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# DISTRIBUTED PARAMETER MODEL FOR THE ZHANGZHOU GEOTHERMAL FIELD, CHINA

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## ABSTRACT

A distributed parameter model for the Zhangzhou geothermal field, China, is set up using the AQUA programme and calibrated by matching the measured and the calculated drawdown and temperature data from 10 observation wells over the past 8 years. Based on this, predictions of the reservoir response to the planned production rates were made up to the year 2010. The flow model indicates that with the present production, the reservoir is under near steady-state condition. The maximum production rate without injection was found to be about 100 l/s with the condition to keep the Quaternary aquifer productive. The production rate can be further increased if a doublet is employed for injection/reinjection. The heat transport model shows that the reservoir temperature will change due to both the increased production rates and the temperature of the reinjected water in the predicted time period.

## 1. INTRODUCTION

The main task of the geothermal reservoir modeller is to calibrate the parameters for a geothermal system using the available field data and to predict the future behaviour of the reservoir during production and reinjection. A number of different methods for modelling the behaviour of geothermal reservoirs are currently available to reservoir engineers, such as lumped parameter models and distributed parameter models. The selection of the proper method for a particular study mainly depends on the amount and quality of field data and the objectives of the study.

The Zhangzhou geothermal field in Fujian Province, P.R. China is a typical low-temperature fracture zone system, where heat is transferred by convection, involving deeply penetrating meteoric waters and some saline water, from a resource base in the upper crust (thick granodiorite), to the surface, along the intersection of two deep-cutting faults (trending northnortheast and westnorthwest) (Wang et al., 1989). The natural state model for it, has been developed by Hu (1989) and Yang et al. (1990), and now it is possible to recalibrate the parameters for the model as a lot of water level-, temperature-, and production data are available.

In the present paper, the AQUA programme, a distributed parameter model, was used for the calibration of the reservoir parameters and the prediction of future response of the reservoir with different production and reinjection rates. Some suggestions for the future development and reservoir management of the Zhangzhou geothermal field are presented.

## 2. THE AQUA DISTRIBUTED PARAMETER MODEL

AQUA is a programme package developed by Vatnaskil Consulting Engineers (1990), to solve the groundwater flow and transport equations using the Galerkin finite element method. It is a useful tool for geothermal and environmental problems, including groundwater flow and contaminant transport modelling.

### 2.1 Governing equation

Geothermal reservoir modelling involves fluid flow, mass and heat transfer. The following differential equation is the basis of the mathematical model:

$$a\frac{\partial u}{\partial t} + b_i\frac{\partial u}{\partial x_i} + \frac{\partial}{\partial x_i}(e_{ij}\frac{\partial u}{\partial x_j}) + fu + g = 0 \tag{1}$$

The equation is two dimensional, indices *i* and *j* indicate *x* and *y* coordinates axis, respectively.

### 2.2 Flow model

For transient flow, Equation 1 is reduced to

$$a\frac{\partial u}{\partial t} + \frac{\partial}{\partial x_i}(e_{ij}\frac{\partial u}{\partial x_j}) + fu + g = 0 \tag{2}$$

The parameters in Equation 2 are defined as

$$u = h;\ \ e_{ij} = T_{ij};\ \ f = 0;\ \ g = Q + k/m\,(h_o - h);\ \ a = -S$$

Using *x* and *y* as indices instead of *i* and *j*, Equation 2 becomes

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_{yy}\frac{\partial h}{\partial y}) + \frac{k}{m}(h_o - h) + Q = S\frac{\partial h}{\partial t} \tag{3}$$

where

$h$ = Pressure head (m);
$T_{xx}$ = Transmissivity along principal axis ($m^2/s$);
$T_{yy}$ = Transmissivity perpendicular to the principal axis ($m^2/s$);
$Q$ = Pumping/injection rate ($m^3/s$);
$k/m$ = Leakage coefficient (1/s), where $k$ is the permeability of the semi-permeable layer and $m$ the thickness;
$h_o$ = Pressure head of upper aquifer (m);
$S$ = Storage coefficient.

For long term exploitation, storage of the reservoir is controlled by compressibility of the water and the rock in terms of the elastic storage coefficient and by the delayed yield effect. So the equation for the transient flow is

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_{yy}\frac{\partial h}{\partial y}) + \frac{k}{m}(h_o - h) + Q = S\frac{\partial h}{\partial t} + \alpha\phi\int_o^t \frac{\partial h}{\partial t}e^{-\alpha(t-\tau)}d\tau \tag{4}$$

where

$\alpha$ = $1/K$ and $K$ is the time constant (s);
$\phi$ = Effective porosity.

For steady-state conditions, Equation 1 is reduced to

$$\frac{\partial}{\partial x_i}(e_{ij}\frac{\partial u}{\partial x_j}) + fu + g = 0 \tag{5}$$

The parameters in Equation 5 are defined as

$$u = h;\ \ e_{ij} = T_{ij};\ \ f = 0;\ \ g = Q + k/m(h_o - h)$$

and using $x$ and $y$ as indices instead of $i$ and $j$, Equation 5 becomes

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_{yy}\frac{\partial h}{\partial y}) + \frac{k}{m}(h_o - h) + Q = 0 \tag{6}$$

The following boundary conditions are allowed in AQUA:

a. Dirichlet boundary condition; the pressure head, the piezometric head or the potential function are prescribed at the boundary as a function of time;
b. Von Neumann boundary condition; the flow at the boundary is prescribed by defining source nodes (recharge or pumping) at the no flow boundary nodes;
c. Cauchy boundary condition; the flow rate is related to both the normal boundary derivative and the head.

### 2.3 Heat transport model

For heat transport, the parameters in Equation 1 are defined as follows:

$$u = T;\ \ a = \phi b R_h;\ \ b_i = v_i b;\ \ e_{ij} = -bK_{ij};\ \ f = \gamma + Q;\ \ g = \gamma T_o - QT_W$$

By using $x$, $y$ instead of the indices $i$, $j$, Equation 1 reads

$$\frac{\partial}{\partial x}(\varphi b D_{xx}\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\varphi b D_{yy}\frac{\partial T}{\partial y}) - v_x b\frac{\partial T}{\partial x} - v_y b\frac{\partial T}{\partial y} = \varphi b R_d\frac{\partial T}{\partial t} + \varphi b R_d \lambda T - (T_o - T)\gamma - Q(T_w - T) \tag{7}$$

The heat dispersion coefficients $K_{xx}$, $K_{yy}$ are defined by

$$K_{xx} = a_L v^n + D_h \varphi \tag{8}$$

$$K_{yy} = a_T v^n + D_h \varphi \tag{9}$$

The heat retardation coefficient $R_h$ is given by

$$R_h = 1 + \beta_h \frac{(1-\varphi)\rho_s}{\varphi \rho_l} \tag{10}$$

with the retardation coefficient $\beta_h$ as

$$\beta_h = \frac{C_s}{C_l} \tag{11}$$

where
$T$ = Temperature (°C);
$T_o$ = Temperature of vertical inflow (°C);
$C_l$ = Specific heat capacity of the fluid (kJ/kg°C);
$C_s$ = Specific heat capacity of the porous medium (kJ/kg°C);
$D_h$ = Heat diffusivity ($m^2/s$).

