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# MODELLING OF REINJECTION INTO THE LAUGALAND GEOTHERMAL FIELD, S-ICELAND

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## ABSTRACT

The Laugaland geothermal field is located in southern Iceland. It is a low temperature system, with the temperature of the hot water in the range of 40-97°C. Hitaveita Rangaeinga has been producing hot water from the field since 1982 at an average rate of 20 l/s and a temperature of 98°C. The production has been continuously measured and the water level observed on a monthly basis. The temperature and chemical components have also been monitored.

A two dimensional numerical model has been set up by using AQUA - an advanced software for modelling geothermal fields. An excellent matching between calculated and measured data was obtained. The best calculated location of a reinjection well was found to be 600 m to the northeast of the production well LWN-4 along a northeasterly trending dyke which crosses the production field. A 50-60 m water level recovery in LWN-4 would be achieved in 200 days after the start of reinjection with a reinjection rate of 10 l/s. With the temperature of the injected water at 40°C, thermal breakthrough will not reach LWN-4 in 10 years and the temperature decline would be only 2-3°C. Another possible site for the reinjection well was 180 m away from LWN-4, perpendicular to the dyke to the east.

Based on the experience from Laugaland, the management of the Tianjin geothermal system in China is discussed. A long term geothermal monitoring programme is suggested in order to provide information for modelling studies and eventually reinjection operation.

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# 1. INTRODUCTION

Modelling of geothermal reservoir behaviour has been studied for many years throughout the world. Some methods have already been successfully developed and applied to many different types of geothermal fields. Advanced numerical models, are very general and can simulate geothermal systems in as much detail as desired. AQUA is a sophisticated programme package developed by Vatnaskil Consulting Engineers for the purpose of numerical modelling.

In this report the author uses AQUA to model the Laugaland geothermal field in southern Iceland. This is a low temperature geothermal reservoir. Exploration and development began there in 1946, but full scale development and utilization didn't start until 1982, when Hitaveita Rangaeinga was established and began to pump hot water from well LWN-4. The calibration of the model is based on production data in LWN-4 gathered over these 11 years and measured water level data in observation well GN-1. Measured data of temperature and silica concentration in LWN-4 is also applied to mass and heat transport modelling. A good match has been achieved between the model and the data, reasonable parameters obtained, location of reinjection well chosen, and predictions with and without reinjection performed.

The author of the report has the great honour to have attended the UNU Geothermal Training Programme (1993) at ORKUSTOFNUN (National Energy Authority) in Reykjavik, Iceland. During a 6 months intensive training period, he has gained a lot of knowledge and skill on geothermal energy. Emphasis was put on reservoir engineering, especially on modelling of geothermal systems by using the AQUA programme. This report is a presentation of the author's research study project.

## 2. MATHEMATICAL PRINCIPLES OF THE AQUA PROGRAMME PACKAGE

For geothermal reservoir modelling, three methods are currently available. They are decline-curve analysis; lumped-parameter models and distributed-parameter models (Grant, 1983). Decline-curve analysis is to fit algebraic equations to observed flowrate decline data from wells. It has some success in vapour-dominated systems. The disadvantages are the lack of sound theoretical basis and that it cannot take into account field operation changes (Grant et al., 1982).

Lumped models use a few blocks to represent the entire reservoir system. One of the blocks acts as the main reservoir, and the others as recharges. The advantages of lumped-parameter models are their simplicity and that they do not require powerful computers. But there exist some disadvantages as well. They do not show real reservoir properties and genuine geothermal system. Also, well spacing and injection locations cannot be taken into consideration (Bodvarsson et al., 1986).

Distributed-parameter models are very general. They can simulate an entire geothermal system in detail, including the main reservoir, cap and bed rocks, leaky aquifers and recharge zones, even tectonic structures sometimes. But they need powerful computers and experienced modellers (Bodvarsson et al., 1986).

The AQUA programme package is a sophisticated distributed-parameter modelling software, which was developed by Vatnaskil Consulting Engineers in 1990. It was designed to solve water flow, mass transport and heat transport problems concerning geothermal reservoirs.

### 2.1 Basic equations and approach

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

The above differential equation is the basis of the mathematical model. The model is two dimensional, indices i and j indicate x and y coordinate axis, respectively. AQUA uses the Galerkin finite element method to solve this equation.

### 2.2 Flow model

For a transient groundwater flow, Equation 1 is reduced to:

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

For a confined reservoir with leakage from upper aquifers, the parameters in Equation 2 are defined as:

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

By using x and y as indices instead of i and j, Equation 2 becomes:

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

where

$h$ - *reservoir groundwater level [m]*
$h_o$ - *water level in upper aquifer [m]*
$Q$ - *pumping/injection rate [$m^3/s$]*
$T_{xx}$ - *transmissivity along x axis [$m^2/s$]*
$T_{yy}$ - *transmissivity along y axis [$m^2/s$]*
$S$ - *storage coefficient*
$k/m$ - *leakage coefficient [1/s], where k is the permeability of the aquitard and m its thickness*

For long term exploitation, storage of the reservoir is controlled by compressibility of the fluid and rock in terms of the elastic storage coefficient and by the delayed yield effect. In this case, the equation for transient groundwater flow is:

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_{yy}\frac{\partial h}{\partial y}) + \frac{k}{m}(h_o - h) + Q = S\frac{\partial h}{\partial t} + \alpha\varphi\int_0^1 \frac{\partial h}{\partial t}e^{-\alpha(t-\tau)}d\tau \tag{4}$$

where

$\alpha$ - *$1/\kappa$, and $\kappa$ is a time constant [s]*
$\phi$ - *effective porosity*

For steady state, Equation 1 reduces to:

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

Then we define

$u = h;\ e_{ij} = T_{ij};\ f = 0;\ g = Q + \gamma$

where

$\gamma$ = *R (infiltration rate) for an unconfined horizontal aquifer [mm/year],*

or

$\gamma$ = *$(k/m)\times(h_o - h)$ for a confined horizontal aquifer [m/s]*

By using x and y indices, Equation 5 becomes:

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

AQUA allows three boundary conditions:

1. Dirichlet boundary condition, the groundwater level, the piezometric head or the potential function is prescribed at the boundary;
2. Von Neumann boundary condition, the flow at the boundary is prescribed by defining source nodes at the no-flow boundary nodes;
3. Cauchy boundary condition, the boundary flow rate is related to both the normal derivative and the head.

## 2.3 Mass transport model

To solve mass transport problems, the parameters in Equation 1 are defined as follows:

$$u = c;\ a = \varphi b R_d;\ b_i = v_i b;\ e_{ij} = -\varphi b D_{ij};\ f = \varphi b R_d \lambda + \gamma + Q;\ g = -\gamma c_o - Q c_w$$

By using x and y instead of indices, Equation 1 then reads:

$$\frac{\partial}{\partial x}(\varphi b D_{xx}\frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(\varphi b D_{yy}\frac{\partial c}{\partial y}) - v_x b\frac{\partial c}{\partial x} - v_y b\frac{\partial c}{\partial y} = \varphi b R_d \frac{\partial c}{\partial t} + \varphi b R_d \lambda c - (c_o - c)\gamma - Q(c_w - c) \quad (7)$$

The above equation applies to a local coordinate system within each element having the main axis along the flow direction. The dispersion coefficients are defined by:

$$\varphi D_{xx} = a_L v^n + D_m \varphi \quad (8)$$

and

$$\varphi D_{yy} = a_T v^n + D_m \varphi \quad (9)$$

The retardation coefficient $R_d$ is given by:

$$R_d = 1 + \beta_c \frac{(1-\varphi)\rho_s}{\varphi \rho_l} \quad (10)$$

and

$$\beta_c = K_d \rho_l \quad (11)$$

where

$c$ - *solute concentration* $[kg/m^3]$
$c_o$ - *solute concentration of vertical inflow* $[kg/m^3]$
$c_w$ - *solute concentration of injected water* $[kg/m^3]$
$v_x, v_y$ - *velocity vector taken from the solution of the flow problem* $[m^3/s]$
$a_L$ - *longitudinal dispersivity [m]*
$a_T$ - *transversal dispersivity [m]*
$v$ - *velocity [m/s]*
$D_m$ - *molecular diffusivity* $[m^2/s]$
$\varphi$ - *effective porosity*
$Q$ - *pumping rate* $[m^3/s]$
$b$ - *aquifer thickness [m]*
$\lambda$ - *exponential decay constant [1/s]*
$K_d$ - *distribution coefficient*
$\rho_l$ - *density of the fluid* $[kg/m^3]$
$\rho_s$ - *density of the porous medium* $[kg/m^3]$
$\gamma$ - *R (infiltration rate) for unconfined horizontal aquifer [mm/year]*
$\gamma$ - $(k/m)\times(h_o-h)$ *for confined horizontal aquifer [m/s]*
$\beta_c$ - *retardation constant*

## 2.4 Heat transport model

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

$$u = T;\ a = \varphi b R_h;\ b_i = v_i b;\ e_{ij} = -b K_{ij};\ f = \gamma + Q;\ g = -\gamma T_o - Q T_w$$

By using x and y instead of indices, Equation 1 reads:

$$\frac{\partial}{\partial x}(bK_{xx}\frac{\partial t}{\partial x})+\frac{\partial}{\partial y}(bK_{yy}\frac{\partial t}{\partial y})-v_x b\frac{\partial t}{\partial x}-v_y b\frac{\partial t}{\partial y} = \varphi b R_h \frac{\partial T}{\partial t}-(T_o-T)\gamma-(T_w-T)Q \qquad (12)$$

The above equation also applies to a local coordinate system within each element having the main axis along the flow direction.

The heat dispersion coefficients are given by:

$$K_{xx} = a_L v^n + D_h \varphi \qquad (13)$$

and

$$K_{yy} = a_T v^n + D_h \varphi \qquad (14)$$

Heat retardation coefficient $R_h$ is given by:

$$R_h = 1+\beta_h \frac{(1-\varphi)\rho_s}{\varphi\rho_l} \qquad (15)$$

and

$$\beta_h = \frac{C_s}{C_l} \qquad (16)$$

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]*
$\beta_h$ - *retardation constant*
$D_h$ - *heat diffusivity [$m^2/s$]*

Other parameters are previously defined.

For both transport models, two boundary conditions are allowed:

1. Dirichlet boundary condition, the concentration or temperature is specified at the boundary;
2. Von Neumann boundary condition, the concentration gradient or the temperature gradient is set to zero indicating convective transport of mass or heat through the boundary.

# 3. MODELLING OF THE LAUGALAND GEOTHERMAL FIELD WITH AQUA

## 3.1 About Laugaland

The Laugaland geothermal field is located in the central southern lowlands of Iceland (Figure 1). The natural surface geothermal activities were confined to four warm springs, distributed along a 600 m straight line striking N70-75°E (Figure 1). The temperatures were relatively low, ranging from 15 to 43°C (Georgsson et al., 1978).

