Report 4, 1992

NUMERICAL MODELLING OF THE BOTN LOW TEMPERATURE GEOTHERMAL FIELD, N-ICELAND

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ABSTRACT

A two-dimensional numerical model has been developed for the geothermal system at Botn, N-Iceland. This model simulates the measured data which includes water level, chemistry data and temperature during the last decade. The conceptual model in this report is based on geological investigation, geophysical surveys, borehole logging and well testing in this area. The reservoir performance in the model due to production is calculated and future predictions based on the calibration of the distributed parameter model are given. Temperature and water level predictions for different production rates are given for the next 20 years.

Botn is a low temperature geothermal field in the central northern part of Iceland. It is one of four geothermal fields utilized for space heating by the town of Akureyri (population 14,000). Two production wells, HN-10 and BN-1, have been drilled in the field in addition to a few exploration wells. Approximately 18 bars well head pressure was observed in the field prior to production. During the period 1981-1991, the average production rate from wells HN-10 and BN-1 was 24.9 and 5.3 l/s, respectively. As a result of production, initial drawdown of the water level occurred quickly in this field. The water level in HN-10 is now below 200 m depth. However, the calculated drawdown shows that in the production wells, the water level will remain in tact at a certain production rate. A powerful recharge system exists, therefore, which could either be from a ground water system or a deeper geothermal system or both. The temperature decline in this field shows that there are no production problems for the next 20 years with a 3°C temperature decline in the production wells. The mass transport calculations show that about 80% of the production fluid is from the deep aquifer and 20% from the upper aquifer when recharge temperatures of 95°C and 20°C are used respectively in the modelling for the recharge water.

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1. INTRODUCTION

The author of this report had the privilege of participating in the six months' training course of the UNU Geothermal Training Programme at the National Energy Authority in Reykjavik, Iceland in the summer of 1992. This programme began with 5 weeks of introductory lecture courses, followed by 4 weeks of special training in geothermal reservoir engineering. A field excursion and seminars were organized between 8-15 July 1992 and a practical research project was conducted in the last three months. Patrick Muffler from USA gave excellent lectures 7-11 September. The UNU fellows this year also had the honour of attending the International Conference on Industrial Uses of Geothermal Energy which was held 2-4 September at Hotel Saga in Reykjavik.

The main purpose of the last three months' research work was to obtain knowledge and skill in modelling low temperature geothermal reservoirs. The work included establishing a conceptual model according to geological, geophysical and well logging data. The calibration and prediction processes were performed by using the AQUA programme developed by Vatnaskil Consulting Engineers (1990). The author had the honour of being supervised by Dr. Snorri Pall Kjaran and Sigurdur Larus Holm from Vatnaskil Consulting Engineer (VCE).

2. MATHEMATICAL MODEL OF GROUNDWATER FLOW

2.1 Governing equations of reservoir behaviour

The general equations describing the single phase fluid flow, heat or mass dispersion in a porous media, can be directly derived through the use of the mass and heat conservation law and control volume method. However, in order to get solvable differential equations Darcy's law and Fick's law are added in mass and heat balance equations, respectively. Of course boundary conditions should be specified by selecting one of three types of boundary conditions for each boundary. The limitations or the validated improvement for both laws in some cases, such as nonlinear flow conditions, natural convection effects and so on will not be discussed here.

The basic assumptions for the equations in this report are

1) Single phase;
2) No chemical reaction between fluid and solid domain matrix;
3) Confined aquifer;
4) Natural convection is ignored;
5) Rock and fluid have the same temperature in an indefinitely small volume.

The three dimensional flow differential equations can be written as

$$\frac{\delta}{\delta x}(K_x \frac{\delta h}{\delta x}) + \frac{\delta}{\delta y}(K_y \frac{\delta h}{\delta y}) + \frac{\delta}{\delta z}(K_z \frac{\delta h}{\delta z}) = S_s \frac{\delta h}{\delta t} \tag{1}$$

where S_s is the specific storage coefficient which is defined as

$$S_s = \rho g(\alpha_p + \beta) \tag{2}$$

where b is the aquifer thickness, α_p and β are the solid matrix and water compressibility, respectively, g is the acceleration of gravity.

If we introduce the transmissivity into Equation 1 and assume the aquifer to be of constant thickness, and flow to be horizontal, Equation 1 becomes

$$\frac{\delta}{\delta x}(T_x \frac{\delta h}{\delta x}) + \frac{\delta}{\delta y}(T_y \frac{\delta h}{\delta y}) = S \frac{\delta h}{\delta t} \tag{3}$$

Generally, a confined aquifer has at least one semipermeable layer. This aquifer is called a leaky confined aquifer. If wells which are drilled in this main aquifer withdraw (or inject) fluid from this aquifer, vertical leakage both from the top and bottom semipermeable aquifers will happen.

Now let's define $\gamma = (k/m)(h_i - h)$ as a vertical leakage rate through the top or bottom of a semipermeable layer. Where h_i represents the initial water level of an aquifer above or below the main aquifer which is separated from them by semipermeable layers. If we consider both the leakage and a source or sink to be present in the main aquifer, Equation 3 can be written as

$$\frac{\delta}{\delta x}(T_x \frac{\delta h}{\delta x}) + \frac{\delta}{\delta y}(T_y \frac{\delta h}{\delta y}) + \gamma + Q = S \frac{\delta h}{\delta t} \tag{4}$$

The equation describing heat transport problems for the single phase in a confined aquifer is similar to that of the flow. It can be written as follows:

$$\frac{\delta}{\delta x}(bK_{xx}\frac{\delta T}{\delta x})+\frac{\delta}{\delta y}(bK_{yy}\frac{\delta T}{\delta y})-ub\frac{\delta T}{\delta x}-vb\frac{\delta T}{\delta y} = \varphi bR_h\frac{\delta T}{\delta t}-(T_o-T)\gamma-(T_w-T)Q \tag{5}$$

On the left hand side of the equation above, the first two terms are heat conduction terms. The last two terms are convective transport terms. The last two terms on the right hand side of the equation above represent the heat loss (or gain) due to the cold (hot) water flow into the main aquifer from the upper and/or bottom layer and from injection wells.

The equation for mass transport is almost the same as that for heat transport. It is as follows:

$$\frac{\delta}{\delta x}(\varphi bD_{xx}\frac{\delta D}{\delta x})+\frac{\delta}{\delta y}(\varphi bD_{yy}\frac{\delta D}{\delta y})-ub\frac{\delta C}{\delta x}-vb\frac{\delta C}{\delta y}$$

$$= \varphi bR_d\frac{\delta C}{\delta t}-\varphi bR_d\lambda C-(C_o-C)\gamma-(C_w-C)Q \tag{6}$$

The difference between Equation 5 and 6 is that concentration decay has to be considered in some cases, represented by the terms of $\varphi bR_d\lambda C$ on the right hand side of the equation.

A general differential equation describing Equations 4, 5 and 6 can be written as

$$a\frac{\delta u}{\delta t}+b_i\frac{\delta u}{\delta x_i}+\frac{\delta}{\delta x_i}(e_{ij}\frac{\delta u}{\delta x_j})+fu+g = 0 \tag{7}$$

The symbol u can indicate velocity, temperature or concentration of the fluid in the aquifer. The indices i and j indicate the x and y coordinate axes.

2.2 A brief review of low temperature geothermal reservoir modelling

Geothermal reservoir modelling is a relatively new discipline. However, the theories and methods being used can be traced back to the last century. There are some difficulties in high temperature geothermal reservoir modelling as it is associated with two phase flow in a porous media, one of the main research projects in heat transfer engineering discipline. For low temperature reservoir modelling, most of the methods can be directly transferred from groundwater and petroleum reservoir modelling. With more powerful, high speed computers widely available, calculations which were hard to reach in the past, can be finished by computers within a limited time (Kjaran and Eliasson, 1983).

A lumped parameter model is the simplest method in reservoir modelling. In lumped parameter modelling the reservoir is treated as one element with some average properties. Of primary interest in such modelling is the reservoir production mechanism as a whole. It can be used both in high and low temperature geothermal reservoirs (Gudmundsson and Thorhallsson, 1986; Axelsson and Bjornsson, 1992). It is especially suitable for low temperature geothermal fields. However, it cannot give any information about the properties of rock or fluid locally.

With the aid of a computer a detailed distributed parameter model can overcome the disadvantages of the lump parameter model. In this case, small blocks or elements with different properties can be given, so that temperature or enthalpy, water level or pressure in different elements and their changes with time can be obtained (Bodvarsson and Witherspoon, 1989).

There are no mathematical difficulties in solving the differential equations. A stable and convergent solution can be achieved if a rational matrix format is established, and initial values and iteration time step have been decided upon. Finite element and finite difference methods are commonly used.

2.3 The main functions of the AQUA program

Equation 7 is solved by the Galerkin finite element method in the AQUA program. AQUA is a program package developed by Vatnaskil Consulting Engineers (1990) to solve groundwater flow and transport problems using both FORTRAN and "C" computer language. Definition of the parameters in Equation 6 is given in Table 1.

TABLE 1: Symbol definition of Equation 6 in different models

Models	u	e_{ij}	f	g	a	b_i
Flow in confined aquifer	h	T_{ij} (T_{xx} and T_{yy})	0	$Q+(k/m)h_o$	$-S$	0
Heat transport	T	$-bK_{ij}$ (K_{xx} and K_{yy})	$\gamma+Q$	$-\gamma T_o-QT_w$	φbR_h	V_ib
Mass transport	C	$-\varphi bD_{ij}$ (D_{xx} and D_{yy})	$\varphi bR_d\lambda+\gamma+Q$	$-\gamma C_o-QC_w$	φbR_d	V_ib

2.3.1 Input and output menus

The AQUA program package includes various graphical preprocessors which can generate data input and result output very easily. Before running, an AQUA nodal file and boundary condition file have to be inputted. There are five options in the main menu. They are: edit input data; run model; view output; utilities and <ESC> to DOS system. Selecting an option from the main menu leads to similar submenus, selection from which leads to some programs being executed. The areal parameter data, such as transmissivity, leakage coefficient, storage coefficient in each element, source/sink data, initial value at each node and so on, can be entered by following the input data menu. The output file includes areal data distribution files such as contour line, time series output files such as waterlevel or temperature changing with time. Both input data and output data can be viewed graphically.