Other parameters are previously defined. For heat transport, there are two boundary conditions allowed:

a. Dirichlet boundary condition; the temperature is specified at the boundary;
b. Von Neumann boundary condition; the temperature gradient is set to be zero indicating convective transport of heat through the boundary.

## 3. MODELLING OF THE ZHANGZHOU GEOTHERMAL FIELD

The conceptual model of Zhangzhou was proposed by Wang et al (1989). Based on it, the numerical model is set up for the AQUA programme and calibrated by matching the computed and the measured data.

### 3.1 Geological background

The Zhangzhou geothermal field, lies in the southeastern part of an artesian basin, the Zhangzhou rhom-bus-shaped fault basin, in Fujian Province, China. It is surrounded by a large catchment and drained by the Julong River (Figure 1). The basin is about 1000 km$^2$ and has an average elevation of 30 m a.s.l. The outer terrain in the north and northwestern sectors stands about 500 to 1500 m above sea level. The Zhangzhou thermal area lies close to the Julong River and most of it is located inside the city. The production wells are 7-10 m a.s.l. At Zhangzhou the Julong river is close to sea level, and the water level in the river fluctuates with variations in the rainfall. Subsequently changes in subsurface water level and temperature are observed (Figure 2).

The basement rocks surrounding Zhang-zhou basin consist mainly of Mesozoic granodiorite and metamorphic rocks of Jurassic age covered by thin (<30 m) Quaternary sediments inside the basin. The whole catchment is dissected by two sets of steeply dipping old faults striking northeast and northwest, respectively. Within the basin, sets of younger faults have been mapped trending northnortheast and westnorthwest (Figure 3). It has been postulated that the hot water in the Zhangzhou prospect ascends along highly permeable segments of the younger faults, especially at the intersection of the faults (Wang et al., 1989).

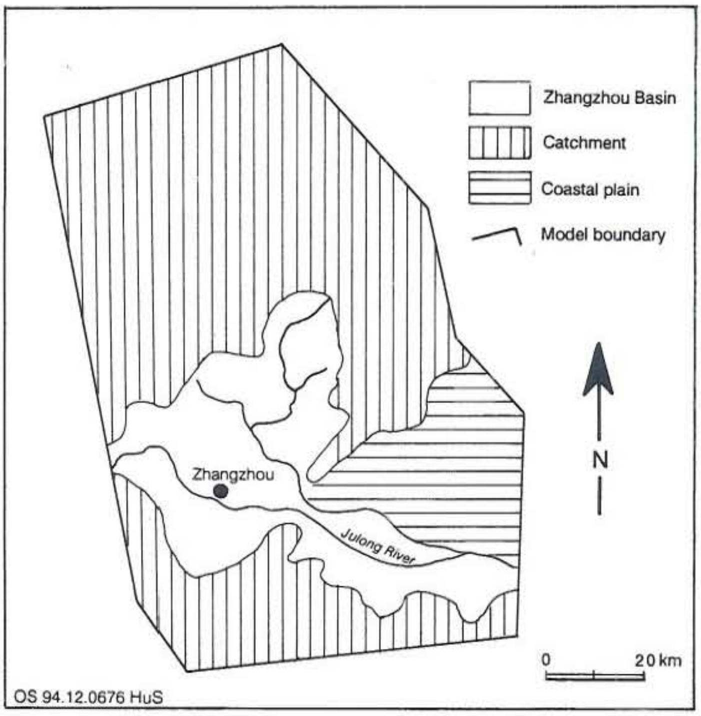

FIGURE 1: Location of the Zhangzhou geothermal field and the boundary of the model

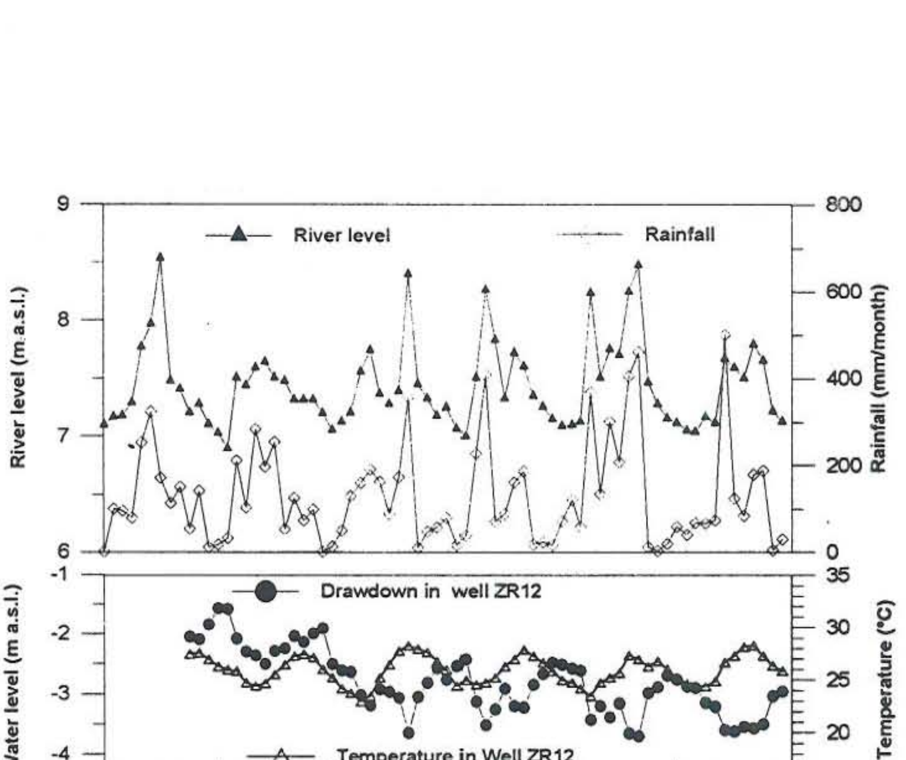

FIGURE 2: Time variation of river level, rainfall, subsurface water table and temperature

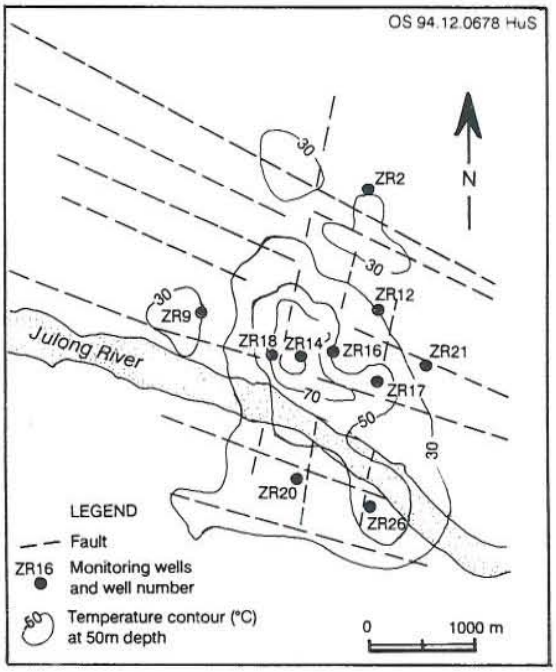

FIGURE 3: Temperature distribution at 50 m depth in the Zhangshou geothermal field and location of faults and wells

More than 100 shallow wells (≤ 100 m) have been drilled in the Zhangzhou prospect over an area of 25 km$^2$, and all the wells stand in granitic rocks. Isotemperature contours at 50 m depth indicate an inner reservoir (about 0.5 km$^2$) where the temperatures are greater than 60°C (Figure 3). The highest temperatures (120°C at 90 m) have been found in two shallow wells near the centre of the inner reservoir.