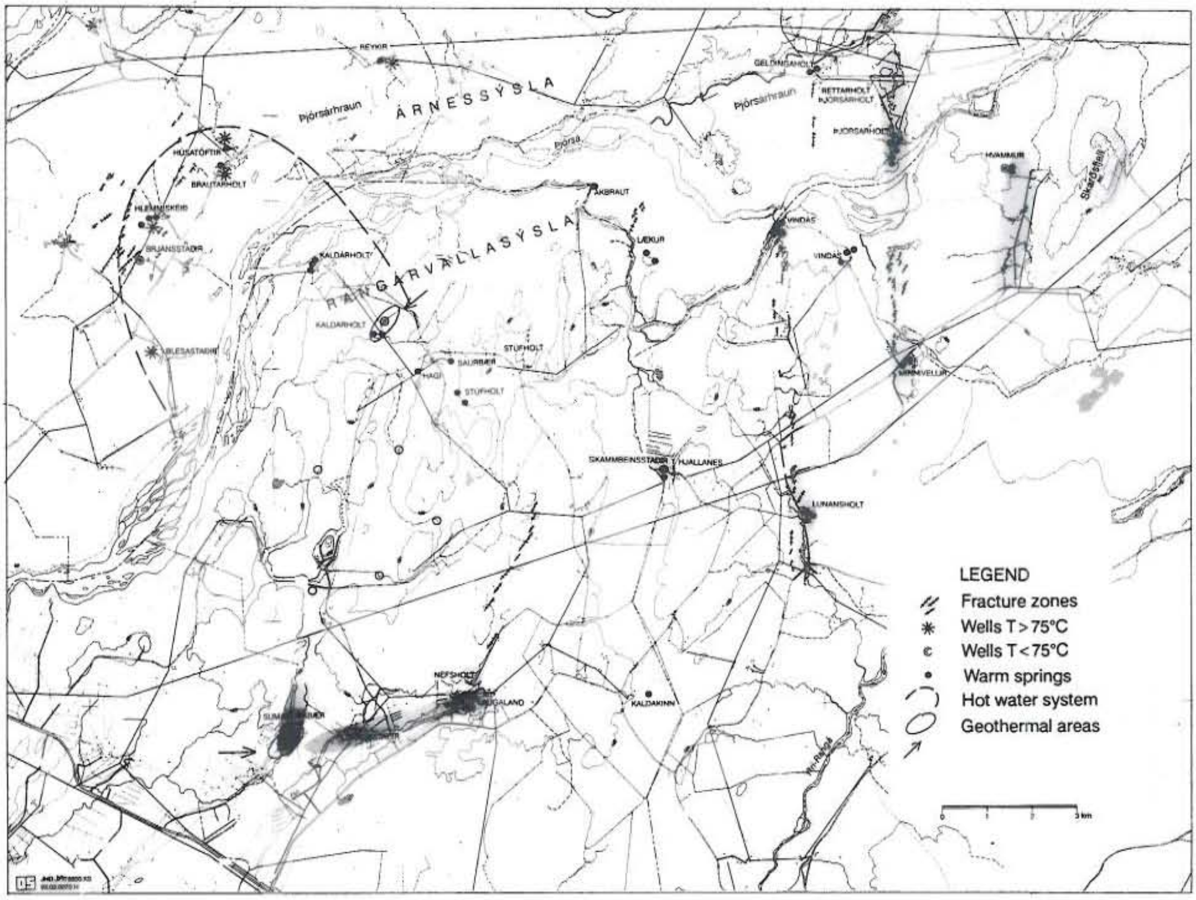

FIGURE 1: Geological background of the Laugaland geothermal field (Bjornsson et al., 1993)

Initial development of the Laugaland geothermal field began in 1946. Two shallow wells (L-0 and L-1) were drilled at the warmest spring, yielding 3 l/s of 42°C water from L-1(91 m). Well L-2 was completed in 1963 with a depth of 206 m, producing 4 l/s of about 50°C water (Georgsson et al., 1978).

The first deep well was drilled in 1977 (LN-3). It was 1308 m deep and designed to intersect a fracture. It turned out to be a failure because, yielding only 1 l/s of water after completion. But temperature logging was very encouraging, as it indicated a geothermal system of around 90°C existing in the vicinity at 700-1000 m depth (Georgsson et al., 1978). During the summer of 1980, well LWN-4 was carefully sited and drilled to 844 m deep. With a free flow of 21 l/s and 94°C temperature, it was a success. Unfortunately, it was soon clogged due to lack of casing. Later, in the spring of 1982, well LWN-4 was deepened down to 1014 m and cased to the depth of 292

m. It was estimated that 30-40 l/s of 97°C water could be extracted, and the drawdown would be about 100 m after a year (Georgsson et al., 1987). Well GN-1 was drilled in 1984. It was 1046 m deep and capable of producing a substantial amount of 84°C water. But the hydraulic connection between it and well LWN-4 was so close that it did not increase much the productivity in the area (Georgsson et al., 1987).

Hitaveita Rangaeinga was established in 1982. Since then, hot water has been pumped from LWN-4 and piped to Hella and Hvolsvollur for district heating, 10 km and 25 km away from Laugaland, respectively. Most of the warm springs have now disappeared because of drawdown of the water level.

## 3.2 Model set-up

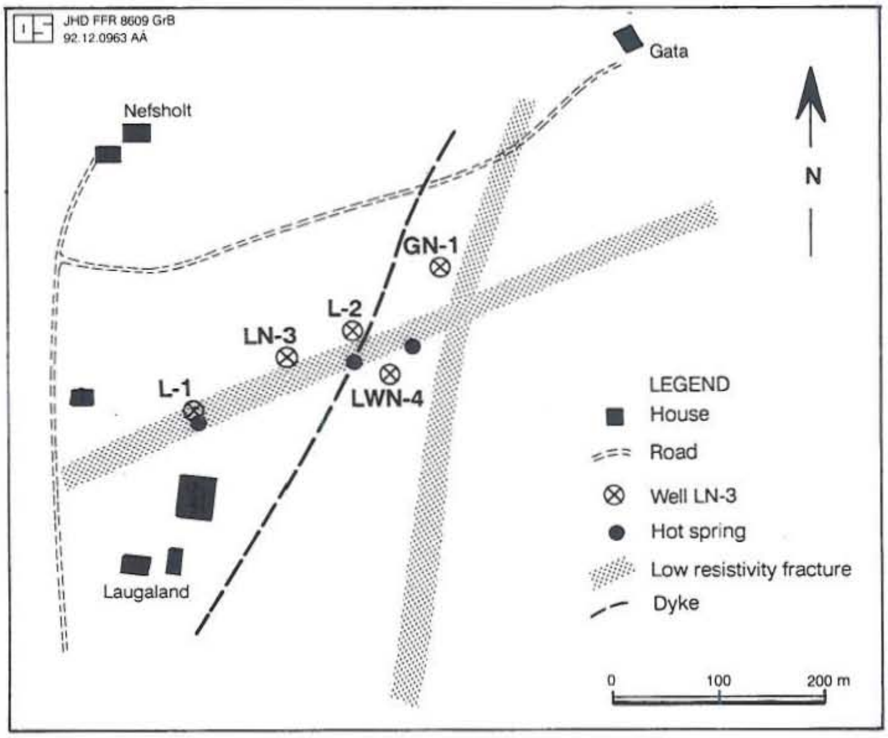

FIGURE 2: Geological structures in the Laugaland geothermal field (Björnsson er al., 1993)

A detailed geological mapping was carried out at Laugaland in 1977. The results indicated that the four warm springs are scattered along a fissure (Georgsson et al., 1978). Later on during the summer of 1983, a head-on profiling was applied to this area, in order to find out permeable and vertical structures in the field. According to the information, it is believed that two fissures intersect each other at Laugaland. One of them has the direction of N75°E, and the other strikes N15°E (Figure 2). Besides, a dyke crosses this area which is nearly parallel to the N15°E fissure. Well tests and production history indicate that the dyke is impermeable. The best permeability is along the dyke and the fissure of N15°E (Georgsson et al., 1987; Bjornsson et al., 1993).

Based on the information mentioned above, a rectangular model was set up. The model has an area of $10\times20$ km$^2$ with its long sides parallel to the dyke. The anisotropy angle is set 90° along the N15°E fissure. No-flow boundary condition is used because the model is made so large that the boundaries have no influence on the behaviour of the geothermal reservoir.

## 3.3 Flow problem

Calibration was carried out by using production data of well LWN-4 and water level data from observation well GN-1. The data is based on an 11 year production history from 1982 to 1993, with monthly measurements Figure 3).

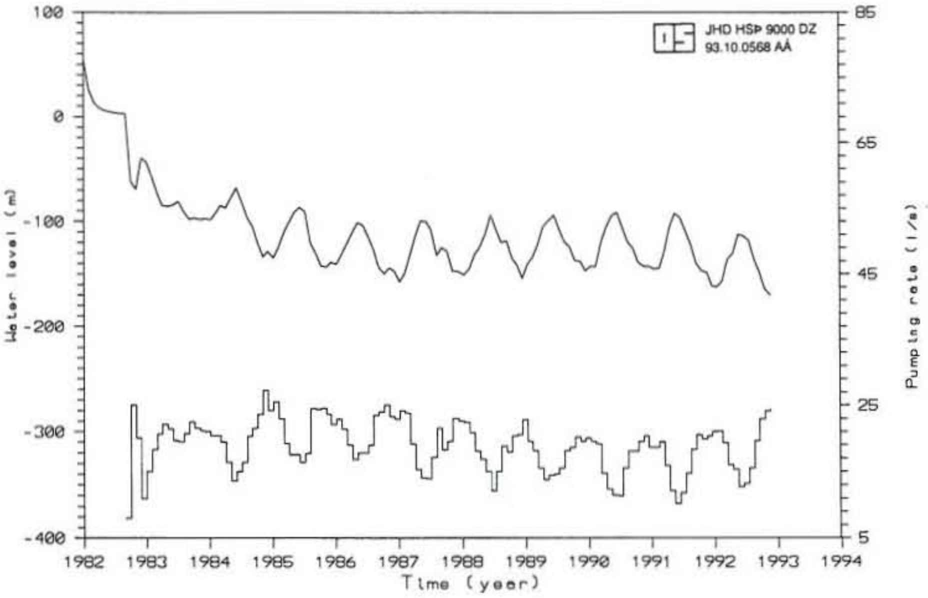

FIGURE 3: Production history in LWN-4 and water level in GN-1

From water level observation in well LN-3, it is clear, that the dyke has almost cut off the hydraulic connection of the two sides. To take this condition into consideration, the dyke has to be in the model. This is done by defining the dyke as a large group of elements with very little permeability in the middle of the area. Many dykes with different lengths have been tried, and finally it was found that a dyke of 16,000 m long and with a transmissivity of $4.4\times10^6$ $m^2/s$ gave the best results (Figure 4).