2.3.2 Flow and mass transport

The AQUA program can solve the transient flow as well as the transport of mass. Generally it is very useful for calculating certain chemical components which can show certain field characteristics. Modelling of undesirable chemicals can be used for monitoring the pollution of groundwater and so on.

Heat transport modelling can be modelled similarly to the mass transport. Temperature instead of chemical concentration is the main variable, initial temperature, vertical leakage flow and temperature should be given.

3. MODELLING OF THE BOTN LOW TEMPERATURE FIELD, N-ICELAND

3.1 The main features of the Botn geothermal field

3.1.1 Locality

The Botn geothermal field is located in Central North Iceland, about 15 km to the south of the town Akureyri (population 14,000). It is one of four geothermal fields utilized for space heating by the town. The elevation of the field is about 25 m above sea level, high in the west and low in the east (Figure 1).

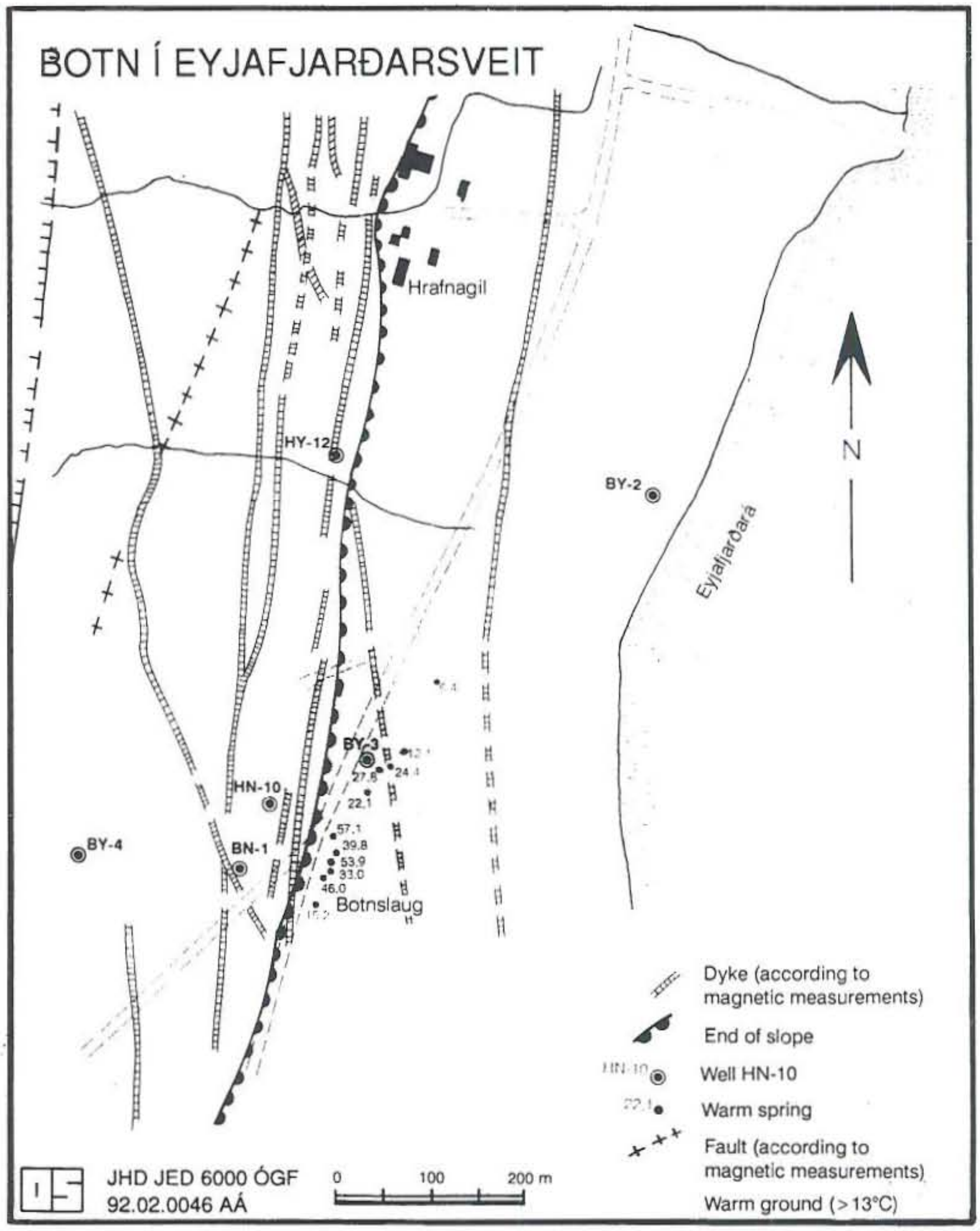

FIGURE 1: The Botn geothermal field, location of vertical structures and wells (Axelsson and Bjornsson, 1992)

3.1.2 Geology

The main types of rock in the Botn geothermal field are Tertiary basaltic piles and sediments. There is one dyke trending NE-SW which seems to be a main flow path connected with four main fractures trending N-S. A hard impermeable boundary is located in the western part of the field, in southwesterly to northeasterly direction. There were some hot springs close to the dyke before exploitation of the field. However, they disappeared soon after production began in 1981.

3.1.3 Geophysics

The ground electrical resistivity measurement was conducted in that area. An area with 40 Ωm resistivity was delineated. It seems to coincide with the location and direction of the dyke (Flovenz et al., 1991).

3.1.4 Production history

Two production wells HN10 and BN01 began producing in January and November 1981, respectively. The main producer is HN10 with an approximately constant flow rate of 24.9 l/s from an aquifer below 200 m depth. The main feed zones are as follows (depth, temperature): 200 m, 71°C; 400 m, 82°C; 800 m, 90°C; 1000 m, 92°C. Another production well BN01 has about 5.5 l/s average production rate. The main feed zones for BN01 are as follows: 30 m, 40°C; 90 m, 55°C; 240 m, 70°C; 600 m, 85°C; 1500 m, 100°C. The well data is shown in Table 2.

TABLE 2: Botn geothermal field, well parameters

Well no.	Date of completion	Elevation (m a.s.l.)	Depth (m)	Production casing length/diameter (m/m)	Note
BN01	Dec.'81	23.2	1830	28/0.25	production well
BY-2	Dec.'89	5.6	446	103/0.18	observation well
BY-3	Oct.'89	6.6	300	41/0.22	observation well
BY-4	Dec.'89	66.1	403	8/0.22	observation well
HN10	Nov.'80	22.4	1050	456/0.3	production well
HY12	Dec.'89	28.6	318	5/0.22	observation well

The production history of well HN10 and BN01 can also be seen in Figure 2 and Figure 3, respectively.

3.2 Calibration of aquifer parameters using AQUA

3.2.1 The model set-up

A 10×2 km^2 rectangular area is established for the computer modelling. The dyke is located in the middle of the area and parallel to the long sides of the rectangular block. A closed impermeable boundary is given along the four sides of the block. There are 1382 elements connected by 752 nodes in the area, which are dense around the dyke and wells and with a uniform scarce distribution further away. The drawdown measurements from four observation wells and one production well HN10 are used for calibration (Figures 2 and 3).