## 3.2 Conceptual reservoir model

Stable isotope data (O$^{18}$ and D) indicate that all thermal fluids are meteoric waters whose isotopic composition lies close to the meteoric water line (Wang et al., 1989). The absence of any O$^{18}$ shift indicates that temperatures of less than 200°C prevail at the deepest level of fluid-rock interaction. The thermal water in the inner reservoir is highly mineralized (up to 10 g/kg total solids), being a slightly alkaline Na-Cl type. Most of the mineralization is probably due to mixing of a less mineralized deep hot water with saline pore fluids which occurs, for example, in cold wells lying to the east of the thermal prospect. Shallow wells elsewhere in the basin produce groundwater with less than 0.3 g/l total solids. The geothermometers indicate a reservoir temperature of about 145°C (Wang et al., 1989). The origin and variation of the chloride concentration of the thermal water in the prospect is explained in Figure 4. It has been inferred that meteoric water in the catchment penetrates to depths of 3.5 to 4 km, sweeping heat along radially inward-directed paths with hot fluids ascending through a fractured reservoir of vertical, cylindrical shape. The hot fluids from the deep level are cooled down at a shallow depth by conduction and mixing with the cold groundwater.

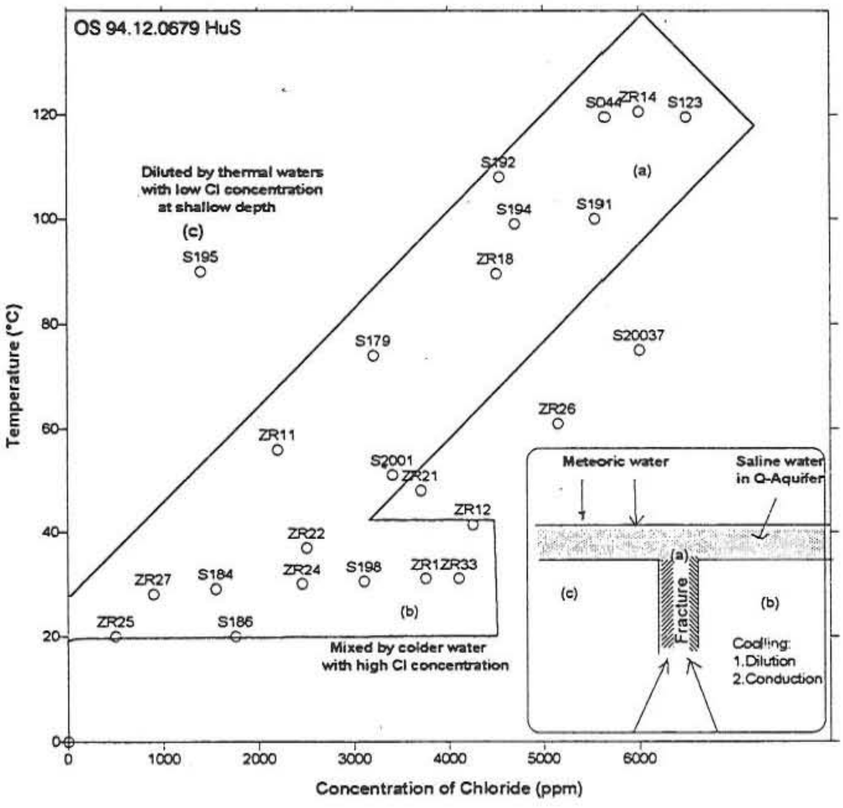

FIGURE 4: Relationship between Cl concentration and temperature of the bedrock water in wells

In this work, a 5000 km$^2$ near rectangular area is established for the reservoir modelling area, its boundaries are determined by the surface water division and set as no flow boundaries. The model was created with 2386 nodes and consists of 4736 elements. As to the initial state prior to production, it was assumed that the reservoir water head was constant so that there was no hydraulic gradient in the model area. Since the W-NW faults were believed to be more permeable, the anisotropy angle was set to be 150° along the faults.

### 3.3 Production History

The hot water in Zhangzhou geothermal field was exploited and utilized for bathing a long time ago, but only on a small scale until the 1990s when the Wuzhong Central Delivery Thermal Plant and several fish farms were built (Table 1). In that plant, the hot water with a temperature of 80-85°C is reinjected by a doublet. At present, the production is still small but there is a great potential for further development.

TABLE 1: Production and reinjection history in Zhangzhou geothermal field

| Site | Production ($m^3$/day) | | | Reinjection ($m^3$/day) | | |
|---|---|---|---|---|---|---|
| | Rate | Month | Initial | Rate | Month | Year |
| Wenquan Public Bath | 400 | Dec. to Feb. | 1986 - | | | |
| | 200 | Mar. to Sept. | | | | |
| Dazhong Public Bath | 400 | Dec. to Feb. | 1986 - | | | |
| | 200 | Mar. to Sept. | | | | |
| Gongren Public Bath | 85 | Dec.to Mar. | 1986 - | | | |
| | 30 | June to Sept. | | | | |
| | 50 | Other time | | | | |
| Wenquan Hotel | 300 | Dec. to Feb. | 1993.1- | | | |
| | 100 | Other time | | | | |
| Renming Ladies Bath | 6 | Oct. to Jan. | 1986 - | | | |
| Gongren Sanatorium | 35 | Year-round | 1986 - | | | |
| Wuzhong Central Delivery Thermal Plant | 1500 | Year-round | 1990.11 | 1500 | Year-round | 1992.10 |
| The Swimming Pool | 200 | June to Oct. | 1990 - | | | |
| Xiazhuang Fish Farm | 500 | Year-round | 1992.9- | | | |
| Xingtang Fish Farm | 600 | Dec. to Apr. | 1991.12 | | | |
| | 425 | Other time | - | | | |

28 wells were used for observation inside or outside the production area. The drawdown in September 1993, relative to the natural state in September, 1986 (Figure 5) shows changes with time due to the increasing production and the doublet reinjection which started in October, 1992.

### 3.4 Calibration of aquifer parameters using the AQUA model

The process of simulation is a trial and error process, i.e. adjusting the parameters within some limits in order to match the calculated values with the measured ones.