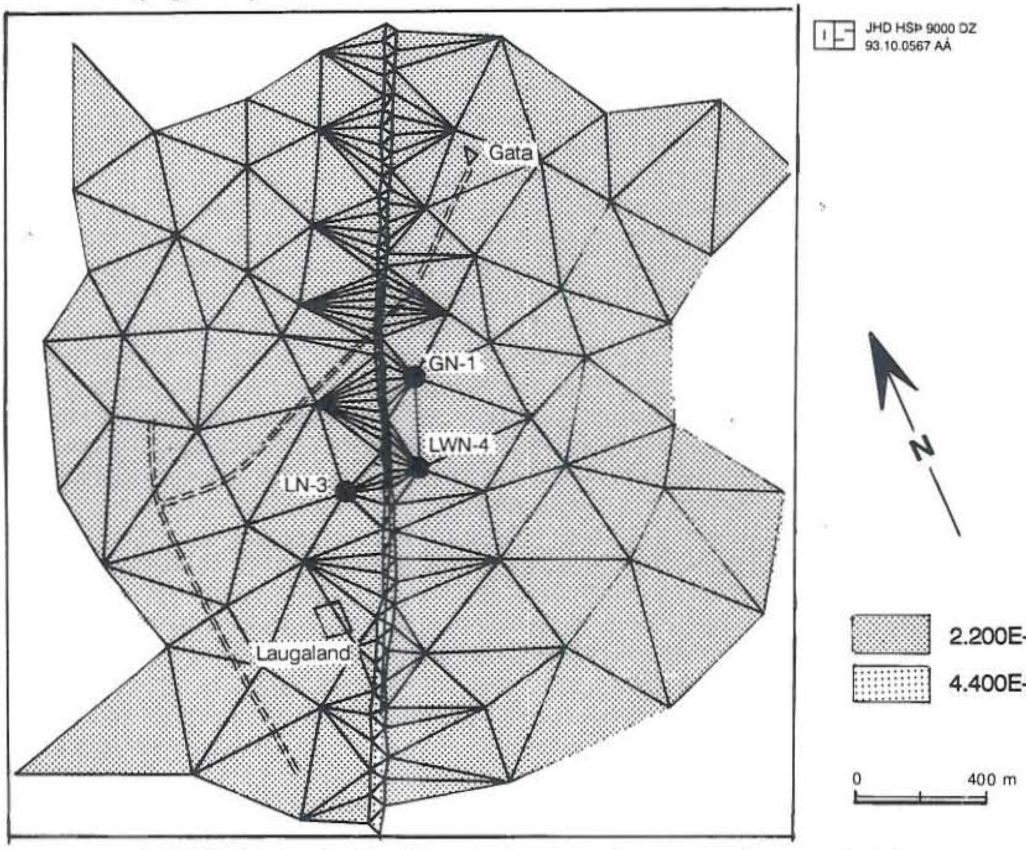

FIGURE 4: Definition of the dyke in terms of transmissivity

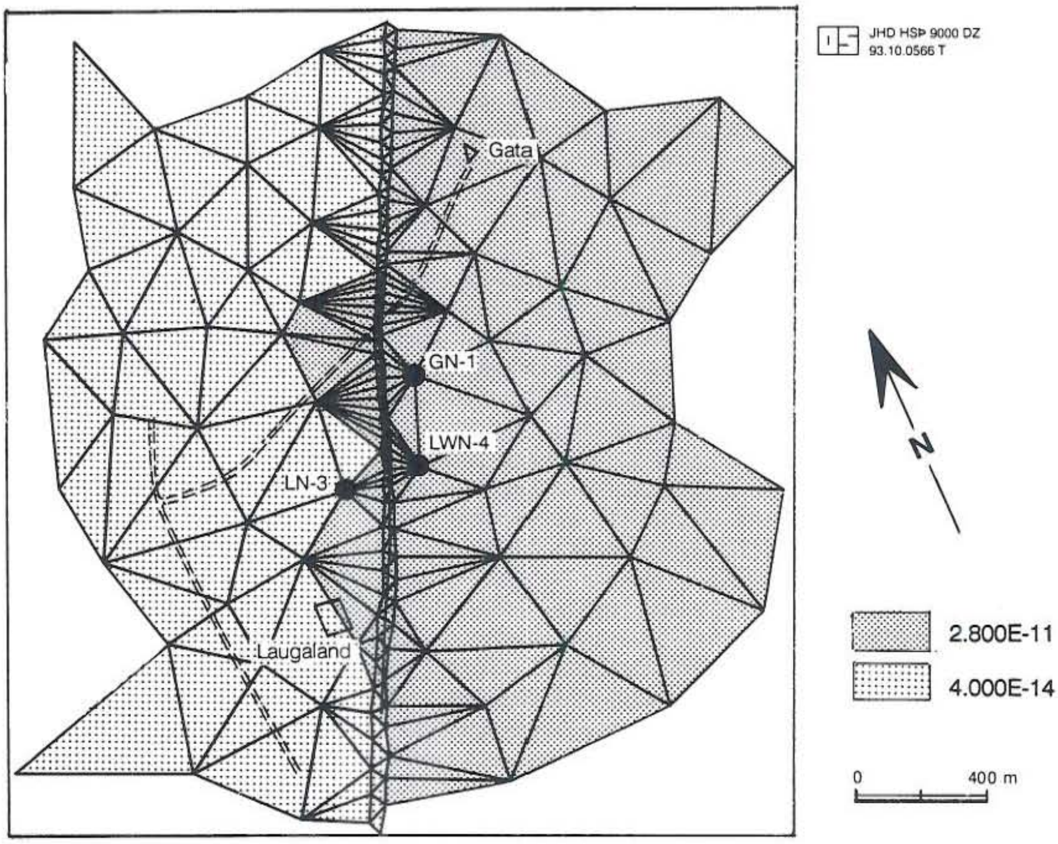

FIGURE 5: Two leakage areas with different values

The area is divided into two parts in terms of leakage. The highest leakage coefficient of $2.8\times10^{-11}$ 1/s is in the vicinity of the wells, to the right of the dyke with an area of 500×800 $m^2$. The global leakage coefficient is given as $4.0\times10^{-14}$ 1/s (Figure 5).

Results of the calibration are shown in Figure 6. It is clear that a good matching has been achieved between measured and computed data in well GN-1, and the presence of the dyke in the model has successfully prevented too much drawdown spreading to well LN-3.

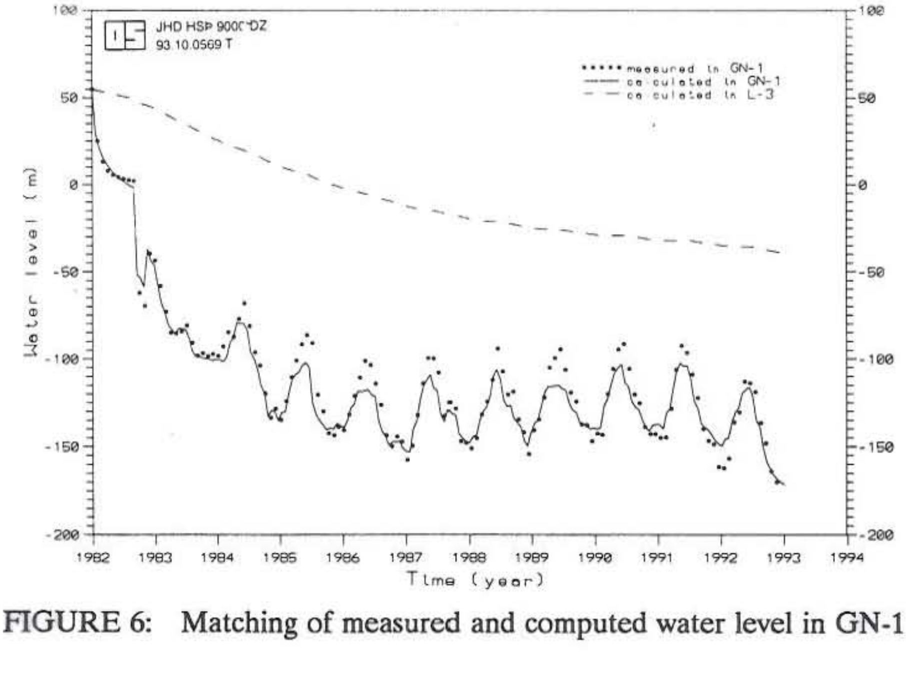

FIGURE 6: Matching of measured and computed water level in GN-1

The following parameters gave the best match between computed and measured drawdown:

*Anisotropy angle - 90°*
*Transmissivity* $[T_{xx}]$ *-* $2.2\times10^{-3}$
*Effective porosity* $[\varphi]$ *- 1.0%*
*Square root* $[T_{yy}/T_{xx}]$ *- 0.05*
*Storage coefficient [S] -* $8.0\times10^{-4}$

Figure 7 demonstrates the cross-section of water level in the vicinity of the wells. The direction is perpendicular to the dyke.

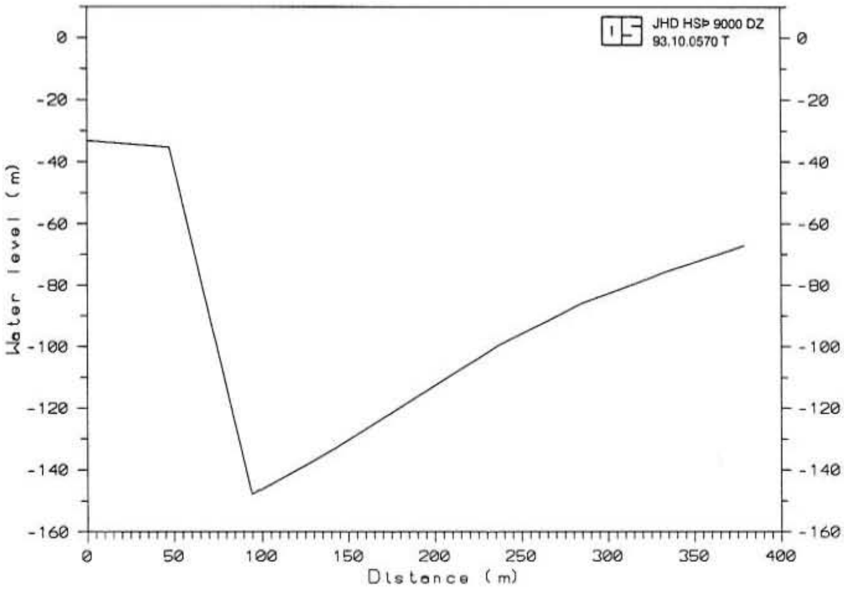

FIGURE 7: Cross-section of water level perpendicular to the dyke

### 3.4 Mass transport

Silica concentration data monitored in LWN-4 is used to calibrate the model. The result of the calibration is given in Figure 8.

