

# Modeling and Prediction of Tracer Tests in Dongli Lake Area in Tianjin, China

Wanli Wang, Guiling Wang, Chunlei Liu, and Vaiva Čypaitė

**Abstract**—The Jxw geothermal reservoir in the Dongli Lake area is an extensive, low temperature geothermal system hosted mainly by Mesoproterozoic dolomitic limestones. In order to study the flow paths and predict the recovery time and tracer concentration in the production well, a numerical method using Visual MODFLOW software were applied. For the most pessimistic case (longitudinal dispersivity equals to 383.5 m), the tracer will take more than a year to arrive at the production well, with concentration values outside of the detection limit. Results show that there is no direct connection between production and injection wells.

**Index Terms**—Numerical model, tracer test, geothermal reservoir, recovery.

## I. INTRODUCTION

In conventional geothermal development, tracer testing can provide information on the flow-paths between reinjection and production wells, helping to predict the danger and rate of cooling during long-term reinjection [1]. It has been widely used and proved to be an important tool in studying the impact of reinjection in the reservoir [2], [3].

Most tracer test interpretations are only used in a qualitative manner to assess injector-producer connectivity without taking advantage of other information carried within a full tracer response curve [4]. To interpret the tracer testing quantitatively, a numerical method using Visual MODFLOW software were applied.

This paper aims to model the flow patterns in the geothermal reservoir. A numerical model was built in order to demonstrate physical processes in the study area and predict the change of concentration in a long time period after trace injection.

## II. GENERAL INFORMATION OF THE JXW GEOTHERMAL RESERVOIR

### A. Geology and Hydrogeology

The study field Wumishan geothermal reservoir (Jxw) is

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located in Tianjin Binhai New District. It mostly consists of Mesoproterozoic dolomitic limestones [5] with high temperature and high production rates [6]. The fracture rate of this reservoir varies from 40% to 70% and in some wells the rate is up to 80 - 90% [7].

The heat source for the reservoir is presumably from lava flow of the upper mental and radioactive decay from granite (8~16 km depth). According to isotopic analysis, the origin of the water is meteoric from ancient times. The Quaternary and Tertiary formations consist of clay and sandstone, forming a good caprock of the geothermal reservoir. They are of low thermal conductivity and low permeability with thickness of 280 to 320 m. The Cangdong fault is a major fault in this area which can conduct heat from the bottom of the reservoir to the shallow part by heat convection. Heat convection becomes weaker with distance far from the fault.

Geothermal wells are mostly located near the Cangdong fault (Fig. 1). Until now 13 geothermal wells have been drilled into this reservoir. Average well production rates are in the range of 70–120 m<sup>3</sup>/h, with wellhead temperatures between 88 and 102°C [8], [9]. However, no well completely penetrates the reservoir and its thickness is unknown. Drilling data shows that in the west of the Cangdong fault, the top depth of the reservoir varies from 1752 to 2016 m, with thickness of 480 to 1032 m. However, in the east of the fault, there is only one well penetrating this reservoir with top depth of 3581 m and thickness of 153 m (DL-51).

Due to gradually increased production and development, the water level had been falling 6-9 m per year since 1997 and a regional cone of depression has formed [10]. Therefore, reinjection of the used geothermal water was started in 2001 to maintain reservoir pressure and to prolong the lifetime of the production wells [5]. Injection provides an additional recharge to geothermal reservoirs; however, the water level has still dropped nearly 3 m per year since 2011 due to large scale development [11].

### B. Tracer Testing

In order to study the flow paths and predict the cooling of long term injection, tracer testing was performed. Ammonium Molybdate (Mo) was chosen as the tracer for this test. It is nontoxic at low concentrations and could be used safely in the aquifer. The natural concentration of the tracer was low (background concentration is around 0.5 µg/L) so it was assumed that the tracers introduced for this test could be followed for a reasonable distance and still be detected [12].

On 17 December, 2015, total of 700 kg of Ammonium Molybdate (Mo) were injected into well DL-48B over a period of 2 hours. The injection flow rate was approximately 100 m<sup>3</sup>/h. Throughout the subsequent 3 months, 8 production

wells were sampled every 2 hours (see Fig. 1). Only 1/6 of the samples were tested and analysed. If the tracer had been detected, the frequency of the analysis could be increased.