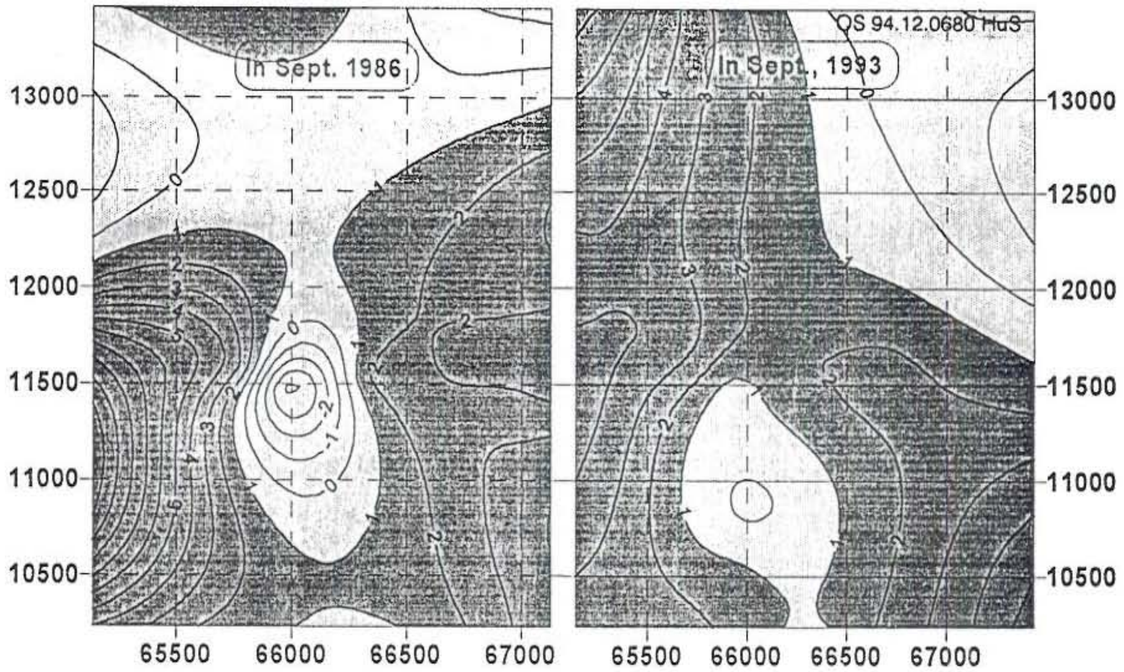

FIGURE 5: Observed changes of drawdown (m) with time

### 3.4.1 Flow problem

The water level data from 10 selected observation wells (Figure 3) were used for calibrating the reservoir parameters including the transmissivity, storativity and porosity. Those data are based on observation for a period of 8 years, 1986-1993, respectively.

The calibration was satisfactory when good matching had been achieved between the measured and the computed data. The transmissivity inside the Zhangzhou basin of the model area turned out to vary from $5x10^{-3}$ to 0.15 $m^2/s$ (Figure 6). The fractured zones are highly permeable, and the background transmissivity outside the basin is $3x10^{-3}$ $m^2/s$. The storage coefficient inside the basin for the model is in the range from $5x10^{-4}$ to $1x10^{-2}$ (Figure 7). In the area outside the basin the storage coefficient is $2.5x10^{-4}$. The porosity is assigned to be 10% for the fracture zone and 1-2% for the outer granite.

The multiplier for Sqrt($T_{yy}/T_{xx}$) is 0.447, i.e. the transmissivity along the westerly to northwesterly trending faults is 5 times greater than in the other direction.

The good fit with the measured drawdown (Figure 8), using the equation for delayed yield, shows that the reservoir is controlled by two different storage mechanisms. At the start of production, storage is controlled by liquid/formation compressibility and later by the mobility of the free surface, the delay yield time constant is 2800 days. The resulting flow field in the model is obviously controlled by the production and reinjection.

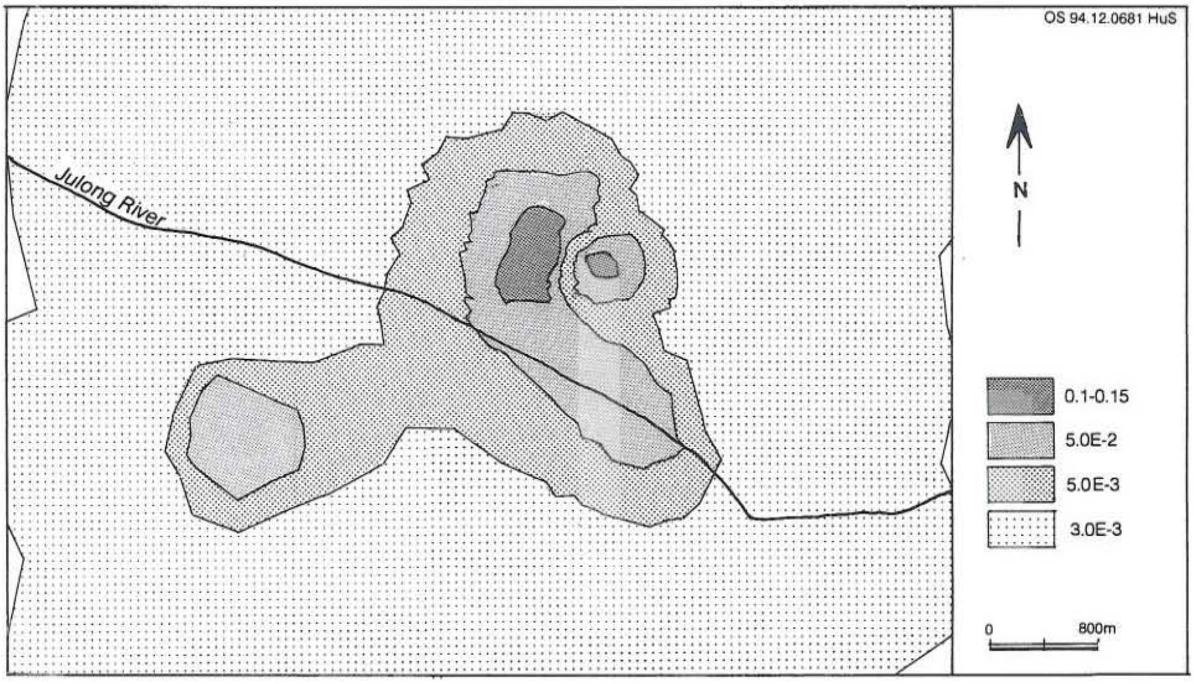

FIGURE 6: Transmissivity distribution ($m^2/s$) in the Zhangzhou geothermal field