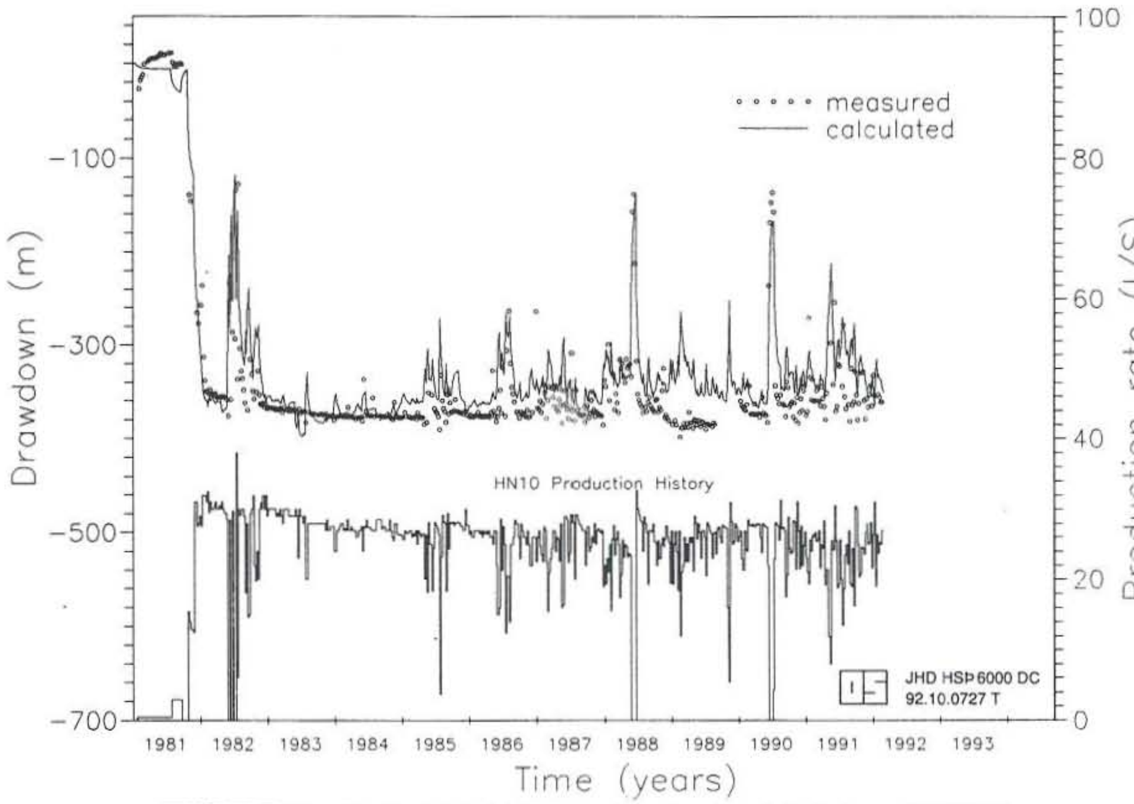

FIGURE 2: Production history and water level data in well HN10

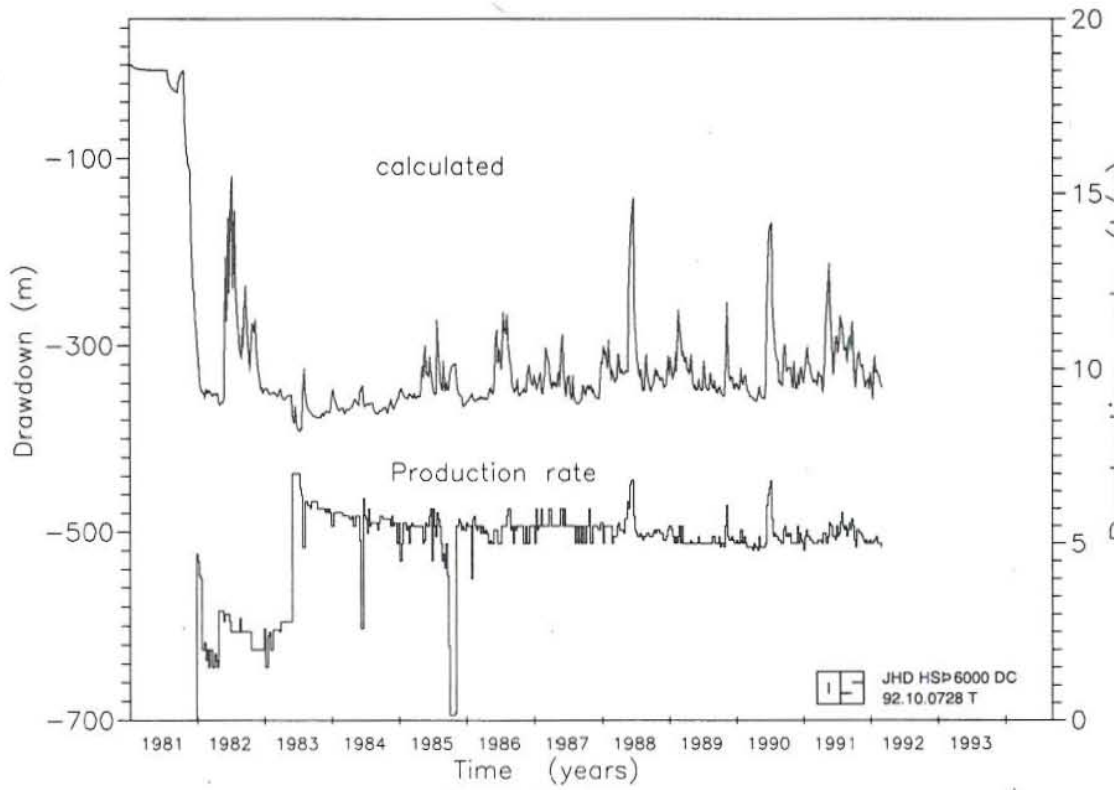

FIGURE 3: Production history and water level data in well BN01

A constant initial water level (elevation for each well is considered) was assumed in the whole area prior to production. A 17 bars well head pressure (170 m water level) is given in production well HN10 as the initial value.

3.2.2 Flow problem

In order to fit calculated and measured time series of water level, temperature and some concentration of dissolved solids in both production and observation wells, different hydrological and thermal parameters should be given in each element according to geological features. So the modelling process itself is also to be considered as a process to confirm the geological setting and the results of the geophysical surveys.

The final parameters which gave the best match between observed and calculated values are as follows:

Transmissivity	*from* 1.2×10^{-13} *to* 3.36×10^{-3} (Figure 4)
Storage coefficient	*from* 9.3×10^{-07} *to* 3.1×10^{-3}
Leakage coefficient	*from* 0.0 *to* 1.01×10^{-8} (Figure 5)
Porosity	*10%*
Thickness of aquifer	*600 m*
Multiplier for $sqrt(T_{yy}/T_{xx})$	*0.3162*