No recovery was detected in the samples after 90 days of sampling which took place until March 18th, 2016. There are some assumptions. One is that the tracer needs longer time to arrive at the production wells. Another consideration is there is no direct flow from injection and production wells as the reservoir is highly fractured.

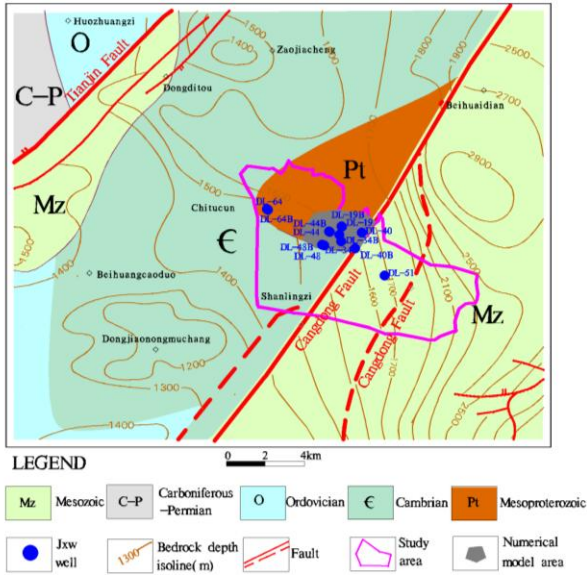


Fig. 1. The scope and geological structures of the study area.

### III. METHODS

MODFLOW is a FORTRAN program developed by the United States Geological Survey (USGS), which can simulate groundwater flow and levels under complex hydrogeological conditions with various hydrological processes and is widely used in regulatory situations [13].

The equation governing groundwater flow through saturated porous media in three dimensions is derived from Darcy's law and the continuity equation, and is given as [14]:

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + w = S_s \frac{\partial h}{\partial t}$$

where ' $K_{xx}(m/d)$ ', ' $K_{yy}(m/d)$ ' and ' $K_{zz}(m/d)$ ' are the hydraulic conductivities along the x, y, and z axes that are assumed to be parallel to the principal axes of the hydraulic conductivity tensor, ' $h(m)$ ' is the hydraulic head, ' $W(1/d)$ ' is the volumetric flux per unit volume representing sources and/or sinks of water, ' $S_s(1/m)$ ' is the specific storage of the material, ' $t(d)$ ' is time. Here,  $K_{xx}$ ,  $K_{yy}$  and  $K_{zz}$  are the functions of space (x, y, z) and W is a function of space and time (t).

In this study, Visual MODFLOW Flex (2015.1) software has been used for simulating the groundwater dynamics. This version includes the simulation of saturated -unsaturated flow process, density dependent flow process, parameter optimization process and solute transport process [15]. A finite difference grid was used and MODFLOW 2000 was chosen as an engine to run a transient state numerical model from 26th August, 2013 to 26th August, 2015.

1) MT3DMS: MT3DMS is a transport model for

simulating advection, dispersion, and chemical reactions of contaminants in groundwater flow systems. This package was used to model the concentration of the observation wells after tracer injection [16].

2) PEST: An effective tool of automating parameter estimation, calibration and sensitivity analysis, and it allows you to run parameter estimation using results from both groundwater flow and contaminant transport simulations [17].

## IV. RESULTS AND DISCUSSION

### A. Numerical Reservoir Modelling

Considering most wells were distributed in the left part of Cangdong fault except well DL-51 and DL-51B, and the fault itself can be a natural boundary condition, a small area with intensive production and injection wells was chosen as the numerical model study area (Fig. 1).

In the conceptual model, this study area was divided vertically into four layers based on borehole geology information and geological situations as mentioned before. Layer 1 is the Quaternary porous formation. Layer 2 includes Cenozoic Minghuazhen Group (Nm) and Guantao Group (Ng). Layer 3 is the Karstic-fracture geothermal reservoir, including Paleozoic Ordovician (O), Cambrian (€). Layer 4 which is the main study reservoir consists of Mesoproterozoic Jixian Wumishan Group (Jxw). One cross section is shown in Fig. 2, indicating these four reservoirs in the model. Based on the information of the deepest well with depth of 4040m in this area, the reservoir below 4000 m depth is poorly developed with pore and fissures. So the bottom boundary was considered as no-flow boundary.