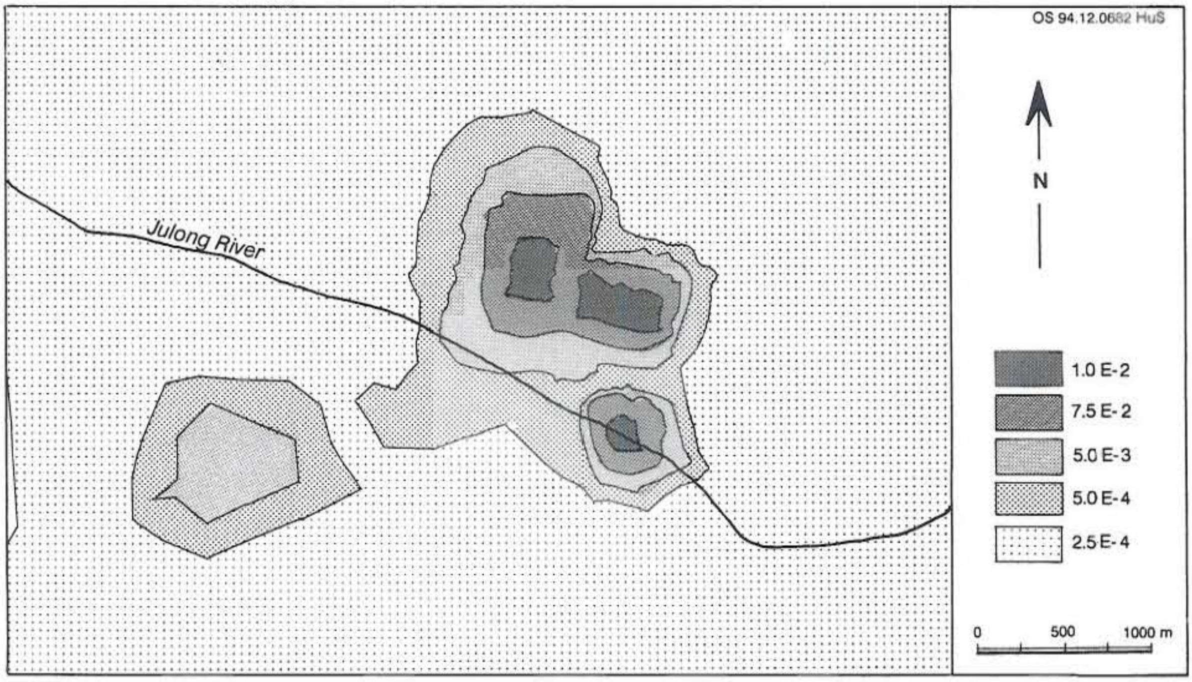

FIGURE 7: Storativity distribution in the Zhangzhou geothermal field

### 3.4.2 Heat transport

Before calculating the heat transport, the initial temperature, the temperature of the vertical inflow into the aquifer and the thickness of the aquifer have to be known. The initial temperature is not constant but varies over the area. The vertical inflow temperature, i.e. the injection temperature is 80°C for the present injection well and 40°C for a planned future injection well. The longitudinal dispersivity, aL, is assumed to be 200 m, and the multiplier for Sqrt(aT/aL) to be 0.447. The aquifer thickness is 1000 m.

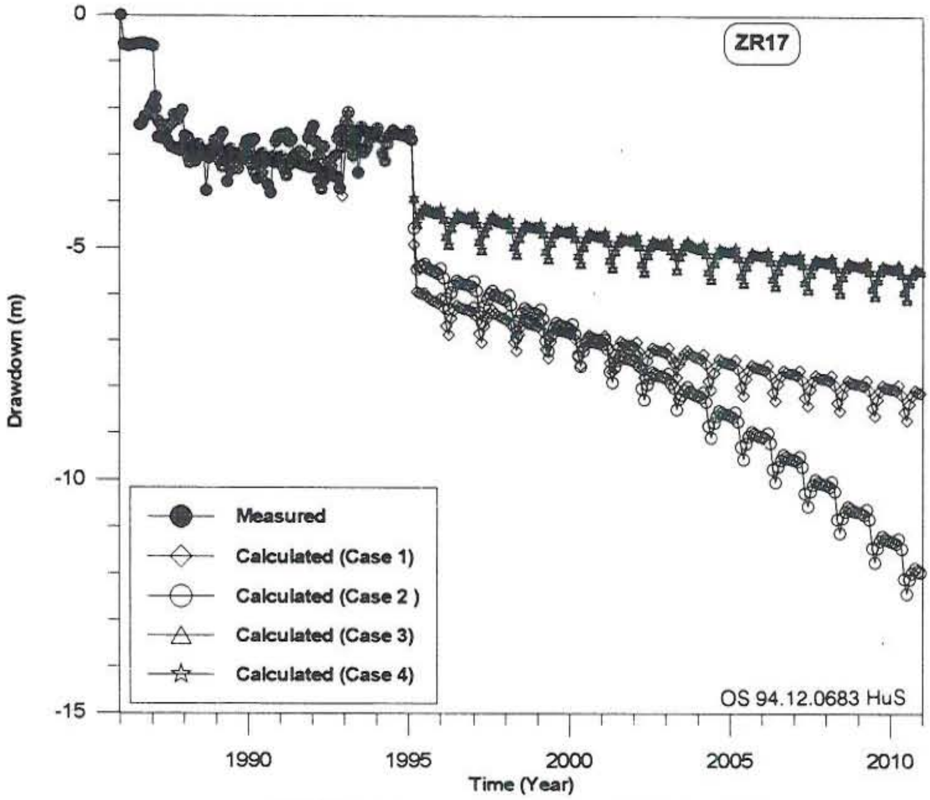

FIGURE 8: Measured and computed drawdown in well ZR17 and future predictions for different production cases

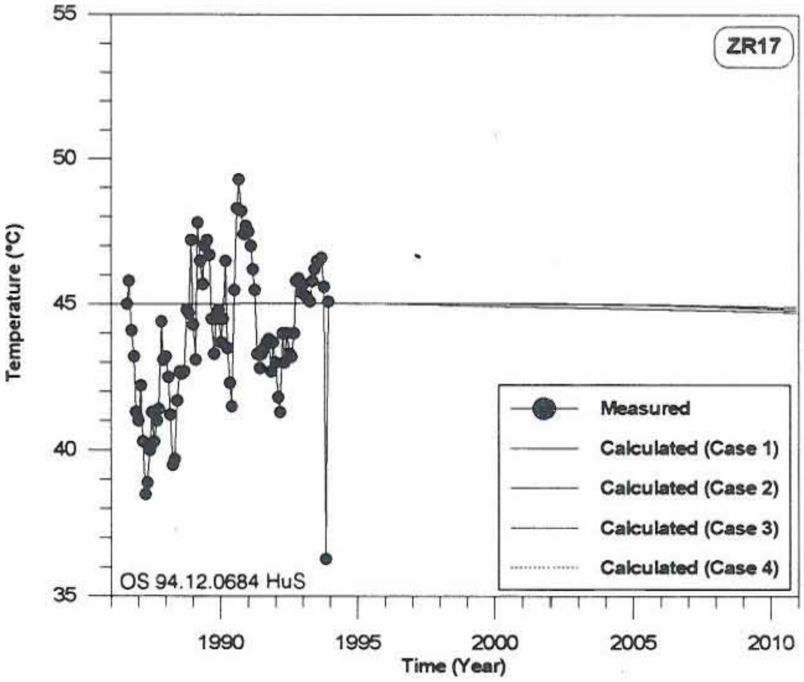

FIGURE 9: Measured and computed temperatures for different production and reinjection rates in well ZR-17 and future predictions for different production cases

The retardation constant, i.e. the ratio of the heat capacity of the rock to that of the water, is 0.213. The measured and calculated temperatures as well as the predicted temperatures in well ZR-17 are shown in Figure 9.

## 4. FUTURE DEVELOPMENT AND RESERVOIR MANAGEMENT

### 4.1 Future development

As the Zhangzhou geothermal field is located in the Zhangzhou City, a larger scale development of the thermal water can be expected. In this work, on the basis of the present production and reinjection, four additional assumed production wells have been planned and sited (Figure 10) to assess the response of the reservoir to increased production and reinjection rates. The planned new thermal plant A, (Figure 10), a main producer in the downtown area, is designed to produce hot water. Here five cases are demonstrated, with constant or increasing production, with or without reinjection (Case 1 to 4 in Table 2). Producers B and C have the same production rates as the Ziazhuang fish farm in Table 1, and producer D the same as the Zingtang fish farm. All the new production wells are assumed to start producing in 1995, and the predictions are carried out to the year 2010. For cases 1 and 3 (Figure 11a), the average production rates increase from the present 40 l/s to 70 l/s. For cases 2 and 4 (Figure 11b), the average production rate increases from 70 l/s to 110 l/s in the year 2010 (Figures 11a and 11b).