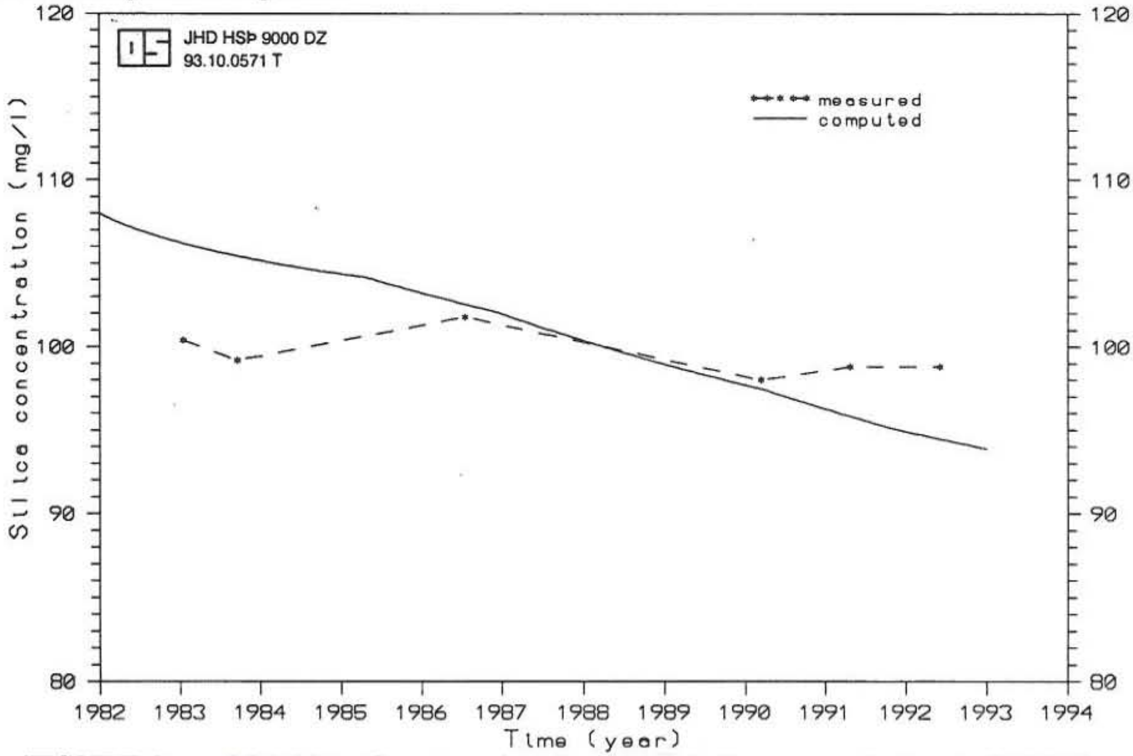

FIGURE 8: Matching of measured and computed silica concentration in LWN-4

The parameters that gave the best fit between measured and computed concentration of silica are:

*Initial concentration* $(C_i)$ *- 108 [mg/l]*
*Concentr. in vertical inflow* $(C_o)$ *- 29 [mg/l]*
*Thickness of aquifer (b) - 100 [m]*
*Effective porosity* $(\varphi)$ *- 1.0%*

*Water level in upper aquifer* $(H_o)$ *- 1 [m]*
*Longitudinal dispersivity* $(a_L)$ *- 50*
*Square root of* $(a_T/a_L)$ *- 1*
*Retardation constant* $(\beta)$ *- 0.0*

### 3.5 Heat transport

The model can now be verified by computing the temperature decline in the reservoir as given by measurements in well LWN-4. We use the following values:

*Initial temperat. of reservoir* $(T_i)$ *- 99.1°C*
*Retardation constant* $(\beta)$ *- 0.24*

*Temperature of vertical inflow* $(T_o)$ *- 20.0°C*

Figure 9 shows the result of the computation, from which we can see a good match has been achieved.

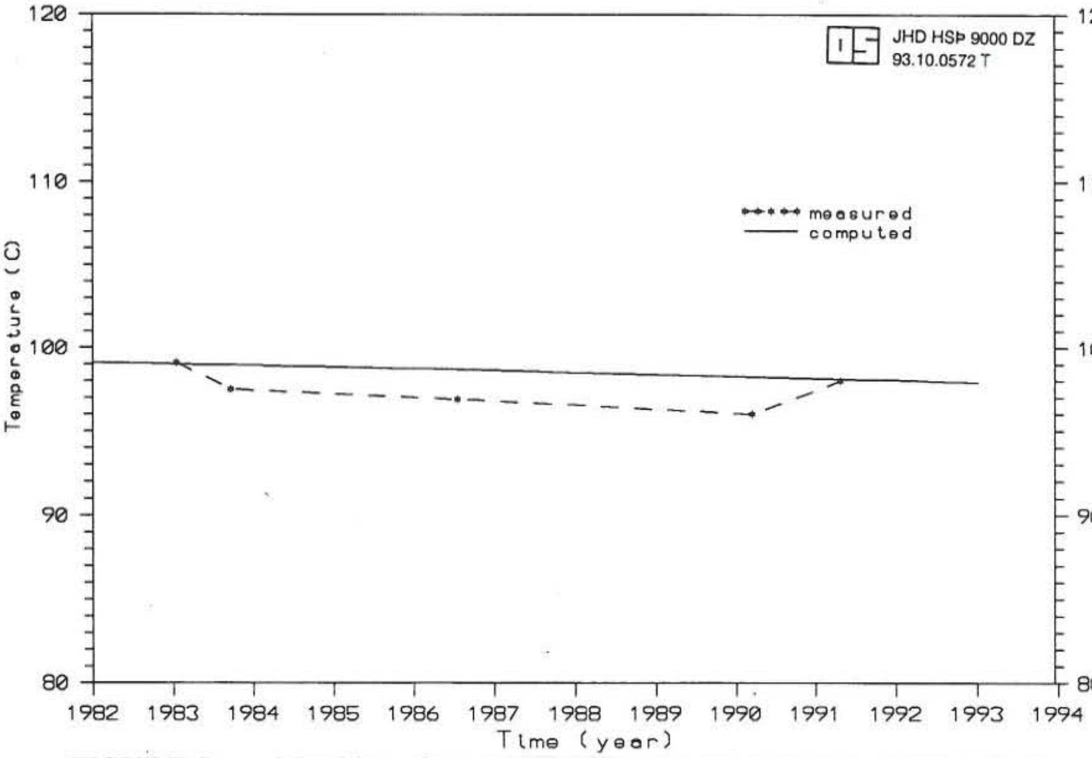

FIGURE 9: Matching of measured and computed temperature in LWN-4

### 3.6 Future prediction

The response of the Laugaland geothermal field to future production has been predicted for the next 10 years till the end of 2003. It is reasonable to assume that the production rate will remain approximately unchanged at 20 l/s, variations with seasons ignored. The results are demonstrated in Figures 10, 11 and 12. There will be a gradual drawdown of about 1 m per year in LWN-4; temperature drop will be so slight that it can be overlooked; silica concentration may gradually increase to a higher steady value due to less average production than previously.

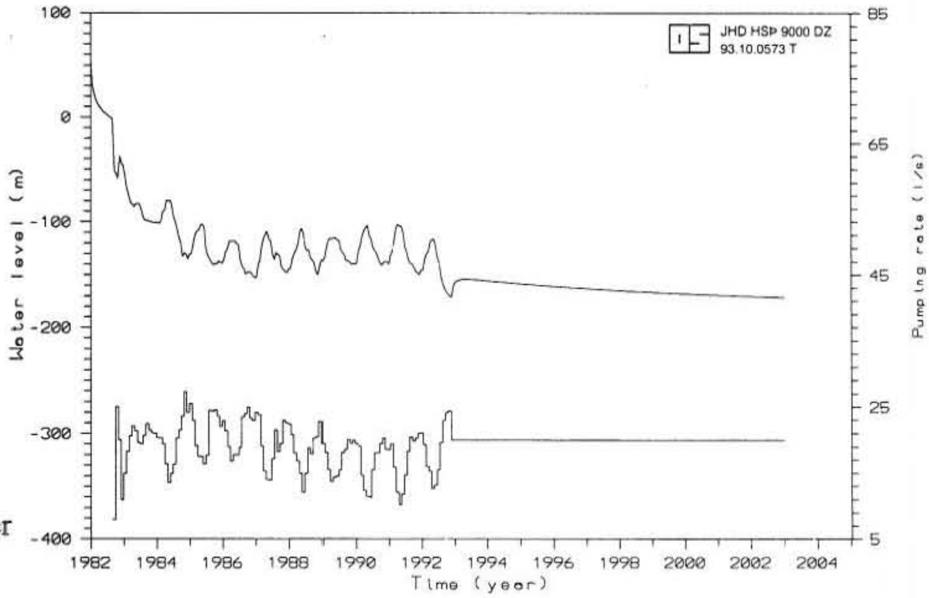

FIGURE 10: Prediction of water level in LWN-4

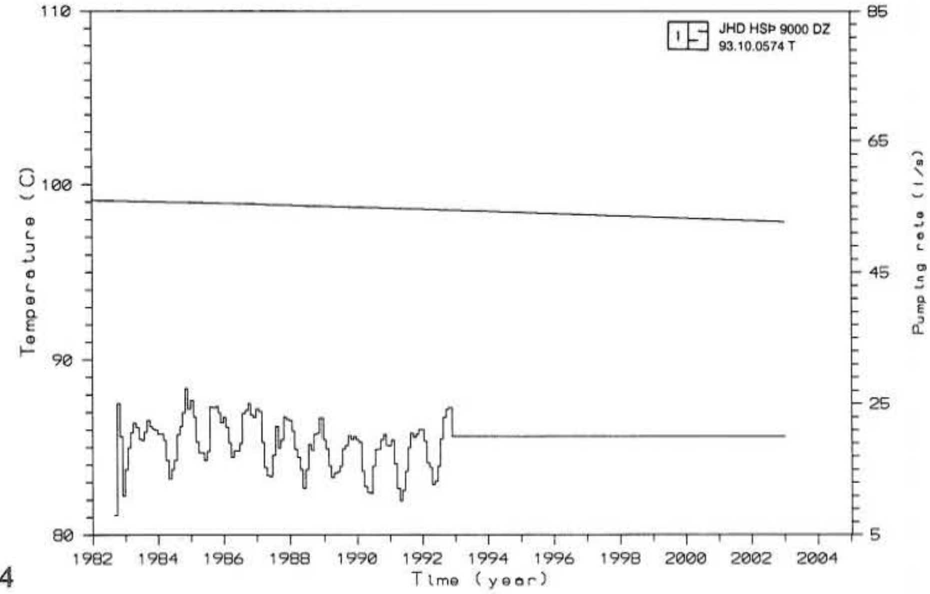

FIGURE 11: Prediction of temperature in LWN-4

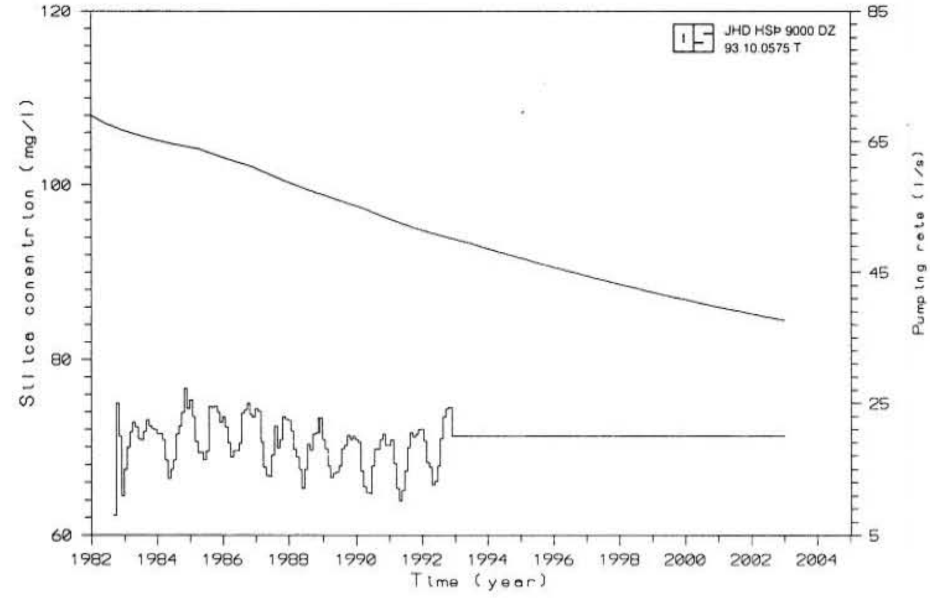

FIGURE 12: Prediction of silica concentration in LWN-4

# 4. REINJECTION INTO THE LAUGALAND GEOTHERMAL FIELD

## 4.1 Choosing the best reinjection site

Reinjection into geothermal reservoirs is becoming more and more important throughout the world in order to sustain longer lifetime and to extract more energy. To choose proper locations for reinjection wells is one of the most concerned issues among geothermal personnel. Many different factors have to be considered for different geothermal fields, but a few factors are common for all:

(1) To achieve a certain amount of pressure increase or to slow down water level decline;
(2) Too much cooling in production wells has to be avoided within a desired time;
(3) Investment to reinjection facilities should be economically acceptable.