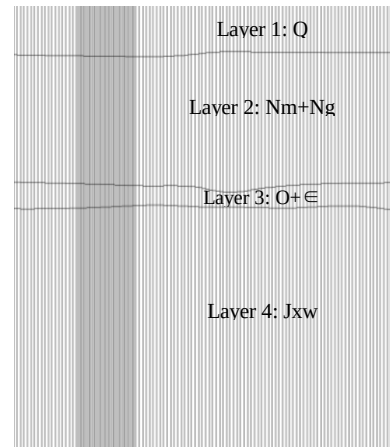


Fig. 2. Cross section of row 41.

The flow direction is mainly from northwest to southeast according to initial water level contours and the inflow and outflow flux of each boundary can be calculated by Darcy's Law. The specified flux boundary was used with these fluxes in the model, and small adjustment was made during the process of calibration.

Each layer was discretized horizontally into a grid of 100×120 cells with cell height of 22.13m and cell width of 31.78m. For more accurately simulate and calculate the water level, concentration and heat transfer with the injection well and production well, grid around well DL-48 and DL-48B was refined by two (Fig. 3).

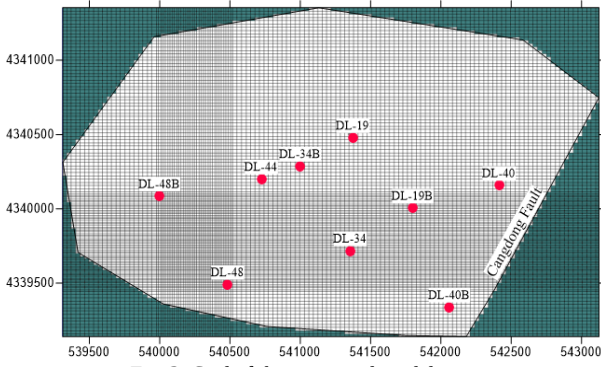


Fig. 3. Grid of the numerical model area.

### B. Calibration

The parameter estimation program PEST was used to minimize errors between observed and simulated heads, which was also used to estimate the distribution of reservoir parameters. Pilot points were placed and fixed of these wells with the known  $K_{x,y}$ , which were obtained from pumping test data reported by the Tian [9] (Table I). Additional pilot points were then added scattering over the study area.  $K_{x,y}$ ,  $K_z$  and  $S_s$  in layer 4 were constrained in the range of 0.1-10 m/d, 0.01-1 m/d,  $1e-7$  to  $1e-4$  1/m, respectively. This resulted in 15 pilot points of 3 kinds of parameters to be calibrated. The spatial hydraulic conductivity and storativity fields were derived by interpolation among pilot points using kriging variograms [18].

TABLE I: THE HYDRAULIC CONDUCTIVITY OF FIXED PILOT POINTS FROM WELL TEST DATA

| Well   | Hydraulic conductivity (m/d) | Well   | Hydraulic conductivity (m/d) |
|--------|------------------------------|--------|------------------------------|
| DL-40B | 2.85                         | DL-40  | 1.03                         |
| DL-48  | 3.3                          | DL-34  | 0.85                         |
| DL-19B | 1.38                         | DL-44  | 0.77                         |
| DL-48B | 1.29                         | DL-44B | 0.73                         |

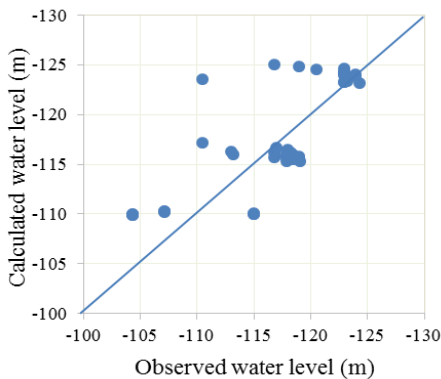


Fig. 4. The fitting of the observed water levels and simulated water levels after PEST.