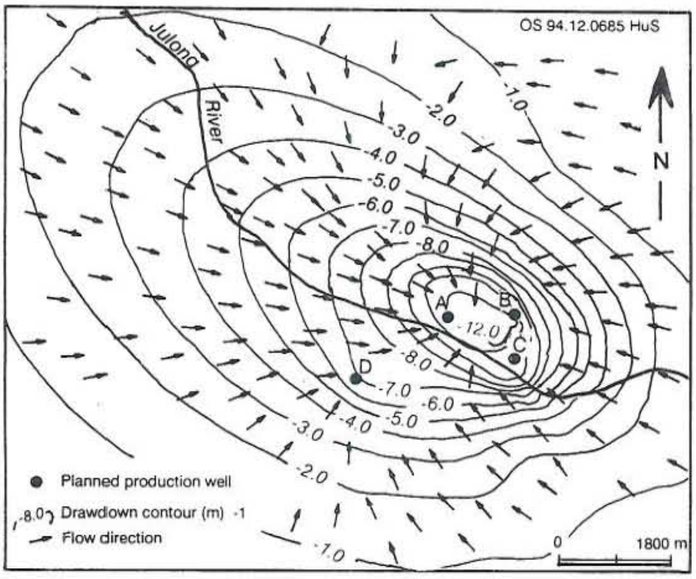

FIGURE 10: The drawdown in the year 2010 for case 2 (Table 2), and the planned new production wells

TABLE 2: Proposed design for the new thermal plant A

| | Production rate | Yearly increase | Reinjection |
|---|---|---|---|
| Case 1 | 1500 m$^3$/day | 0 | 0 |
| Case 2 | 1000 m$^3$/day | 10% | 0 |
| Case 3 | 1500 m$^3$/day | 0 | 100% |
| Case 4 | 1000 m$^3$/day | 10% | 100% |

### 4.2 Future prediction

The future predictions deal with the responses of the reservoir to designed future production and reinjection. In this work, the draw-down and temperatures are predicted with different production and reinjection rates.

#### 4.2.1 Drawdown

The drawdown will drop abruptly at the beginning and then increase continuously, no steady state condition can be reached in the year 2010 under the planned production rates. Case 2 has the largest drawdown and the steepest response (0.6 m/year). In the year 2010 it will have reached 13 m in the production area (Figure 10), which is going to exhaust the Quaternary aquifer since the bottom of the Quaternary layer in the production area is just 20 m below the surface. Therefore, the production rate for case 2 can be taken as the maximum rate without future reinjection. Figures 12-14 show the predicted drawdown for the different cases in three wells. Case 1 has less drawdown (0.1 m/year) than case 2. Because of relatively small production in the later years (Figure 11a and 11b). Its drawdown in the year 2010 is about 8 m, so the production rate for case 1 can be taken as the conservative or proper rate without future reinjection. Cases 3 and 4, which share the same 100% reinjection at the planned new thermal plant, have exactly the same drawdown (just 5 m in the year 2010) corresponding to 0.08 m/year. It is obvious when comparing cases 1 and 2 with cases 3 and 4 that reinjection is necessary in order to increase the production rate without having too much drawdown.