For the Laugaland geothermal field reinjection, seven different hypothetical locations have been tried in the model. Reinjection rate is taken as 10 l/s, constant with time; temperature of reinjected water 20°C; and the operation is set to start at the beginning of production.

1. The first location taken as reinjection site is GN-1, which is about 150 m away from LWN-4. The results are shown in Figures 13 and 14, from which we can tell that even though the water level is 80 m higher than that without reinjection, the cooling breakthrough comes too soon and is too big. Obviously, this is not a proper reinjection well site.

2. The second location for a reinjection well is assumed at a site which is 320 m away from LWN-4, along the dyke to the north. The problem is still an early breakthrough and too much cooling (Figures 15 and 16).

3. This hypothetical reinjection well is 600 m away from LWN-4, along the dyke to the north. From Figures 17 and 18 we see that a 60 m water level recovery is brought about. The temperature in well LWN-4 is quite encouraging, because there is almost no cooling in the production well after 11 years reinjection.

4. This assumed reinjection well is 780 m away from LWN-4, along the dyke to the north. The results are shown in Figures 19 and 20. Both water level recovery and cooling are definitely acceptable.

5. This hypothetical reinjection well site is perpendicular to the dyke to the east, 450 m away from LWN-4. From the illustrations in Figures 21 and 22, it is concluded that thermal breakthrough has not reached LWN-4 within 4000 days after the start of the reinjection, but water level recovery is small. So this is not a satisfying site for a reinjection well.

6. This assumed well is placed 300 m away from LWN-4, perpendicular to the dyke. The results are demonstrated in Figures 23 and 24. The same problems occur as in location number 5.

7. This site is only 180 m away from the production well, perpendicular to the dyke and to the east. From Figures 25 and 26, it is evident that about 50 m water level recovery is achieved in LWN-4, thermal breakthrough time is around 800 days; and the temperature drop is about 6°C after 4000 days of reinjection.

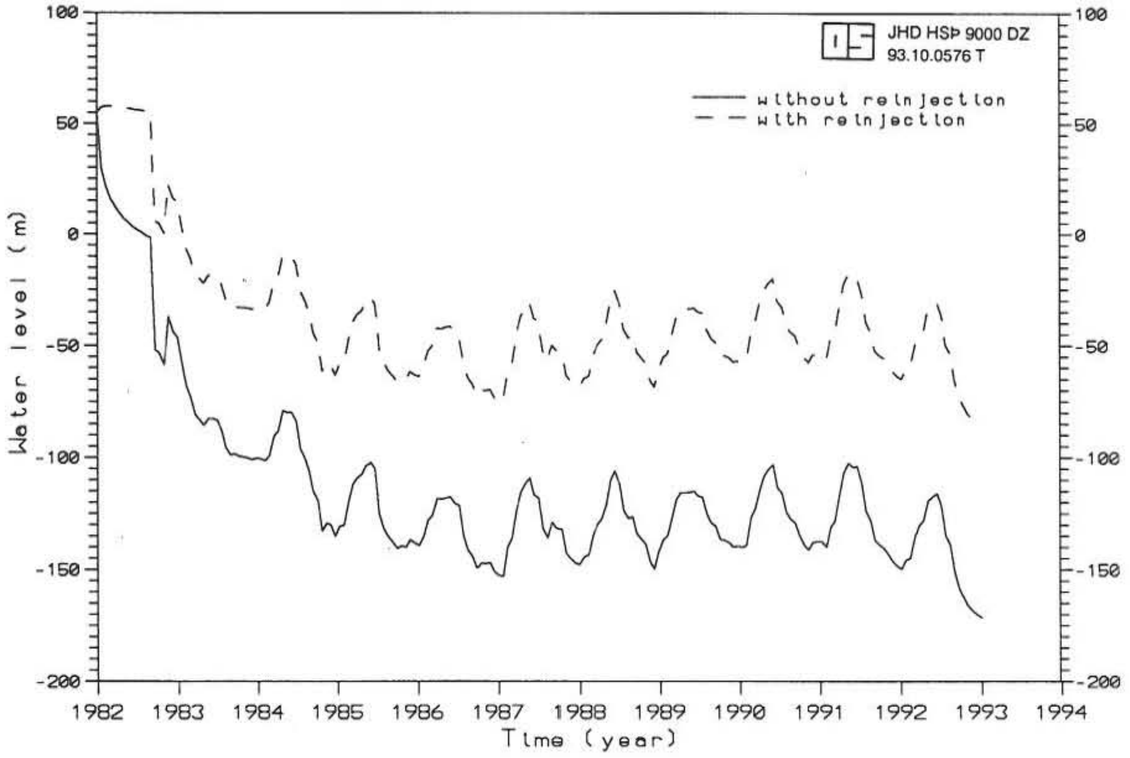

FIGURE 13: Water level in LWN-4 with reinjection in GN-1 (150 m from LWN-4)