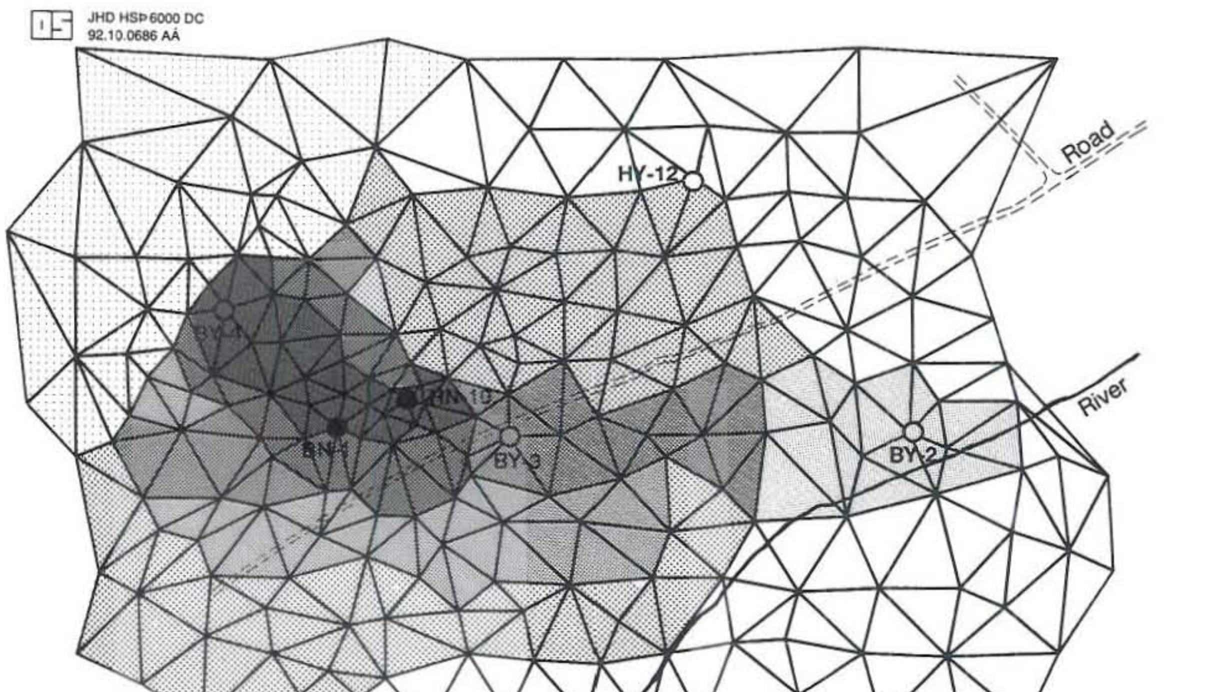

FIGURE 4: Map of transmissivity in the Botn geothermal field

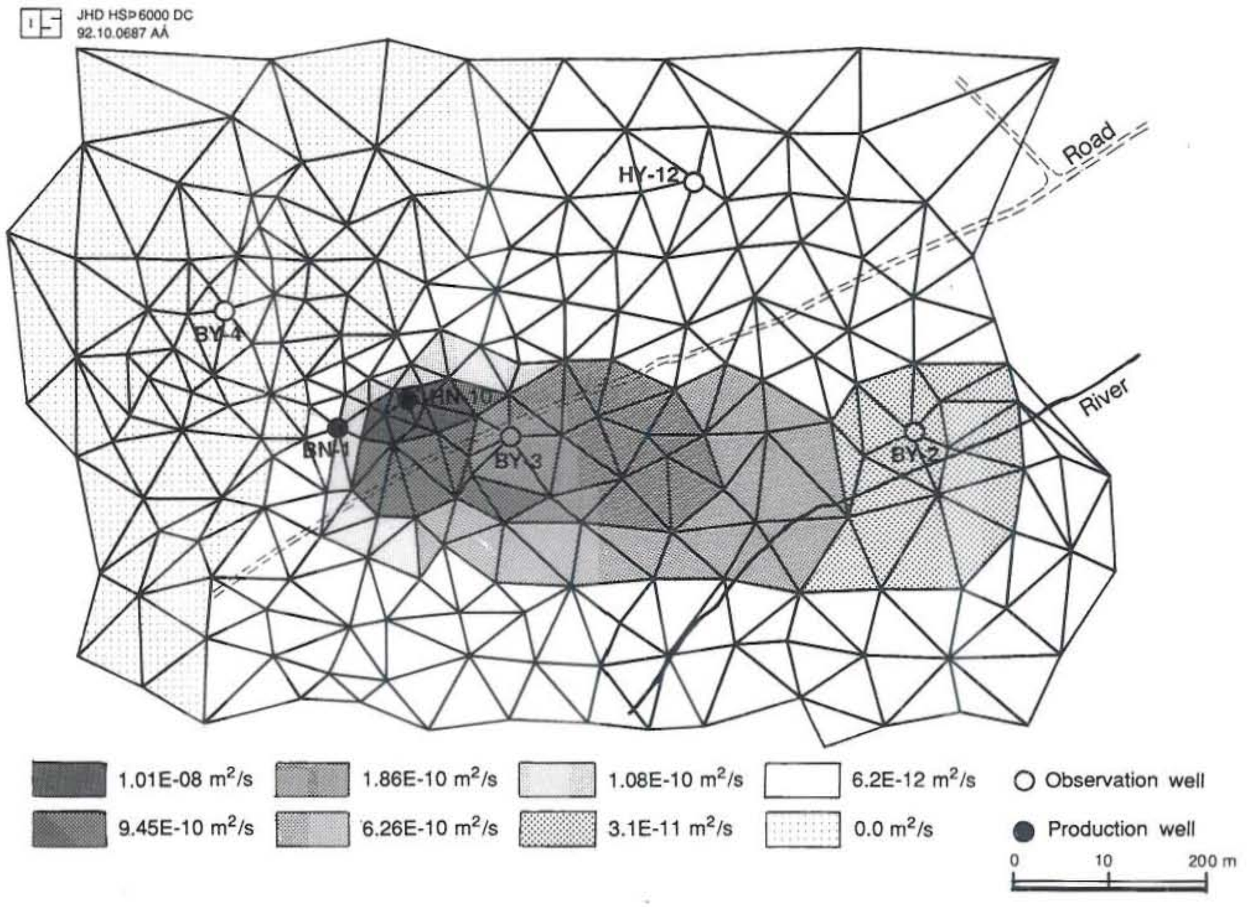

FIGURE 5: Map of leakage coefficient in the Botn geothermal field

The highest values of transmissivity cover the area of the dyke and somewhere between the production wells and observation well BY-4, gradually decreasing towards the boundary far away. The lowest values of transmissivity are distributed along an impermeable boundary just to the west of well BY-4 in a NE-SW direction.

The highest leakage values are given in a area which includes the production wells. Relatively high leakage values are given along the dyke which covers the area of hot spring manifestation prior to exploitation of the field. Apart from the two areas above, zero leakage coefficient is given globally. The comparison between measured and calculated values can be seen in Figures 2, 3 and 6. The contours of the drawdown in 1991 (Figure 7, 4000 days after January 1, 1981) are like a series of elliptical curves, with the northwest part of these lines cut off by the impermeable boundary. The resulting drawdown along the dyke is given in Figure 8.

The elevation of the downhole pump in well HN10 is -246 m. This means that if the drawdown in well HN10 is more than 416 m (i.e. 246+170 m), the pump has to be lowered. This figure does not include the turbulence effects on the production well. Generally, the drawdown in a production well is not linear with the flowrate; rather it increases with the square of the flowrate according to a turbulence coefficient. This turbulence coefficient is measured in a well test. In this case, the turbulence coefficient is about 0.025 $m/(l/s)^2$. If the turbulence effect is taken into account, the flowrate in well HN10 should not exceed 28.5 l/s. If the production in well HN10 is increased 1%, 2% or 3% yearly, the water level in well HN10 will decrease faster and faster, as shown in Figure 9. However, the pump can be operated safely for 31, 21, 17 years respectively without lowering.