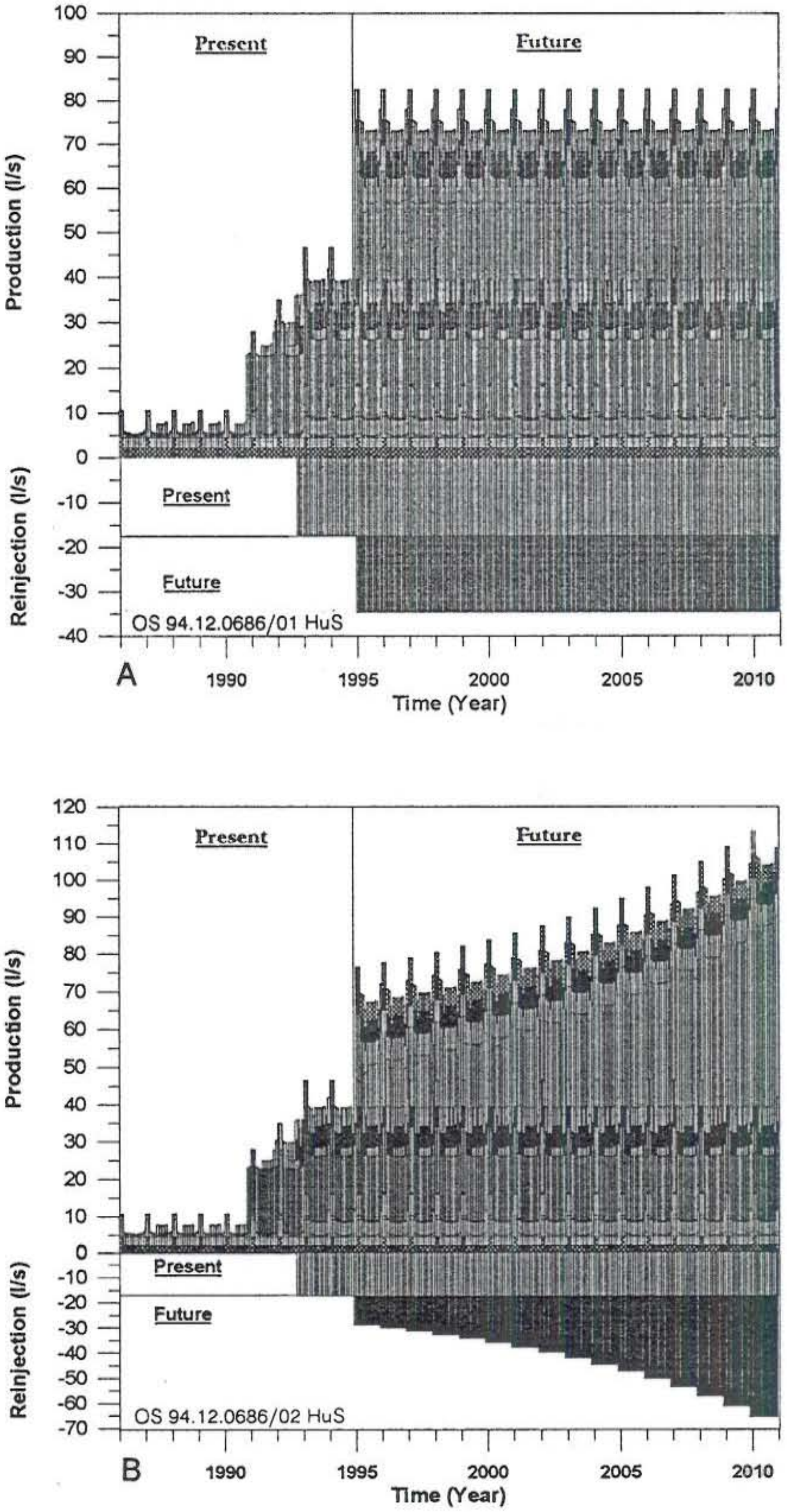

FIGURE 11: Production and reinjection for a) cases 1 and 3; b) cases 2 and 4

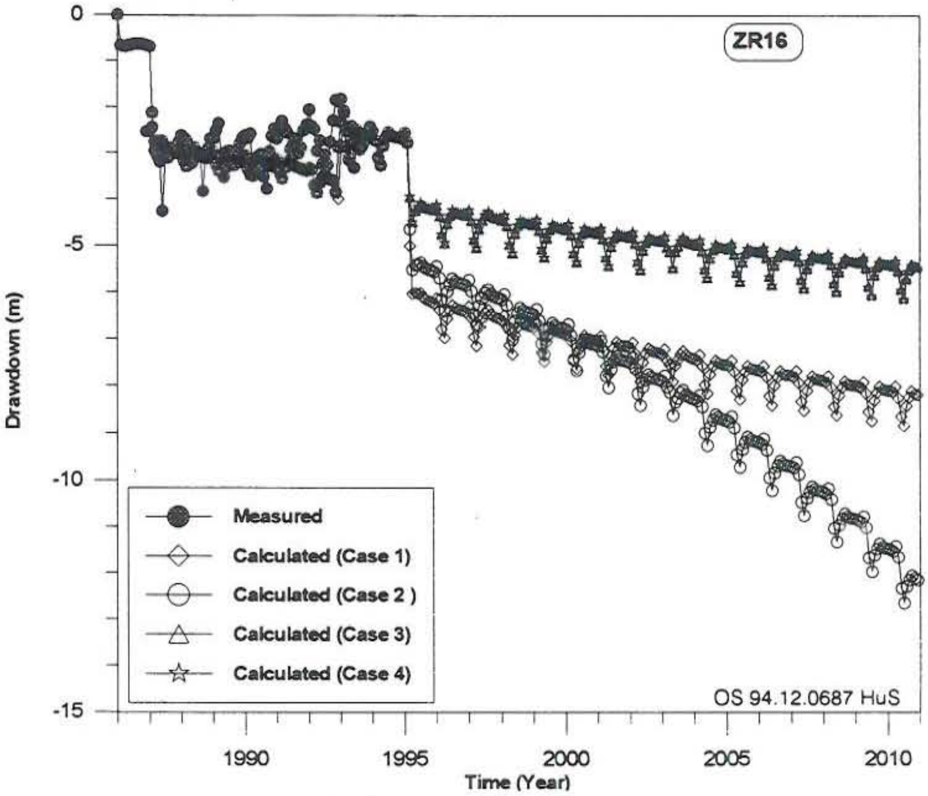

FIGURE 12: The predicted drawdown with time in well ZR16

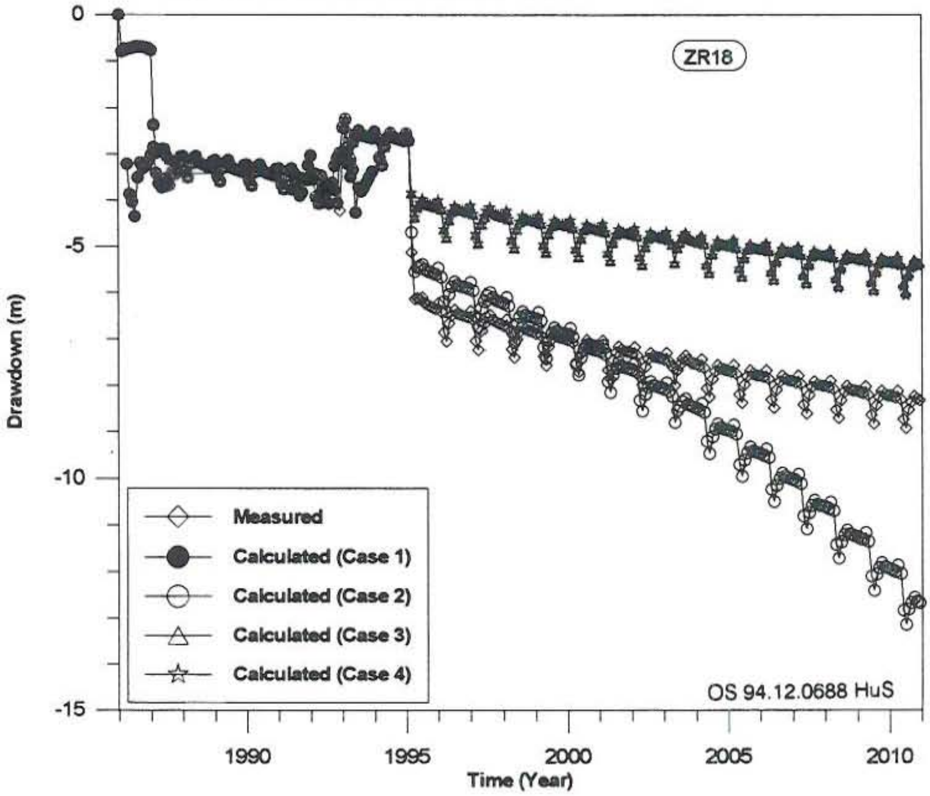

FIGURE 13: The predicted drawdown with time in well ZR18

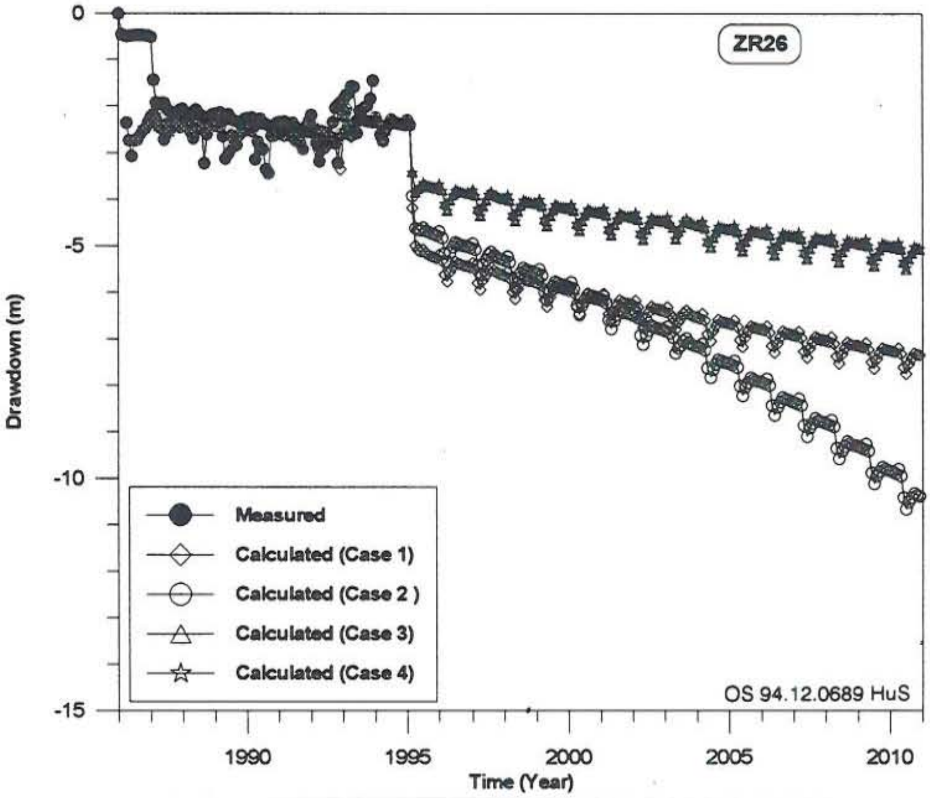

FIGURE 14: The predicted drawdown with time in well ZR26

### 4.2.2 Temperature

The predicted temperatures show some decline (<3°C) due to the production but obvious changes (as much as 10°C) occur in some areas owing to the injected water with a temperature of 80°C at the present thermal centre (Wuzhong central delivery thermal plant in Table 1) and 40°C at the planned new thermal plant A, respectively. The temperature distribution in the year 2010 (Figure 15) is quite similar to the present one (see Figure 3) except for the injection sites. The production area, has a lower temperature than the injection water. The temperature there is going to increase with time, and can increase as much as 10°C under the present and planned injection temperatures (Figure 16). For the recharge area with higher temperature, it will cool slightly down throughout the prediction time period (Figure 17). For the area outside the production area, the temperature will change very little.