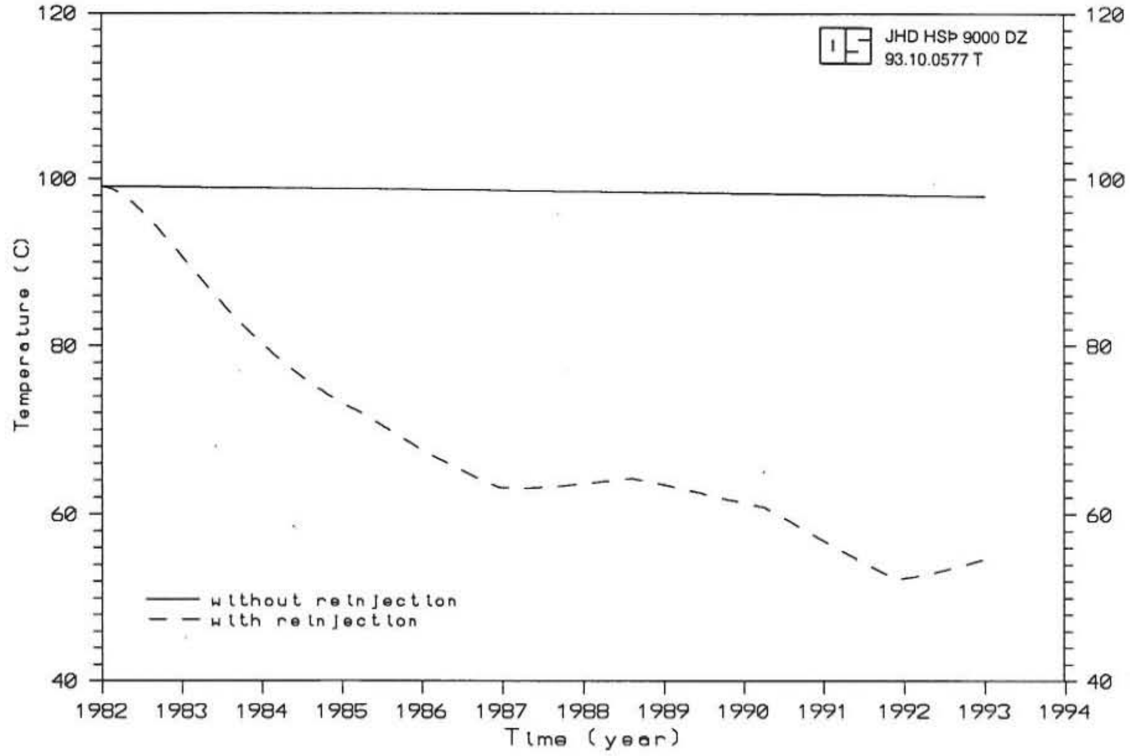

FIGURE 14: Temperature in LWN-4 with reinjection in GN-1

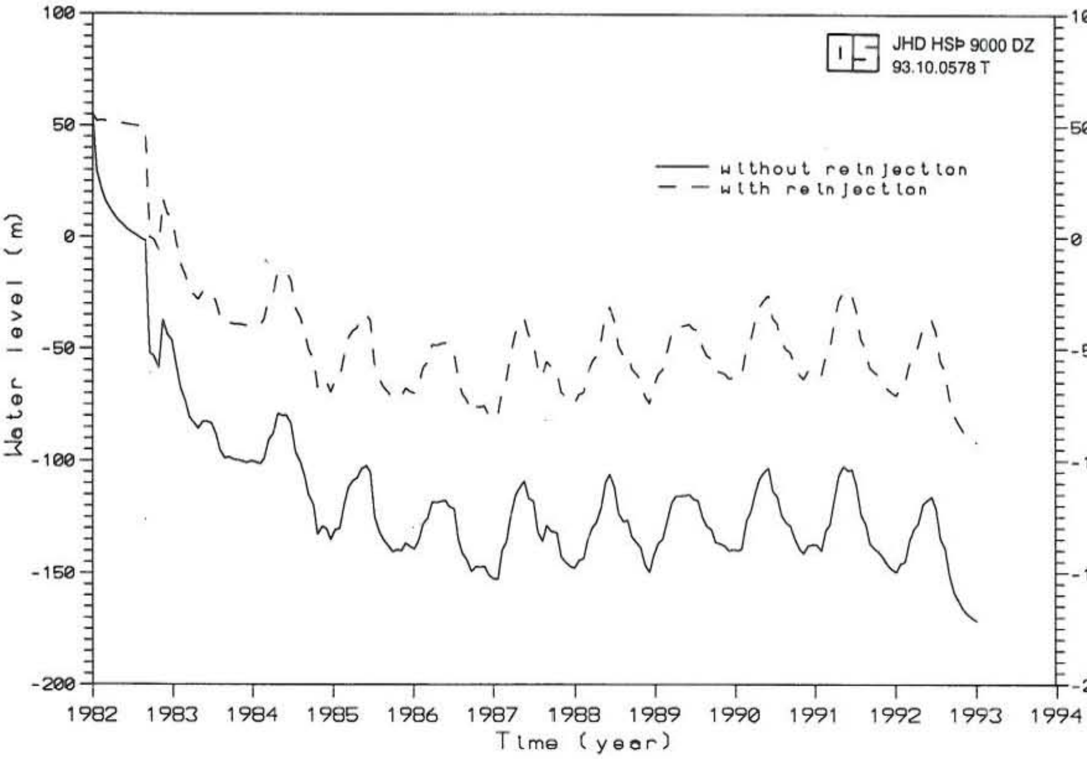

FIGURE 15: Water level in LWN-4 with reinjection 320 m away along the dyke

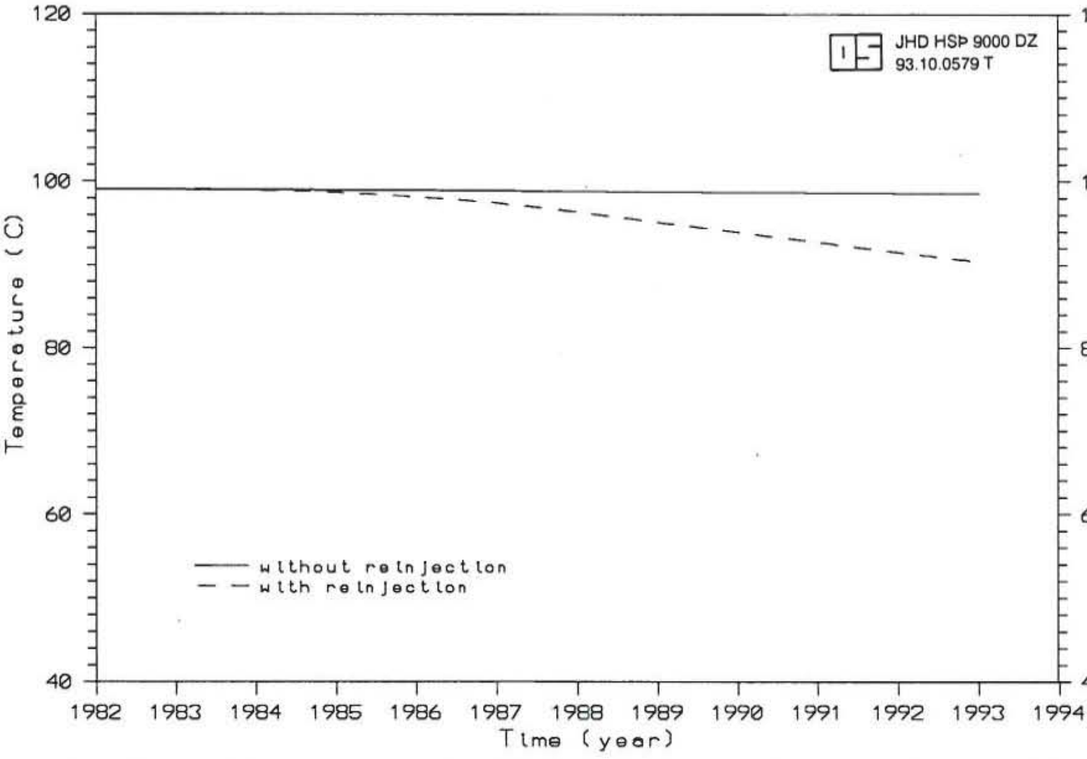

FIGURE 16: Temperature in LWN-4 with reinjection 320 m away along the dyke

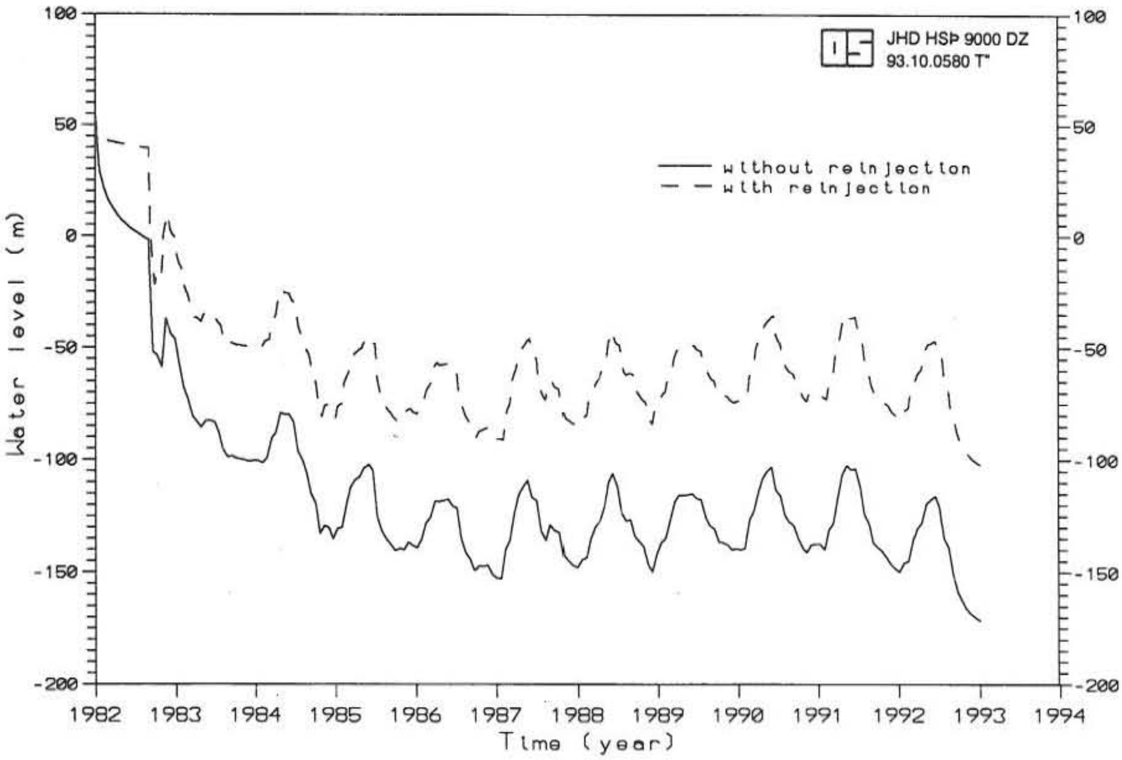

FIGURE 17: Water level in LWN-4 with reinjection 600 m away along the dyke

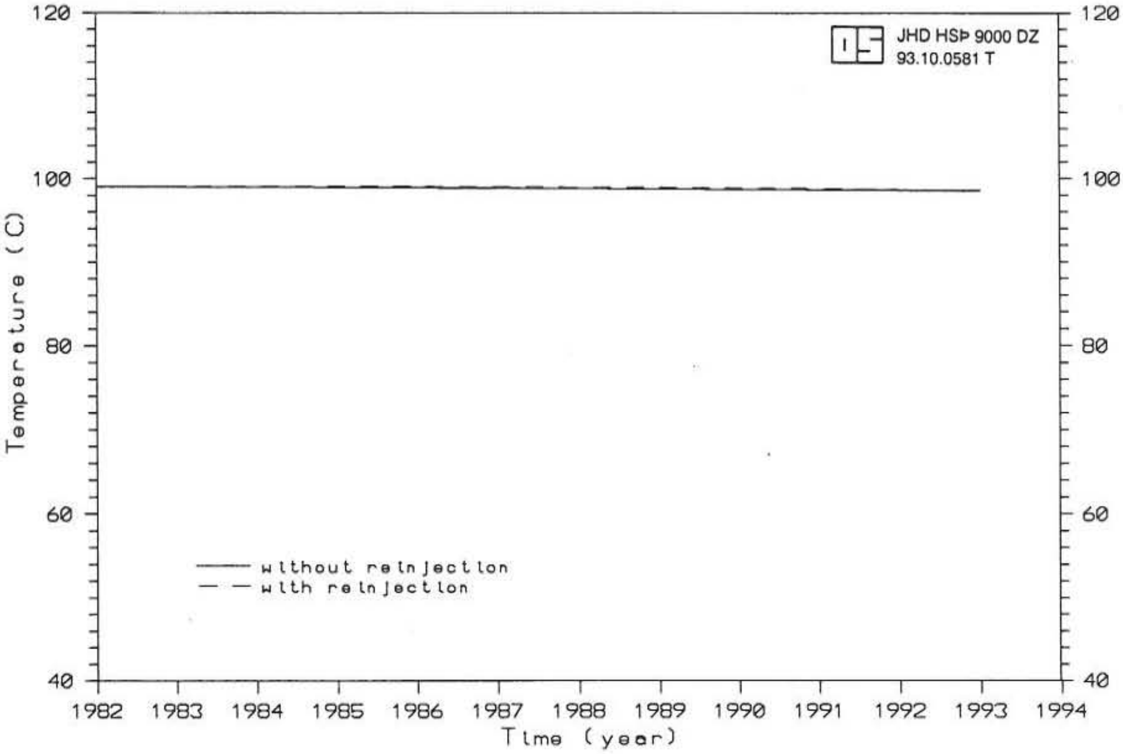