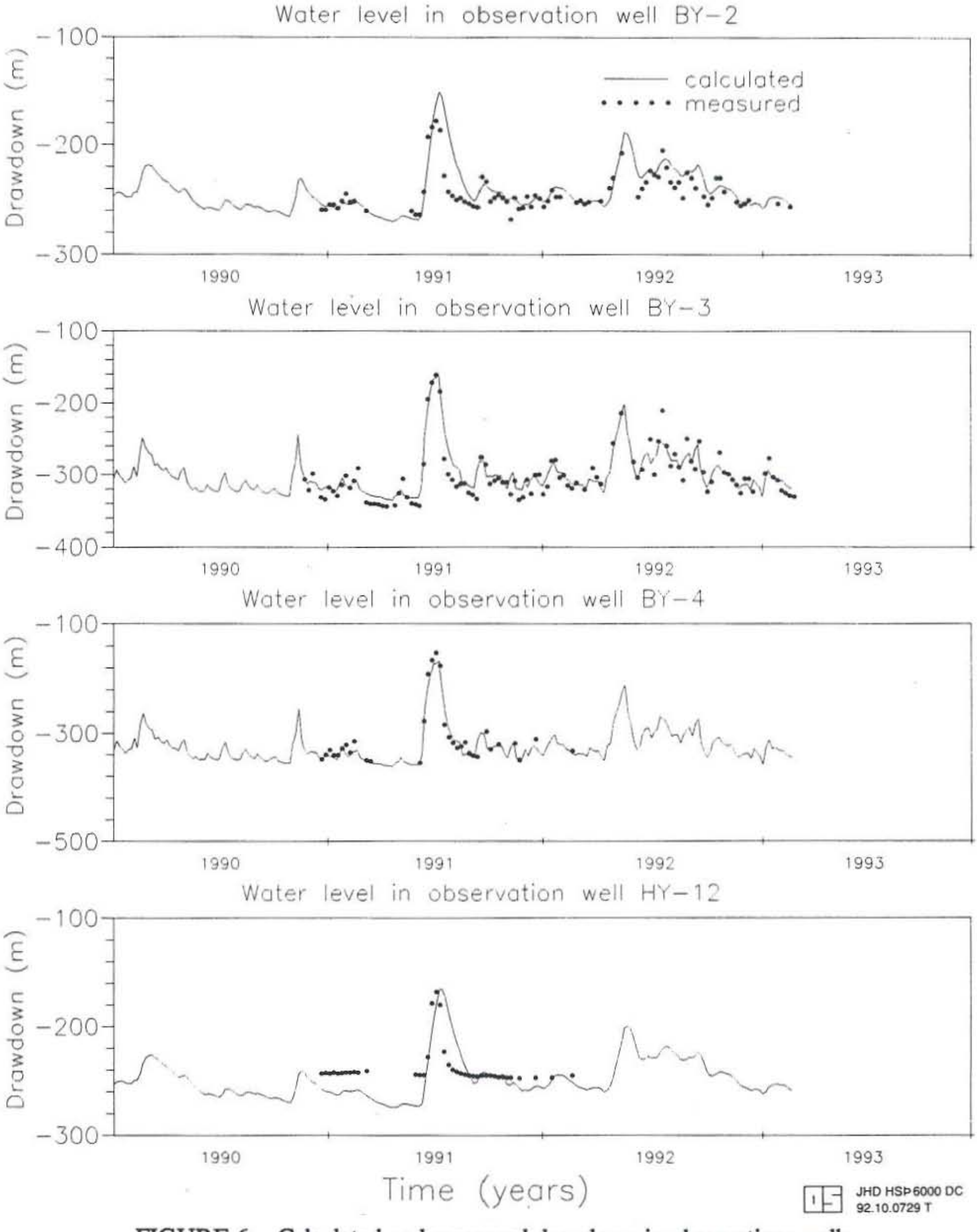

FIGURE 6: Calculated and measured drawdown in observations wells

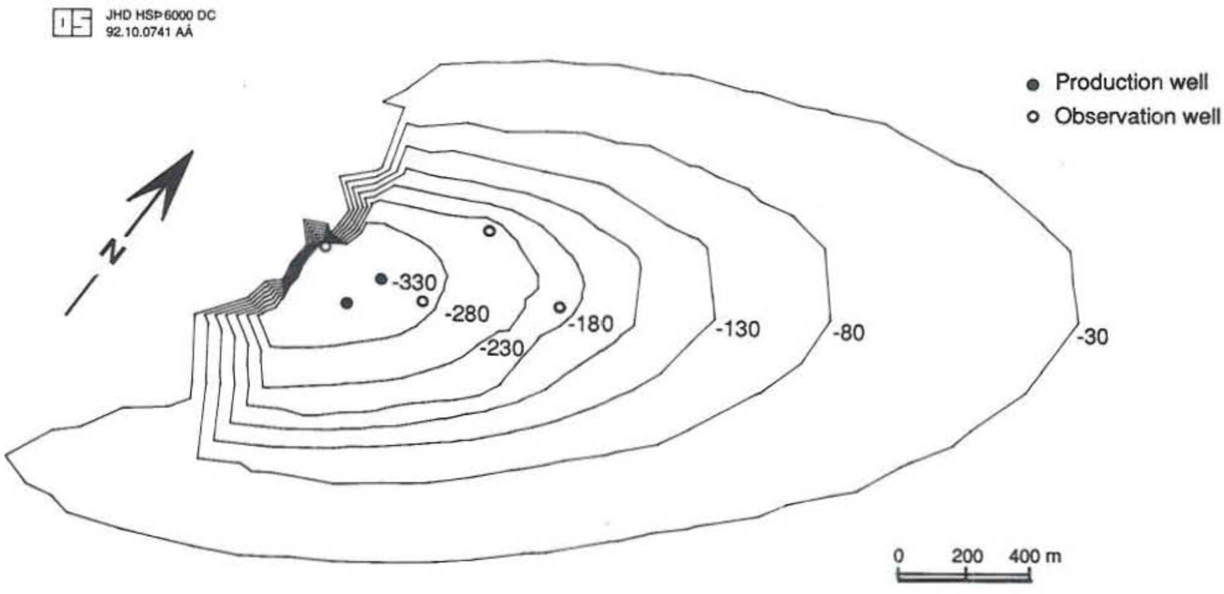

FIGURE 7: The Botn field, map of calculated drawdown in m, in 1991

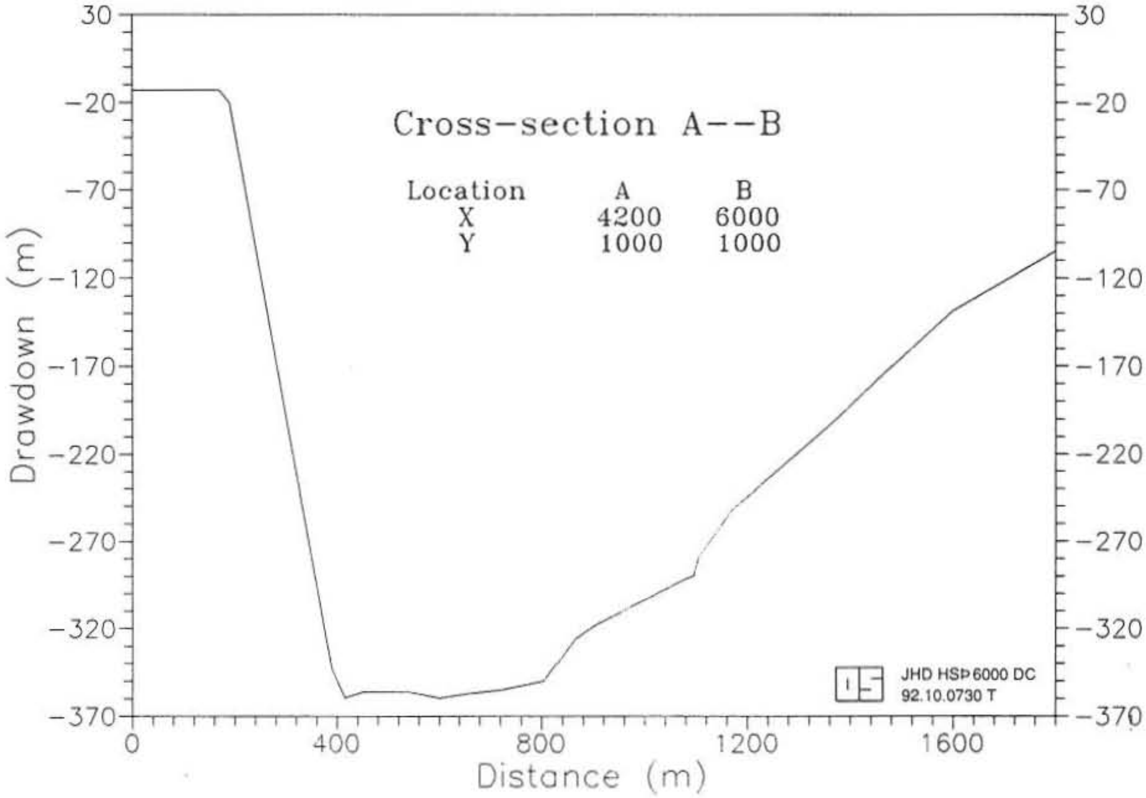

FIGURE 8: Cross-section of drawdown in m along the dyke at the Botn field in 1991

3.2.3 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 fixed. According to the results of logging of the two production wells, these parameters are given as follows:

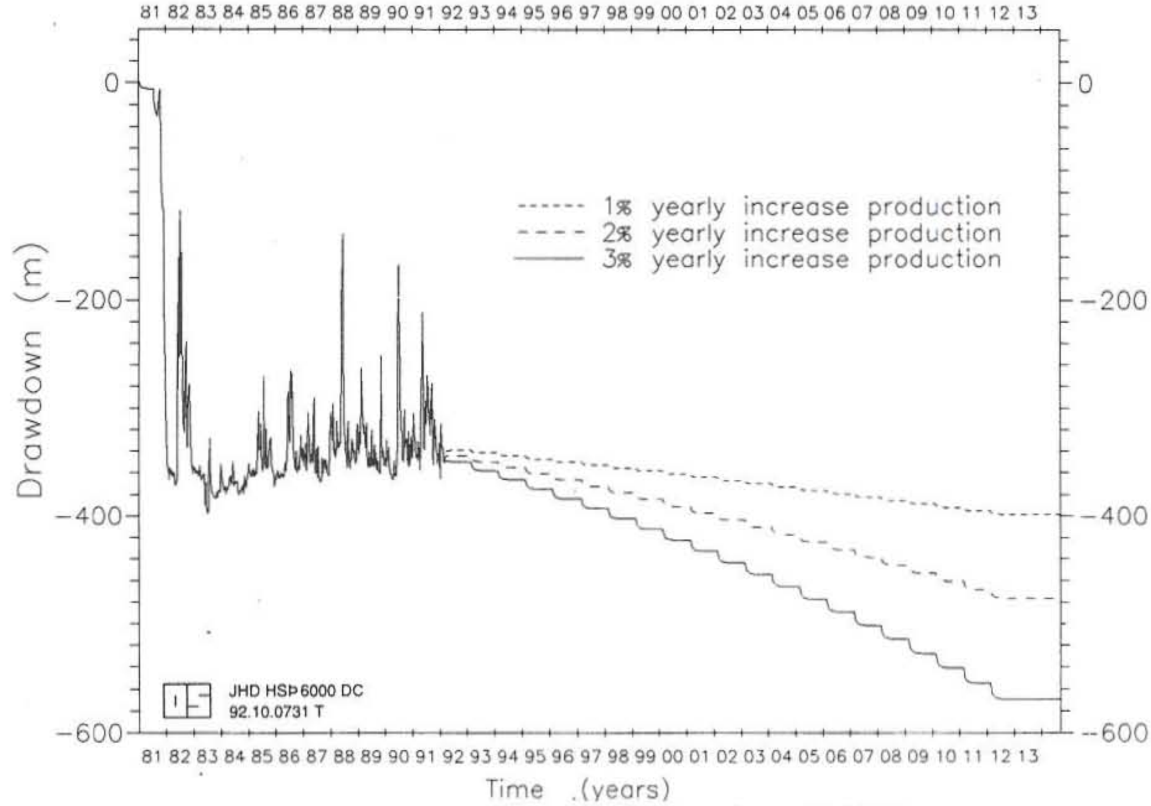

FIGURE 9: Drawdown predictions in well HN10 for 1%, 2% and 3% yearly increase of production

Initial temperature	*89°C*
Longitudinal dispersivity (aL)	*50 m*
Temperature of vertical inflow	*78°C*
Multiplier for sqrt(aT/aL)	*0.316*
Retardation constant	*0.200*
Aquifer thickness	*600 m*

The retardation constant is the ratio of the heat capacity of the rock to that of the water. The results of the temperature calibration are shown in Figure 10. The temperature predictions at different production rates have been estimated. Results show that different production rates can only lead to a slight temperature decline. It will be less than 0.13°C if the production remains at the average rate of the last ten years. However, if water (20°C) is injected into wells BY-4 and BY-2 separately or simultaneously, the temperature in the production wells will decline much faster. Injecting water into BY-2 and BY-4, respectively, will lead to about 7°C and 10°C temperature decline after 10 years at the same constant production rate, as shown in Figure 11.

According to the temperature calculations, the fractions of inflow into the aquifer from the top groundwater system and the bottom recharge system can be estimated. If we assume that the groundwater is 20°C and the hot water recharge from the bottom is 95°C, it will be about 80% from the bottom and 20% from the top. These fractions are used in the mass transport modelling below.