Data on monthly groundwater levels of 4 monitoring wells from December 2013 to December 2015 were used for model calibration (no data during heating periods). After running PEST, we got the new distribution of parameters and they were applied to the new model. The range of  $K_{x,y}$ ,  $K_z$  and  $S_s$  in layer 4 are mostly between 0.45-3.18 m/d, 0.05-0.33 m/d,  $2.09E-6$  to  $1.24E-5$   $m^{-1}$ , respectively, which can better reflect the heterogeneity of the reservoir rather than the zonal approach.

The final calibrated model produced reasonable agreement

between the simulated and observed water levels at the calibration targets (Fig. 4). The absolute residual mean (ARM) was 2.94 m, while the root mean square error (RMSE) was 3.84 m. For a model with area of 6.32  $km^2$ , with a standard error of the estimate of 0.57m, and correlation coefficient of 0.77, was considered to be acceptable.

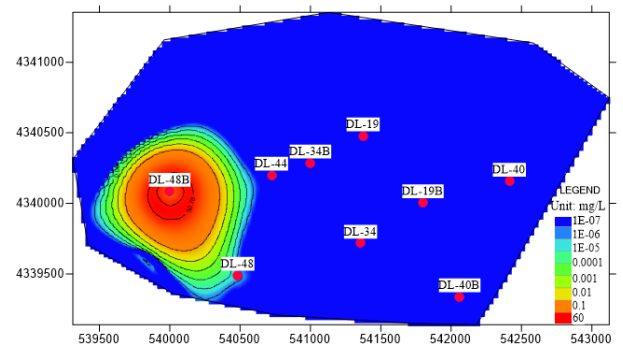
### C. Prediction of Tracer Concentration in Production Well

MT3DMS numerical engine was used to estimate the recovery time and the tracer concentration in the production wells. For further modelling, it was assumed that tracer is conservative and no adsorption or desorption occurs in the reservoir, only convection and dispersion were considered.

Hydraulic conductivity and storativity were deduced from the groundwater flow model. Total porosity was used to determine the chemical reaction coefficients and for calculating the average linear groundwater flow velocity [19]. The longitudinal dispersivity was set as 76.7 m, 230.1 m and 383.5 m for three different simulation scenarios. The injection of tracer was set on the first day of injection with maximum dissolved concentration of  $3 \times 10^8$   $\mu g/L$ . Results show that the tracer concentration was diluted very quickly and it moved very slowly (Table II). For the most pessimistic case ( $a_L = 383.5$  m), it takes more than a year to arrive at the production well, with very small concentration which is out of the detection limit. Even at the end of 10 years, the concentration is still very low which is 0.00424  $\mu g/L$  (Fig. 5). It means more than 10 years is needed to get recovery with the tracer testing.

TABLE II: RECOVERY TIME AND CORRESPONDING CONCENTRATION OF PRODUCTION WELL

| Recovery time (years) | Concentration of well DL-48 ( $\mu g/L$ ) |               |               |
|-----------------------|-------------------------------------------|---------------|---------------|
|                       | $a_L=76.7$ m                              | $a_L=230.1$ m | $a_L=383.5$ m |
| 1.1                   |                                           |               | 1.68E-30      |
| 2.1                   |                                           | 5.78E-29      | 3.60E-20      |
| 5.3                   | 4.96E-31                                  | 1.87E-13      | 1.74E-07      |
| 9.7                   | 6.05E-21                                  | 3.44E-07      | 4.24E-03      |

Fig. 5. Tracer concentration contours in reservoir after 10 years ( $a_L = 383.5$  m).

## V. CONCLUSIONS

A numerical reservoir model was developed for the Dongli Lake geothermal area. It covers an area of 6.32  $km^2$ . An automatic parameter estimation tool (PEST) was used to minimize errors between observed and simulated heads and to estimate the distribution of reservoir parameters. The final calibrated model produced reasonable agreement between the simulated and observed water levels and was applied to predict the tracer concentration in the production well.

For the most pessimistic case of a longitudinal dispersivity of 383.5 m, the tracer will take more than a year to arrive at the production well, at very low with very small concentration, outside the detection limit. Results show that more than 10 years is needed to get recovery with the tracer testing and there is no direct connection between production and injection wells.

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