: The water level depth predictions with reinjection, calculated with the lumped parameter model

Figure 29 shows the predictions of water level depth changes for different reinjection rate scenarios. It shows that in order to maintain the current production rate, the reinjection rate should be more than 75% of the production rate. The maximum reinjection rate is assumed to be 80% of the production rate. That is due to having to consider the loss of the recycling water from space heating. In this situation, the sustainable yield can be up to 780 L/s annually and the average sustainable yield during the space heating period is 1860 L/s, which is about 1.25 times the current production rate. This means that the sustainable yield with reinjection cannot only meet the demands of the city but also has potential for further development of the reservoir.

It should be pointed out that the lumped parameter model can only predict water level changes in the reservoir. Further study of temperature and chemistry changes in the Urban Dezhou reservoir should be considered.

## 7. CONCLUSIONS

The main conclusions of the assessment of the Urban Dezhou reservoir are as follows:

1) The Urban Dezhou reservoir is a low-temperature sedimentary conduction controlled reservoir. The area of the reservoir is about 169 $km^2$ and the reservoir thickness ranges from 300 to 480 m at a depth between 1350 and 1650 m. Due to limited recharge and large amount of production, water level of Dezhou reservoir has been decreasing very quickly, from 8.3 m artesian height in 1998 to 70 m below ground surface in 2015, with an annual decrease of 3.6 m. However, the geothermal water temperature is generally stable around 52-55°C.

2) Three reinjection tests were undertaken in Pingyuan County from 2012 to 2015 without any clogging problems. The biggest reinjection rate without artificial pressure was about 70 $m^3$/h and 100% of the production water could be reinjected. From the reinjection test it can be concluded that reinjection does not lead to cooling in the reservoir during the space-heating period of 120 days. A tracer test model was built to predict the geothermal temperature changes, which shows the temperature remaining stable at 53°C for 50 years.

3) To give an idea of the minimum distance between reinjection wells and production wells, the thermal breakthrough was calculated. To avoid thermal breakthrough in 50 years, the minimum distance should be more than 300 m and to avoid a breakthrough in 100 years, the minimum distance should be over 420 m.

4) To estimate the total recoverable energy in the Urban Dezhou reservoir, Monte Carlo volumetric assessment was undertaken. The estimated total energy is 2340 PJ and the estimated recoverable energy is 540 PJ, with the estimated recovery factor of 23%. Based on the current annual production rate, the lifetime of the Urban Dezhou reservoir is estimated to be about 300 years. However, sustainable resource management should be considered here.

5) The sustainable yield of the Urban Dezhou reservoir based on the two-tank closed lumped parameter model is discussed given two production scenarios with the prerequisite of maximum allowable water level depth of 150 m and a 50 years' time frame. Without reinjection, the estimated sustainable yield is 25% of the current production rate, which cannot meet the demands of the city. A more sustainable situation was shown to be obtained keeping the current production rate but introducing systematic reinjection and a reinjection rate of over 75% of the production rate. The maximum reinjection rate is 80% of the production rate. At this reinjection rate, the sustainable yield is 1.25 times the current production rate. This means the sustainable yield with reinjection cannot only meet the demands of the city but also has the potential for increased development of the reservoir.

6) For sustainable yield, further research in Dezhou reservoir should focus on changes of temperature and the geochemistry contents of geothermal water caused by reinjection.

## ACKNOWLEDGEMENTS

I would like to extend my sincere gratitude to Mr. Lúdvík S. Georgsson, director of the United Nations University Geothermal Training Programme (UNU-GTP) for offering me the opportunity to participate in the six-month training programme. To all the teachers, thank you for giving us such good lectures and sharing precious experiences. To the UNU-GTP staff, Mr. Ingimar G. Haraldsson, Mr. Markús A.G. Wilde, Ms. Málfrídur Ómarsdóttir, Ms. Thórhildur Ísberg, and Ms. María Gudjónsdóttir, thank you for your assistance, you really did a lot for us and I really appreciate it.

To my dear supervisors, Ms. Valdís Gudmundsdóttir and Dr. Gudni Axelsson, thank you very much for your patience, experienced guidance and huge support; my project would not be completed without your help. Special thanks to the teachers: Dr. Svanbjörg Helga Haraldsdóttir, Ms. Sæunn Halldórsdóttir and Ms. Helga Tulinius, for the help in the report presentation.

To my supervisor in China, Dr. Kang Fengxin, thank you for the recommendation for UNU-GTP, the effort to obtain essential data and supporting me in this study.

To my friend fellows, Fardaneh, Amali, Nuno, António and my fellow reservoir engineers and borehole geophysicists. Thank you for your help in the study and daily life.

To my directors in Shandong Provincial Institute of Geology and Mineral Resources. Thanks Mr. Li Changsuo, Mr. Zhao Changhe, Mr. Peng YuMing, Mr. Cheng Xuming, Mr. Qin Pinrui, Mr. Lin Guangqi and all the supporting directors and colleagues.