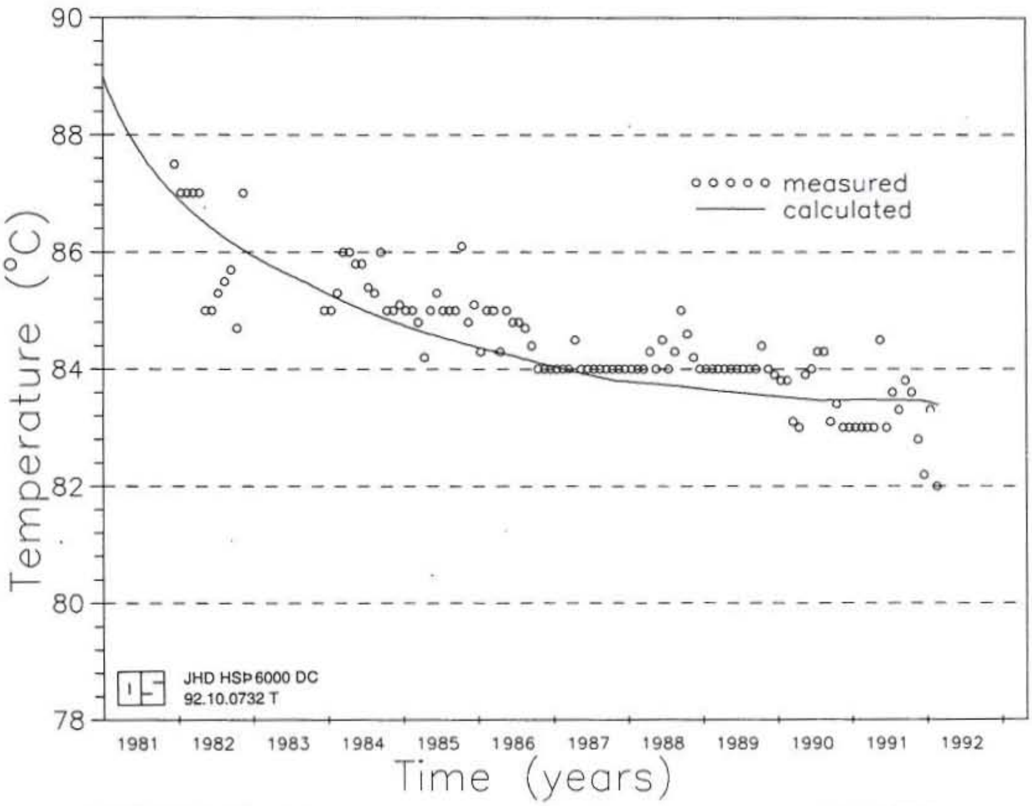

FIGURE 10: Measured and calculated temperature in well HN10

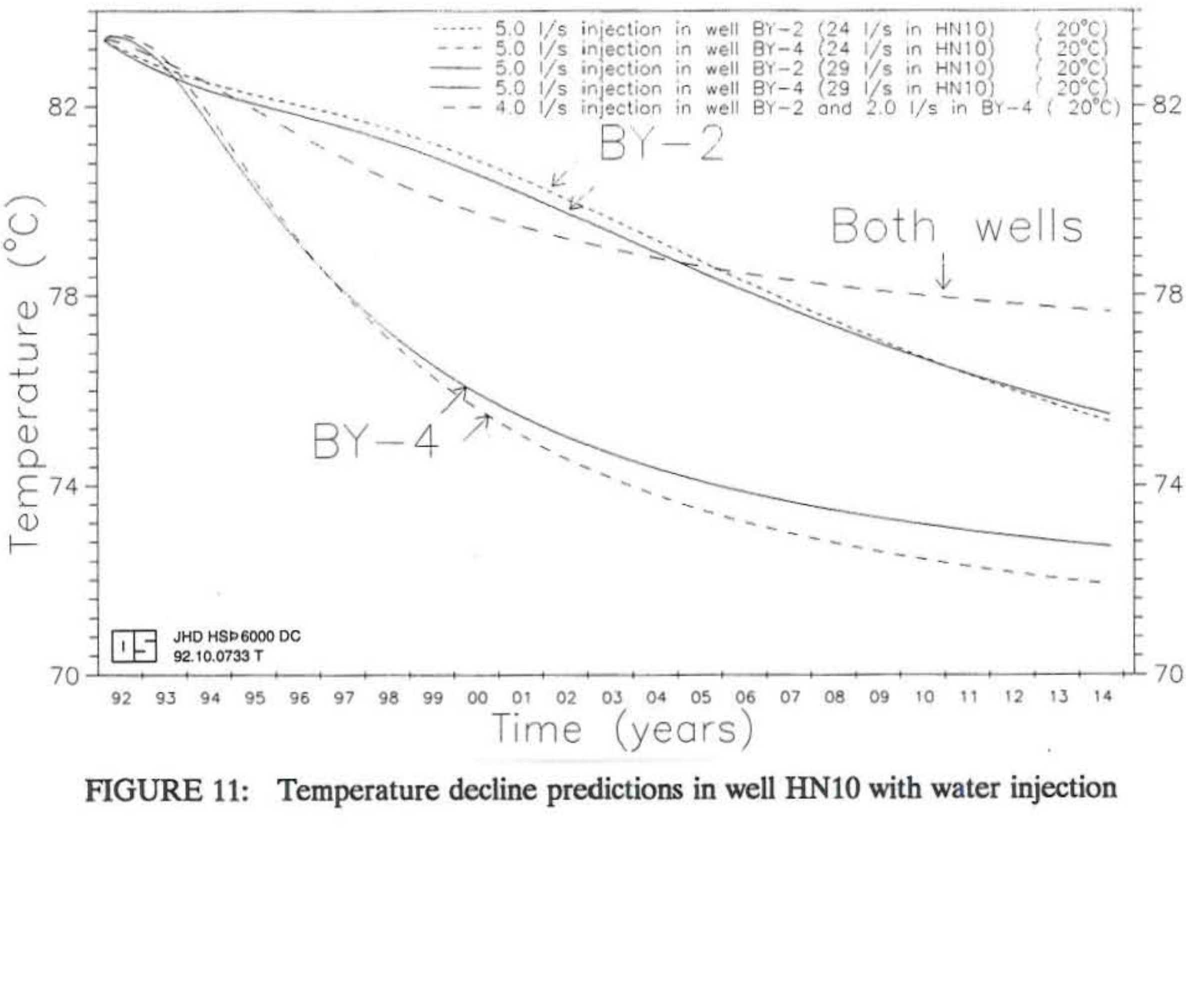

FIGURE 11: Temperature decline predictions in well HN10 with water injection

3.2.4 Mass transport

Silica and fluoride concentration in well HN10 are calculated as shown in Figure 12 and 13. The parameters that gave the best fit between calculated and measured values are as follows:

	Silica	Fluoride
Initial concentration (mg/kg)	*100*	*0.74*
Vertical inflow concentration (mg/kg)	*74*	*0.45*
Groundwater inflow concentration (mg/kg)	*20*	*0.0*

If the same fractions for the vertical inflow are used here as in the temperature simulation, the concentration of silica and fluoride from the bottom can be obtained. The silica and fluoride concentrations from the bottom are 87.5 mg/kg and 0.56 mg/kg, respectively, and are about the same as the stable concentrations of well BN01 which was drilled deep within the aquifer.

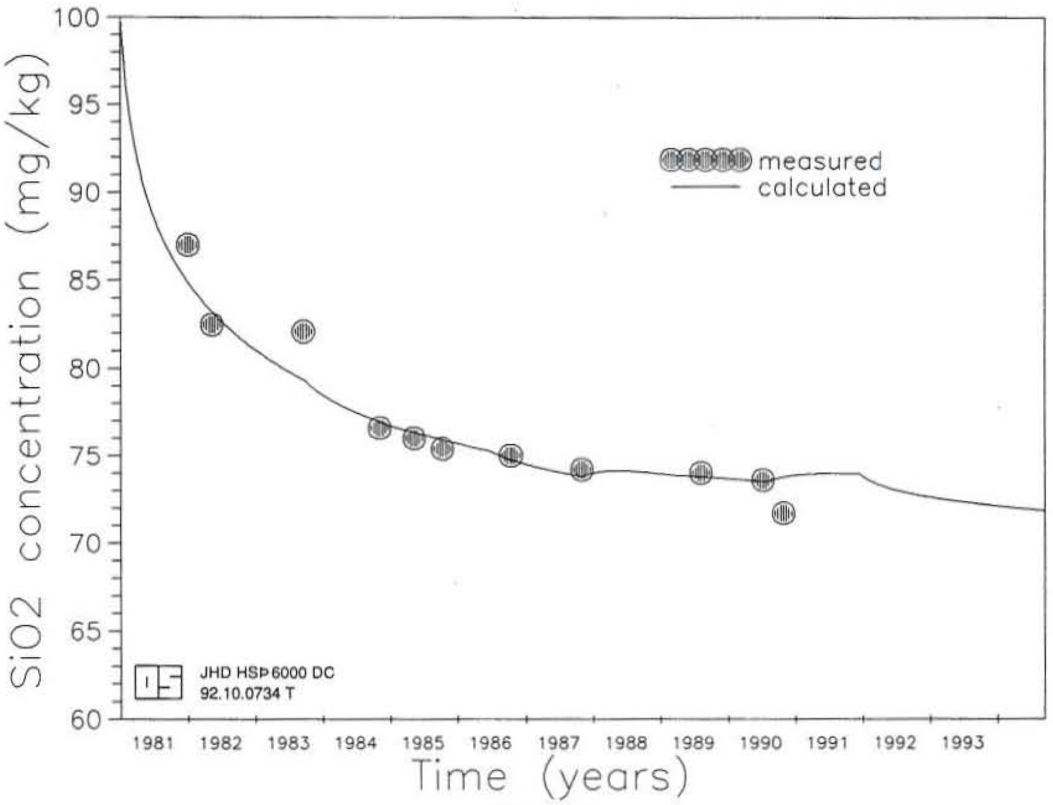

FIGURE 12: Silica concentration in well HN10

3.2.5 Future predictions

The future behaviour of a reservoir is more important than the calibration period itself. Waterlevel and temperature trends over the next 20 years are predicted based on the final, best fitted model in the field. This cannot only be used for forecasting the behaviour of the reservoir, but also for prevention of negative results due to any blind exploitation.

Some future predictions have been shown in Figure 9 and Figure 11. The water level in well HN10 at different production rates with and without injection is shown in Figures 14 and 15.