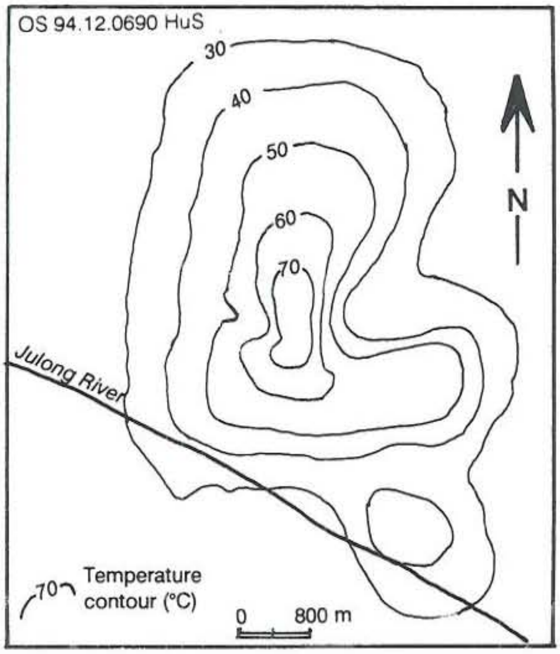

FIGURE 15: The predicted temperature in 2010 for case 4 (see Table 2)

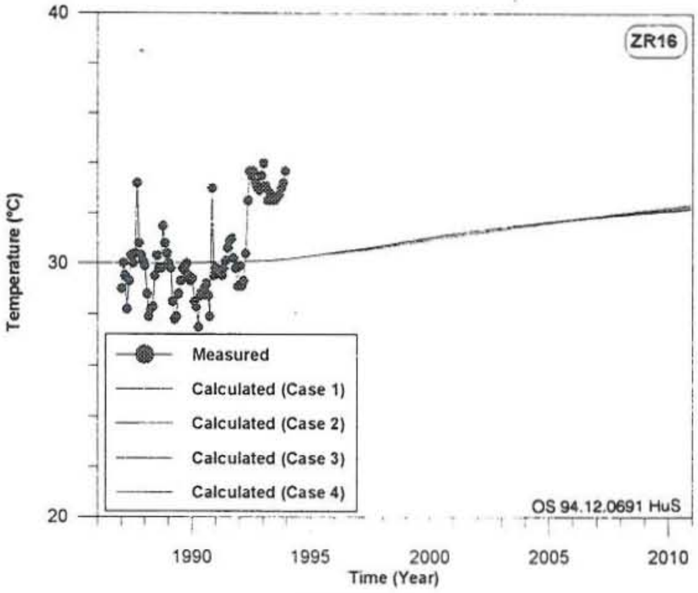

FIGURE 16: The predicted temperature with time in well ZR16

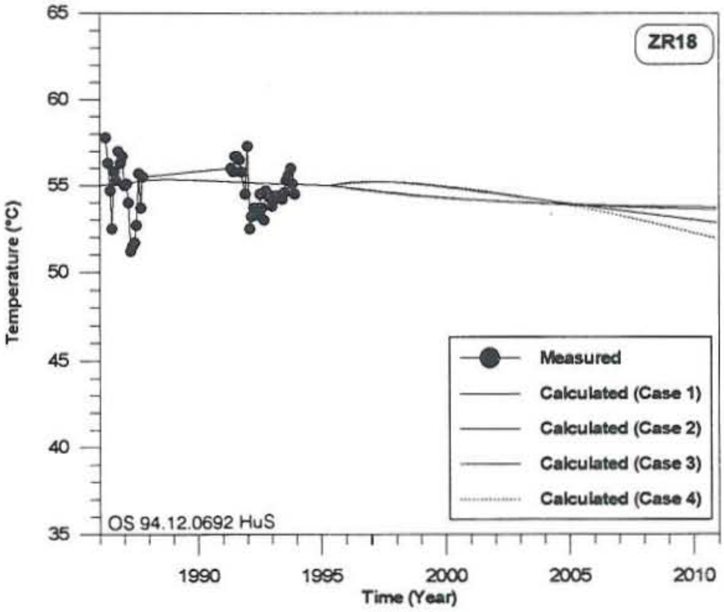

FIGURE 17: The predicted temperature with time in well ZR18

## 5. CONCLUSIONS AND RECOMMENDATIONS

The prime objective of this study was to create a model estimating the natural conditions of the Zhangzhou geothermal field. The reservoir model was calibrated using the water level and temperature observation data from monitoring wells, for the last 8 years. Based on the calibrated model, the predictions of both drawdown and temperature were made. Some preliminary conclusions and recommendation are:

1. The results of the calibration show that the transmissivity is much higher in the fractured zone than outside it. The good fit with the measured drawdown, using the equation for delayed yield, shows that the reservoir is controlled by two different storage mechanisms. At the start of production, storage is controlled by liquid/formation compressibility and later by the mobility of the free surface, the delay yield time constant is 2800 days.

2. The flow model indicates that the reservoir is under steady-state conditions with the present production and injection rates, but for the four calculated cases of the planned production, a steady-state condition in the reservoir cannot be reached in the year 2010. The drawdown in the year 2010 will be 13 m for case 2; 8 m for case 1 and 5 m for cases 3 and 4.

3. The transport model shows that the temperature pattern can be affected by both the reinjection and the production depending on the hydrogeological location. The greatest decline in temperature for case 2 is about 3°C in the recharge area. The temperature in the area near the injection well with higher injection temperature will increase as much as 10°C.

4. For long time development, reinjection is necessary so that the Quaternary aquifer will remain productive. With no reinjection, case 2 represents the maximum production rate (about 110 l/s in 2010) and case 1 shows the proper production rate to keep the Quaternary productive. The production can be increased if reinjection is going to be made. The most optimum geothermal development in Zhangzhou field is doublet production and reinjection, especially for the higher temperature fields in the downtown area.

5. The long-term monitoring work for the development of the Zhangzhou field must be continued, and a few of the production wells should be used for observation wells, but the monitoring frequency can be cut down to 1-2 times a month. The production rates for every well need to be recorded more accurately, which will affect the results of the modelling, especially the results of the prediction.

6. The geothermal reservoir engineering work should be included in any feasibility study for future development.

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