To the colleagues in the Lubei Institute of Geology and Mineral Resources, Shandong. Thank you for the precious data and material for my report.

To all the 2015 fellows, I am very glad for your company and hope our friendship lasts forever.

To my family and friends back home, thank you for the love and support, you are always with me in my heart wherever I am travelling in the world.

## REFERENCES

Arason, Th., Björnsson, G., Axelsson, G., Bjarnason, J.Ö., and Helgason, P., 2004: *ICEBOX – geothermal reservoir engineering software for Windows. A user's manual.* ÍSOR – Iceland GeoSurvey, Reykjavík, Iceland, report 2004/014, 80 pp.

Axelsson, G., 1985: *Hydrology and thermomechanics of liquid-dominated hydrothermal systems in Iceland*. Oregon State University, PhD thesis, 291 pp.

Axelsson, G., 1989: Simulation of pressure response data from geothermal reservoir by lumped parameter models. *Proceedings of the 14th Workshop on Geothermal Reservoir Engineering, Stanford University, California,* 257-263.

Axelsson, G., 2008: Importance of geothermal reinjection. *Presented at "Workshop for Decision Makers on Direct Heating Use of Geothermal Resources in Asia", organized by UNU-GTP, TBLRREM and TBGMED, Tianjin, China*, 16 pp.

Axelsson, G., 2012: Role and management of geothermal reinjection. *Presented at "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador,* 21 pp.

Axelsson, G., 2013: Tracer tests in geothermal resource management. *EPJ Web of Conferences, 50,* article no. 02001, 8 pp.

Axelsson, G., Björnsson, G., and Montalvo, F., 2005: Quantitative interpretation of tracer test data. *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey*, 12 pp.

Bödvarsson, G., 1972: Thermal problems in the siting of reinjection wells. *Geothermics, 1*, 63–66.

Huang J.C., 2012: *Assessment and management of sedimentary geothermal resources.* University of Iceland, MSc thesis, 63 pp.

Liu, J.R., 2003: The status of geothermal reinjection (in Chinese). *Hydrogeology and engineering geology, 30-3*, 100-104.

Liu, J.R., 2008: Experience of geothermal reinjection in Beijing and Tianjin. *Presented at "Workshop for Decision Makers on Direct Heating Use of Geothermal Resources in Asia", organized by UNU-GTP, TBLRREM and TBGMED, Tianjin, China*, 12 pp.

Kang, F.X., 2000: Assessment of sedimentary geothermal reservoirs in Dezhou, China and Galanta, Slovakia. Report 8 in: *Geothermal training in Iceland 2000.* UNU-GTP, Iceland, 139-163.

Kang, F.X., 2010: Sustainable development of geothermal resources in China. Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 5 pp.

Kang, F.X., Zhou, Q.D., Zhang, P.P., and Zheng, T.T., 2015: Reinjection experiment for a sandstone aquifer in Pingyuan, China. *Proceedings of the World Geothermal Congress 2015, Melbourne, Australia*, 8 pp.

Muffler, L.P.J. (editor), 1979: *Assessment of geothermal resources of the United States - 1978.* USGS Circular 790, Arlington, VA.

Williams, C.F., 2007: Updated methods for estimating recovery factors for geothermal resources. *Proceedings of the 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, Ca,* 7 pp.

Zhang, D.Z., Liu, Z.G., and Lu, H.L., 2013: *Geothermal in Hebei* (in Chinese). Geological Publishing House, Beijing, 275 pp.

Zhang, P.P., Zhao, J.C., Tan, Z.R., Bai, T., and Huang, X., 2015a: *Research report of reinjection technology in porous medium geothermal reservoir in Shandong Experimental Research Establishment.* Lubei Institute of Geology and Mineral Resources, Shandong, and Shandong Geology and Mineral Resources New Energy Company Ltd., report (in Chinese), 106 pp.

Zhang, P.P., Ai, Z.G., Bai, T., Yang, Y.B., Gao, Y.L., Huang, X., Liu, Y., Xia, Y., Yan, P.F., and Zhao, S.X., 2015b: *Research report of geothermal reinjection tests in Shandong.* Lubei Institute of Geology and Mineral Resources, Shandong, report (in Chinese), 164 pp.

Zhang, Z.Y., Wang, H., Zhang, J.Q., and Deng, R.Q., 2011: *Report of geothermal resources reinjection explorations for the urban area of Dezhou, Shandong*. Lubei Institute of Geology and Mineral Resources, Shandong, report (in Chinese), 96 pp.

Zhao, N., Wang, G., Feng, W., Li, Y. and Gao, L., 2015: Reinjection effect study of different geothermal well completion in porous sandstone reservoir in Tianjin, China. *Proceedings of the World Geothermal Congress 2015, Melbourne, Australia*, 6 pp.

Zheng, K.Y., Dong, Y., Cheng, Z.H., Tian, T.S., and Wang, G.L., 2015: Speeding up industrialized development of geothermal resources in China – Country update report 2010-2014. *Proceedings of the World Geothermal Congress 2015, Melbourne, Australia*, 9 pp.