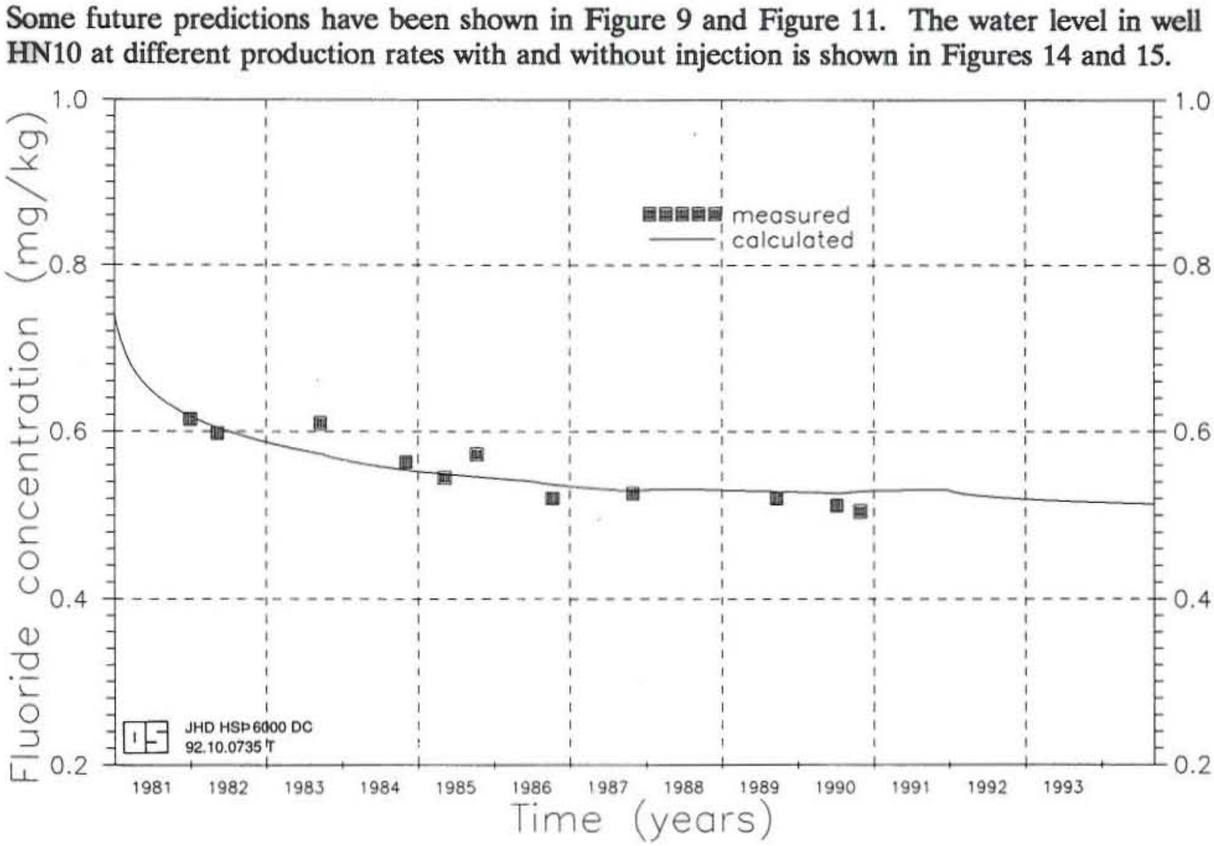

FIGURE 13: Fluoride concentration in well HN10

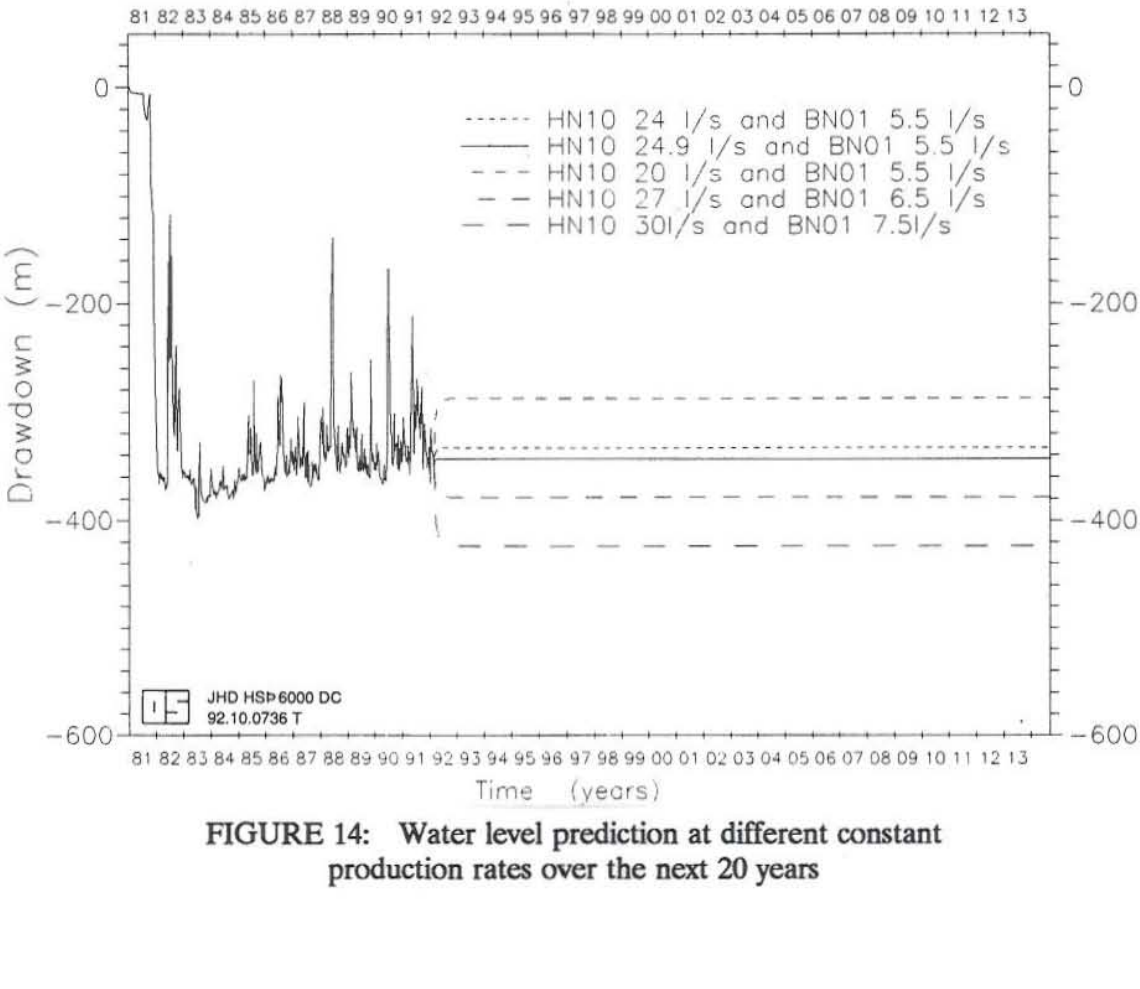

FIGURE 14: Water level prediction at different constant production rates over the next 20 years

Further predictions of temperature at different constant production rates are shown in Figure 16. The temperature contour lines in the year 2013 are shown in Figures 17 and 18 with injection in

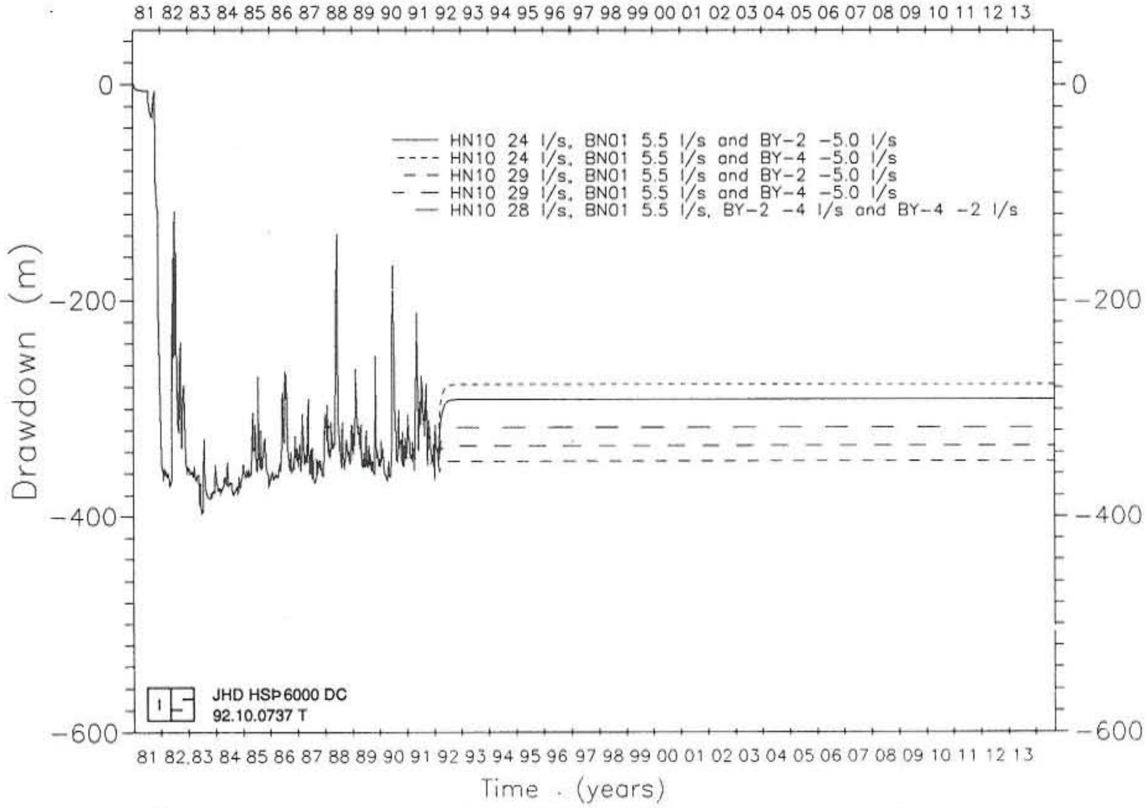

FIGURE 15: Water level prediction at different constant production rates with injection in well HN10

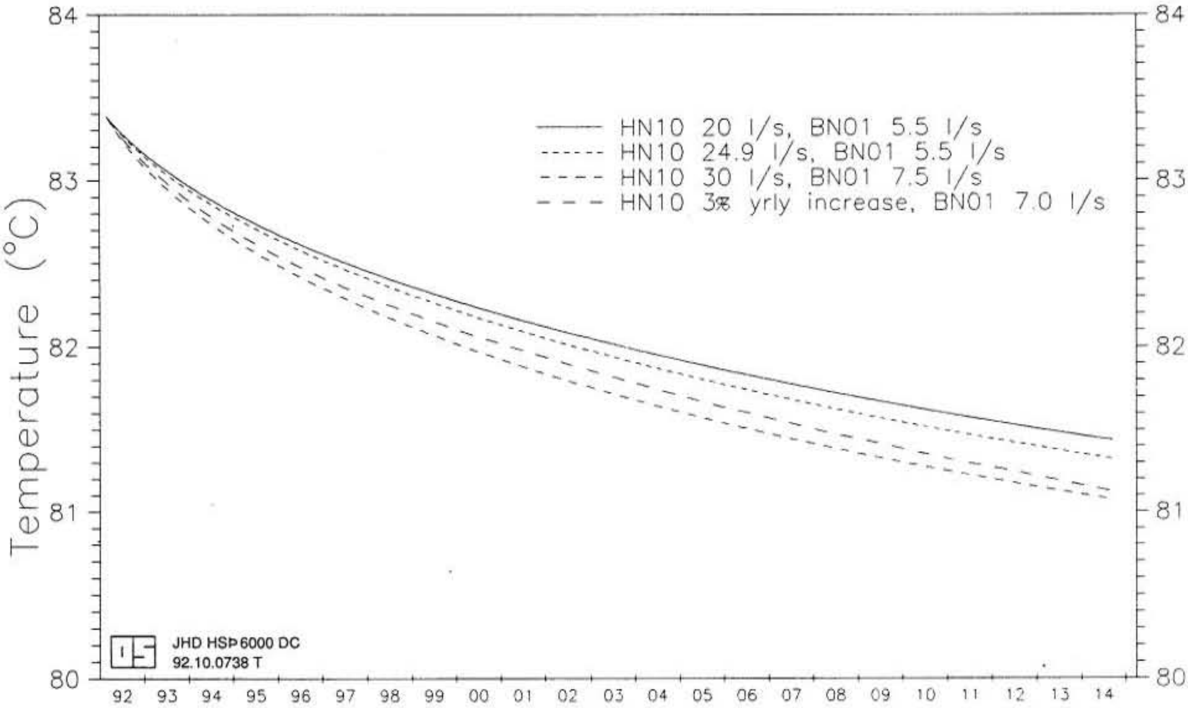

FIGURE 16: Temperature prediction at different constant production rates in well HN10 until the year 2013