FIGURE 18: Temperature in LWN-4 with reinjection 600 m away along the dyke

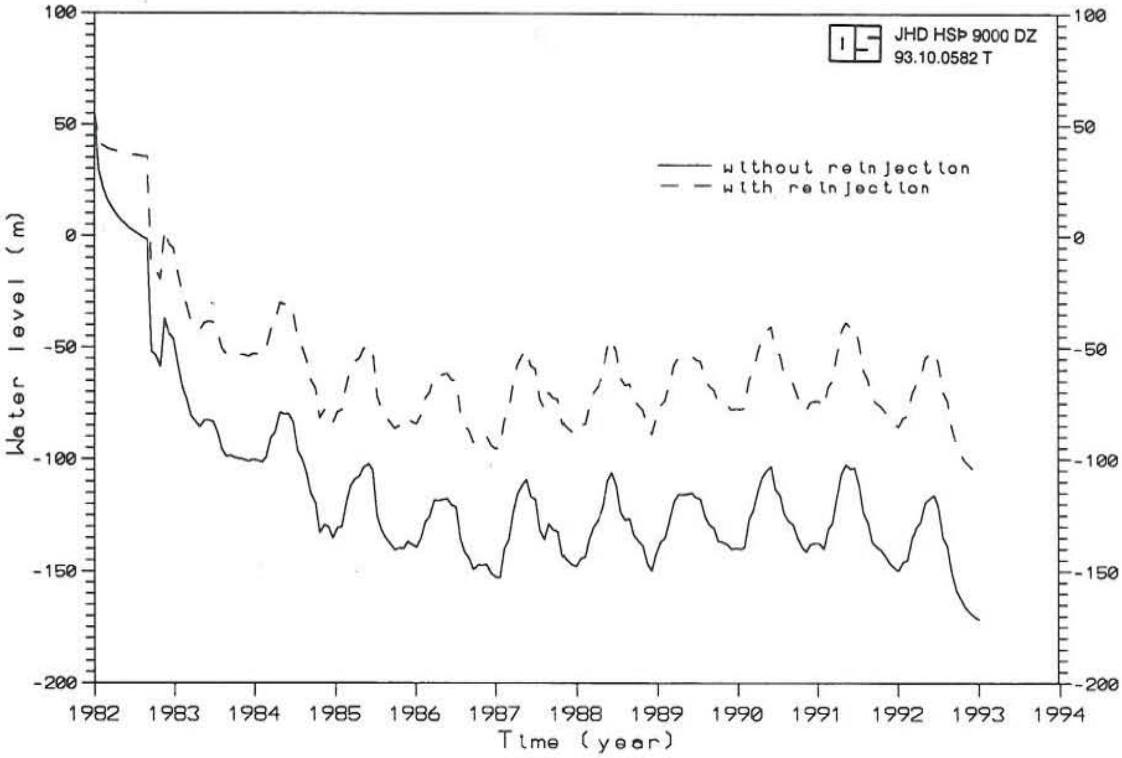

FIGURE 19: Water level in LWN-4 with reinjection 780 m away along the dyke

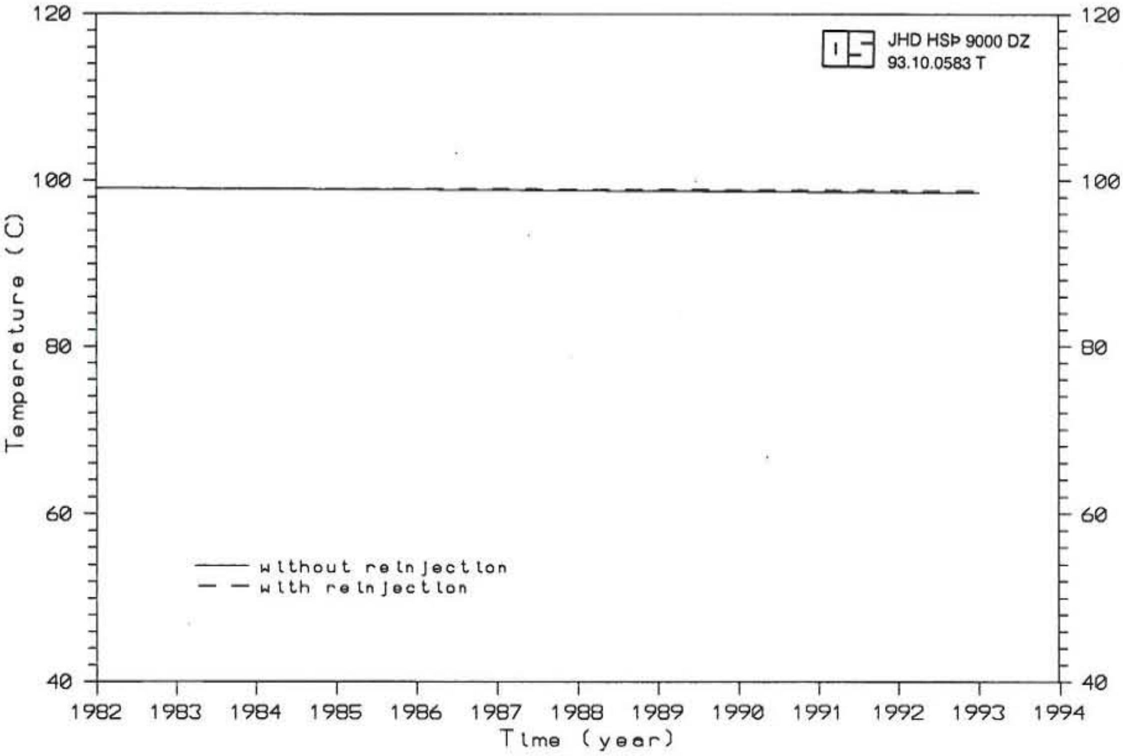

FIGURE 20: Temperature in LWN-4 with reinjection 780 m away along the dyke

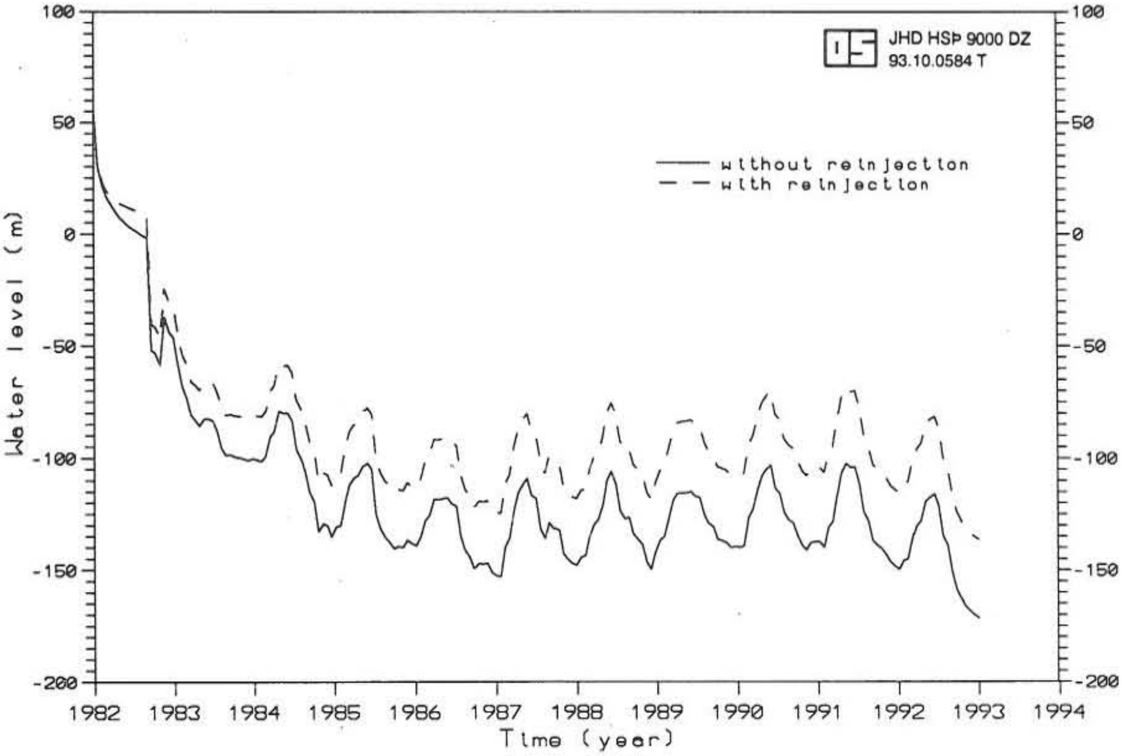

FIGURE 21: Water level in LWN-4 with reinjection 450 m away perpendicular to the dyke

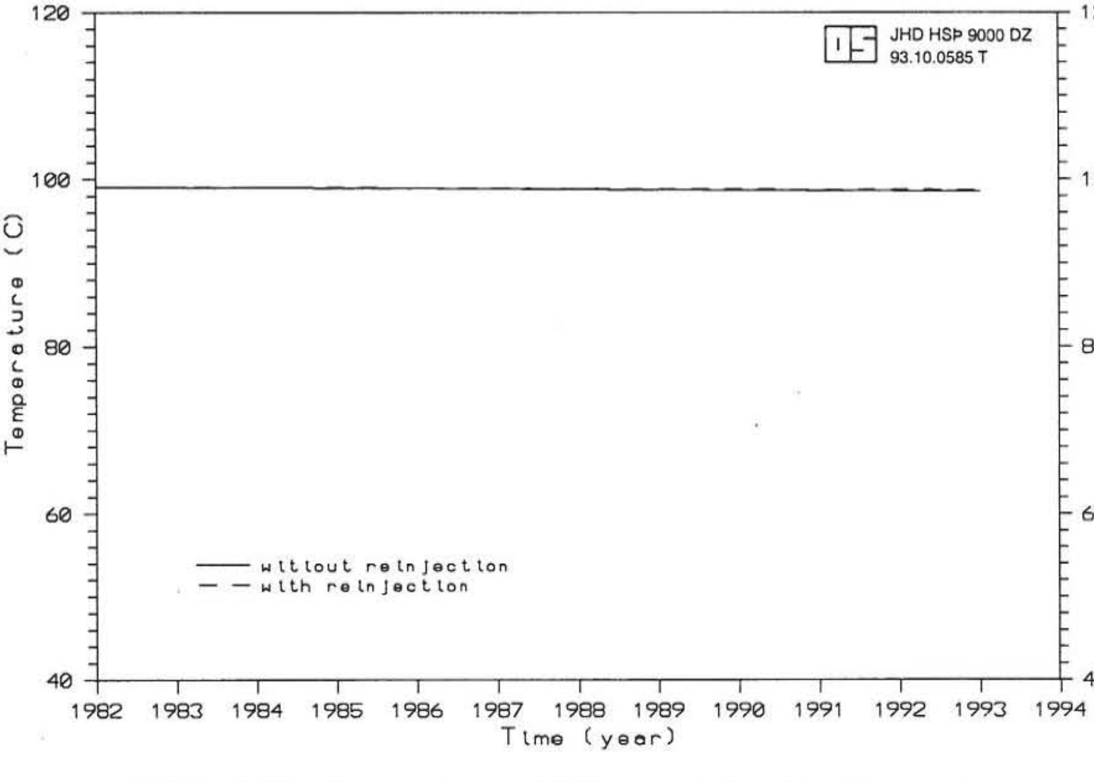

FIGURE 22: Temperature in LWN-4 with reinjection 450 m away perpendicular to the dyke