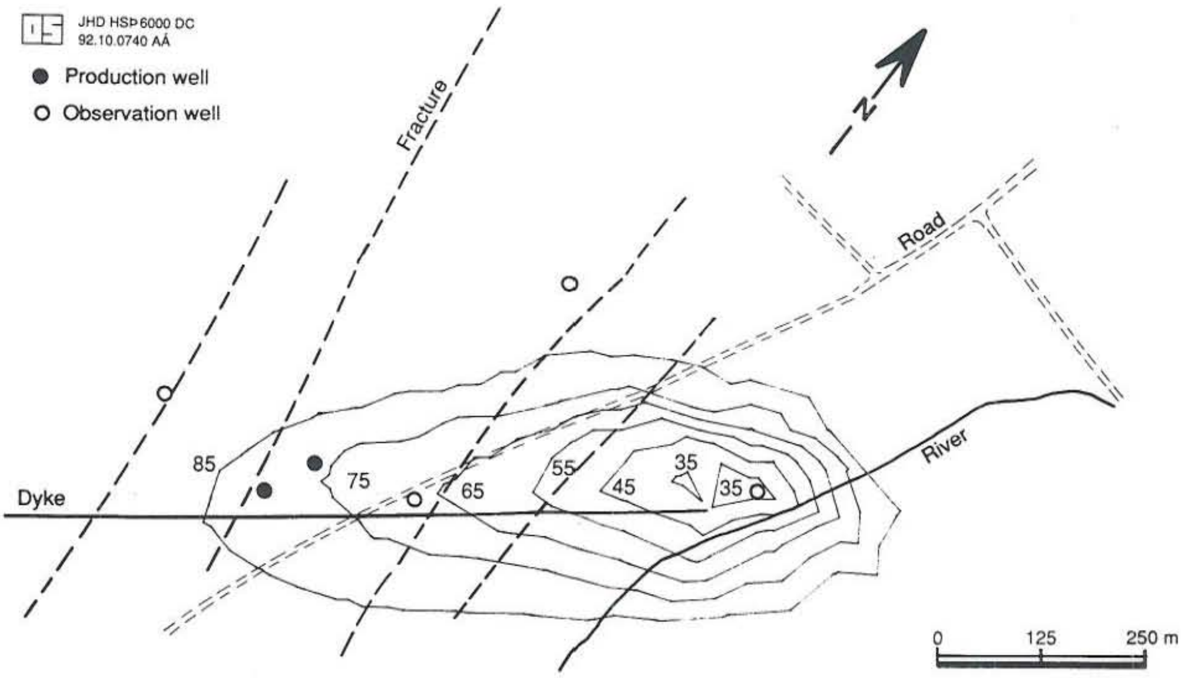

FIGURE 17: Predicted temperature contour lines (°C) in the year 2013 with injection in well BY-2

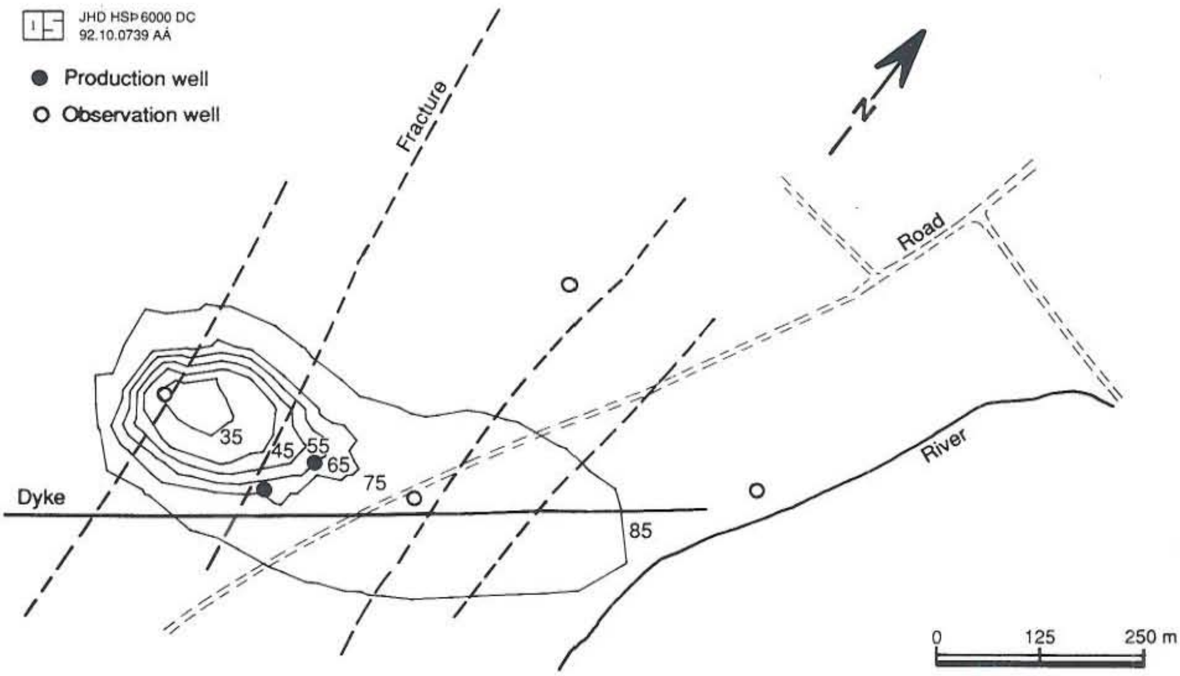

FIGURE 18: Predicted temperature contour lines (°C) in the year 2013 with injection in well BY-4

wells BY-2 and BY-4, respectively. There, the isothermal lines represent the constant temperature curves from 85°C to 25°C with 10°C intervals. The lowest temperature is observed in the middle of the area, and the highest at the boundaries.

4. CONCLUSIONS

Both temperature and waterlevel in the Botn geothermal field will face no problems in the next 20 years, if the present production situation is maintained. It seems there is a quite large recharge system for the Botn field. Any constant production rate changes will result in a constant drawdown after about 250 days. The production rate cannot exceed 28.5 l/s in well HN10 (BN01 7.0 l/s), otherwise the downhole pump would need to be lowered. There is an observable temperature decline over the next 20 years at constant production rates. However, great care must be taken when injection has to be considered. Due to the good connection between the production wells and observation wells BY-4 and BY-2 which are located at the end of the dyke, a better location of an injection well is further north or south of the dyke. Injection from two wells is better than from one, as heat can be extracted from a relative large area, leading to a smaller temperature drawdown in the reservoir.

ACKNOWLEDGEMENTS

I am very grateful to Dr. Snorri Pall Kjaran for his help and guidance and Sigurdur Larus Holm for his patient and detailed assistance in acquainting me with the AQUA program during the study and formulation of the final report.

Special thanks are due to Dr. Ingvar B. Fridleifsson for giving me the chance to attend the UNU Geothermal Training Programme. Also great thanks to Ludvik S. Georgsson for his careful editing and revising my field excursion report, final project report and providing me with a powerful computer for running AQUA.

I am very appreciative to everyone who gave me help, guidance and advice during the six months in Iceland. Thanks to all the lecturers and staff in Orkustofnun. I would especially like to thank Grimur Bjornsson and Gudni Axelsson for helping me with the Botn field modelling, Sverrir Thorhallsson for his generous help and Mrs Audur Agustsdottir in the drawing office for drawing my figures.

I also wish to extend my gratitude to the government of Iceland and the United Nations University for the fellowship.

I would like to thank Prof. Cai Yihan, director of Tianjin Geothermal Research and Training Centre for allowing me to attend the course. Finally, thanks to my wife Meng Yingtao for her comprehension and spiritual support during the whole period.

NOMENCLATURE

a_L	- longitudinal dispersivity (m)
a_T	- transversal dispersivity (m)
b	- aquifer thickness (m)
c	- solute concentration (kg/m^3)
c_0	- concentration of vertical inflow (kg/m^3)
c_w	- concentration of injected water (kg/m^3)
D_m	- molecular diffusivity (m^2/s)
D_h	- heat diffusivity (m^2/s)
K_{xx}	- permeability in the x direction
K_{yy}	- permeability in the y direction
K_{zz}	- permeability in the z direction
m	- aquifer thickness (m)
Q	- flowrate of production or injection well (m^3/s)
S_s	- specific storage coefficient
S	- storage coefficient
T_{xx}	- transmissivity in the x direction
T_{yy}	- transmissivity in the y direction
T_{zz}	- transmissivity in the z direction
T	- temperature (°C)
T_0	- temperature of vertical inflow (°C)
V	- velocity taken from the solution of the flow problem (m/s)
φ	- porosity
λ	- exponential decay constant (s^{-1})
γ	- vertical leakage rate (s^{-1})
ρ_l	- density of the liquid (kg/m^3)
ρ_s	- density of the porous medium (kg/m^3)

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