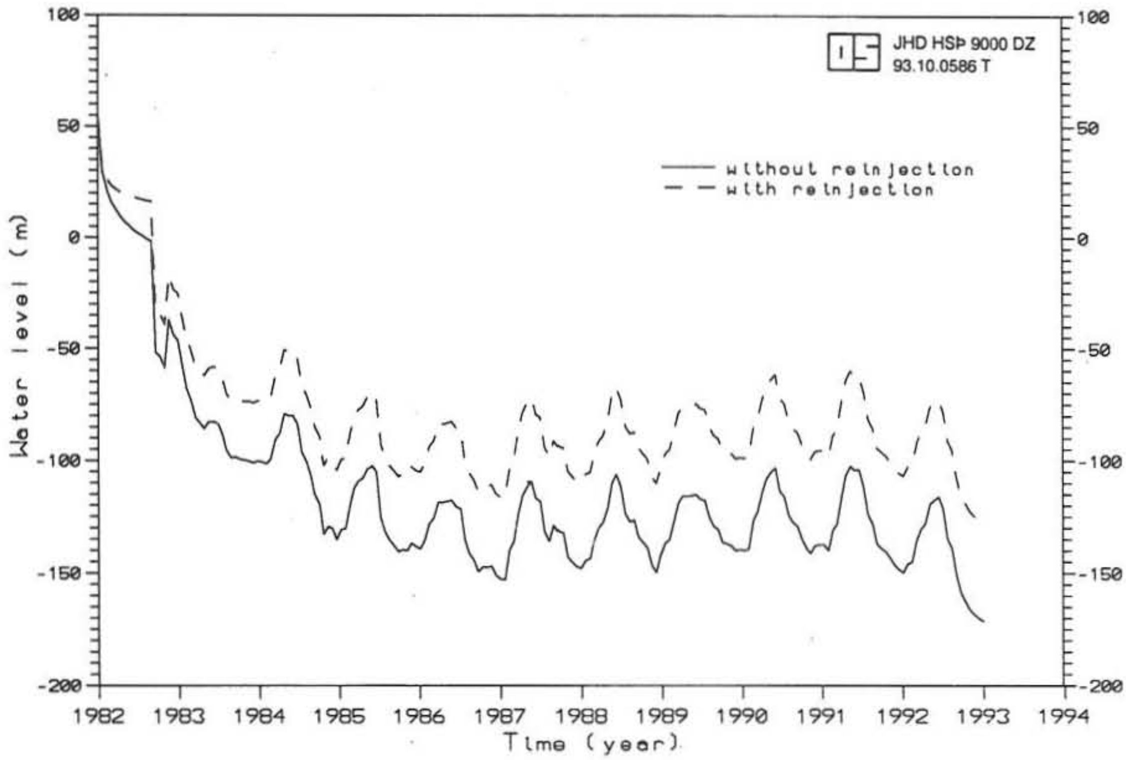

FIGURE 23: Water level in LWN-4 with reinjection 300 m away perpendicular to the dyke

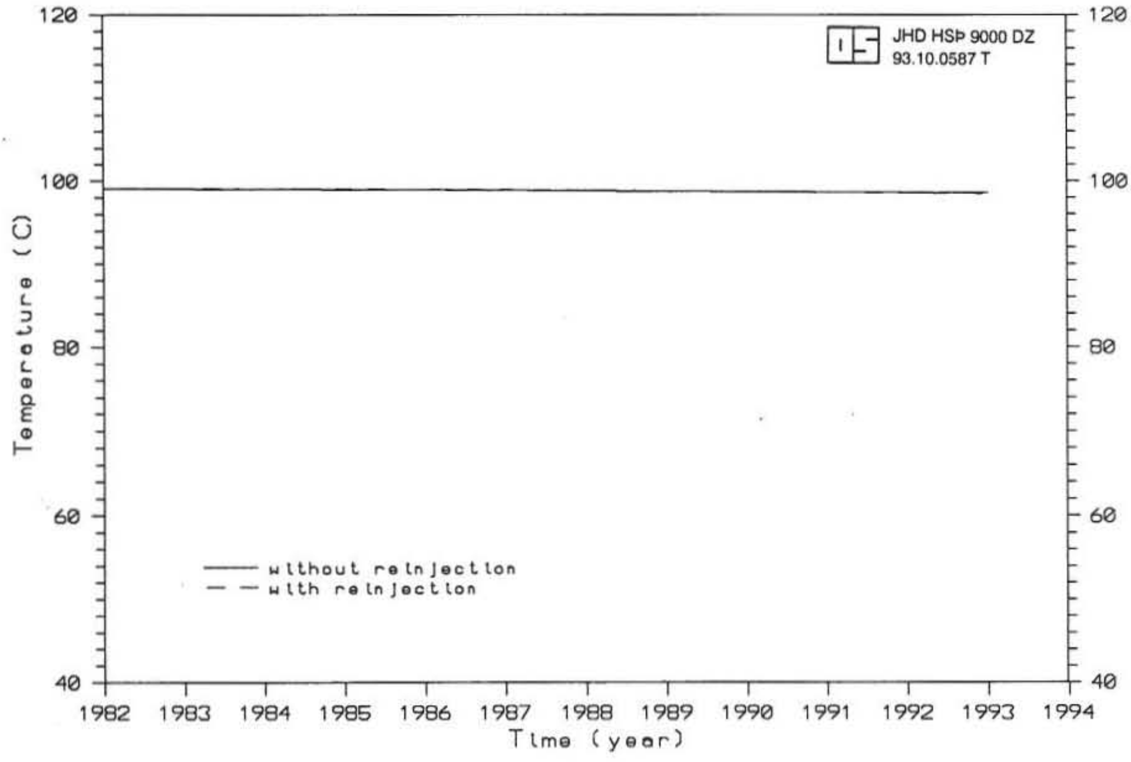

FIGURE 24: Temperature in LWN-4 with reinjection 300 m away perpendicular to the dyke

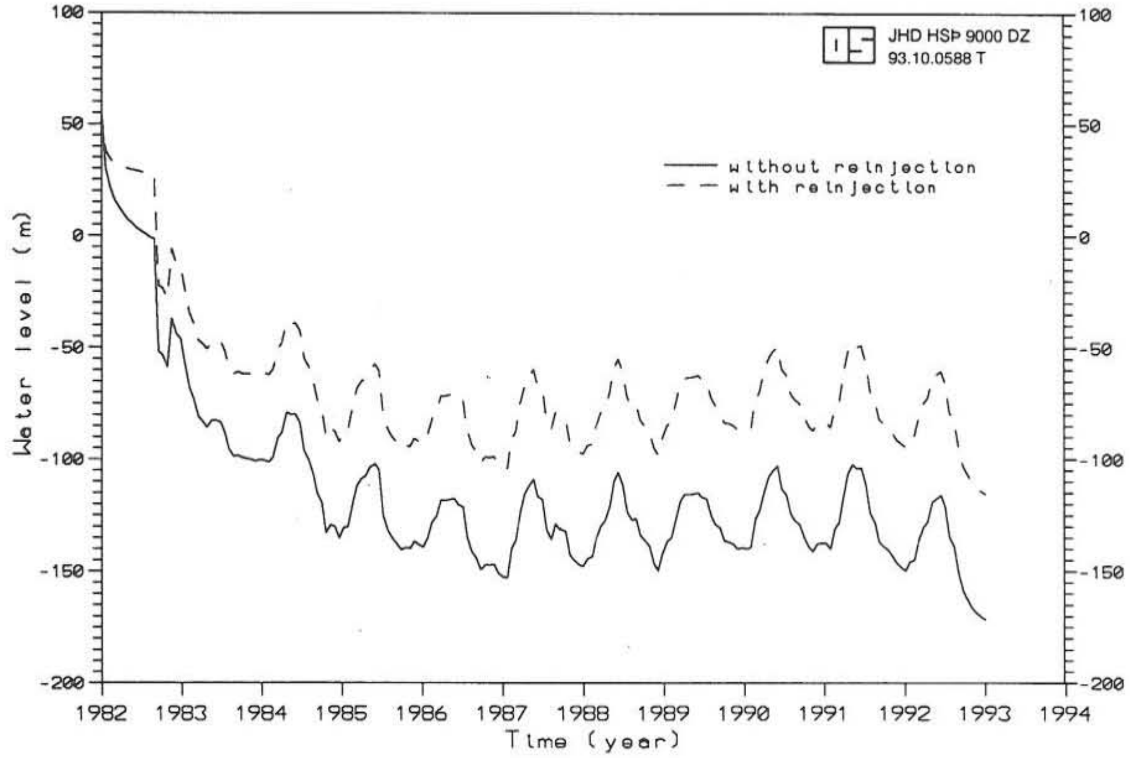

FIGURE 25: Water level in LWN-4 with reinjection 180 m away perpendicular to the dyke

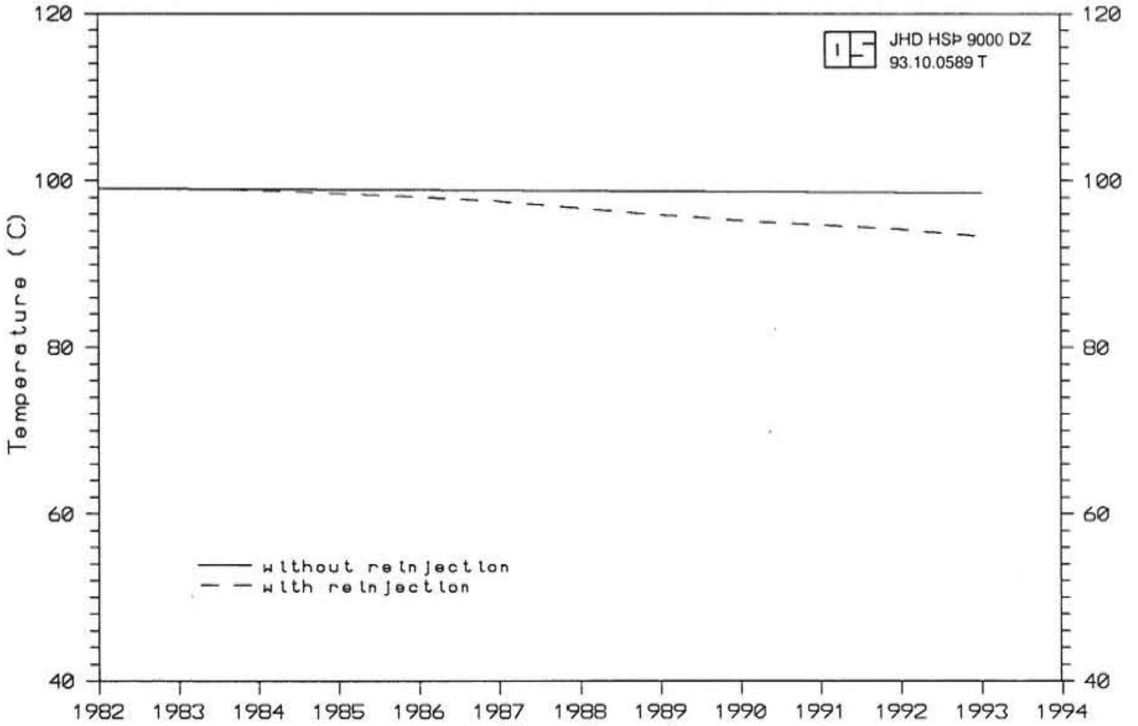

FIGURE 26: Temperature in in LWN-4 with reinjection 180 m away perpendicular to the dyke

Among the 7 cases mentioned above, locations 3, 4 and 7 are promising. If we make a comparison among them, the best one can be found. Location 4 (780 m) is similar to 3 (600 m), but its distance to the production well LWN-4 is 180 m farther away. That means a longer pipeline is needed, so it might not be acceptable from an economical point of view. On the other hand, even though location 7 (180 m) has a short distance to LWN-4, its water level recovery is 10 m less than that of number 3, and its temperature drop is about 6°C more. Therefore, the best choice would be location number 3.

### 4.2 Future prediction with reinjection

For future prediction, some reasonable assumptions have to be made. Production is kept constant at 20 l/s from LWN-1; Reinjection starts in April, 1993 and a 10 l/s reinjection rate is kept throughout the prediction years; Injected water temperature is 40°C. The prediction time is for the next 10 years till the year of 2004. Figures 27, 28 and 29 show the calculated results of water level, temperature and silica concentration in the reservoir for the prediction period.

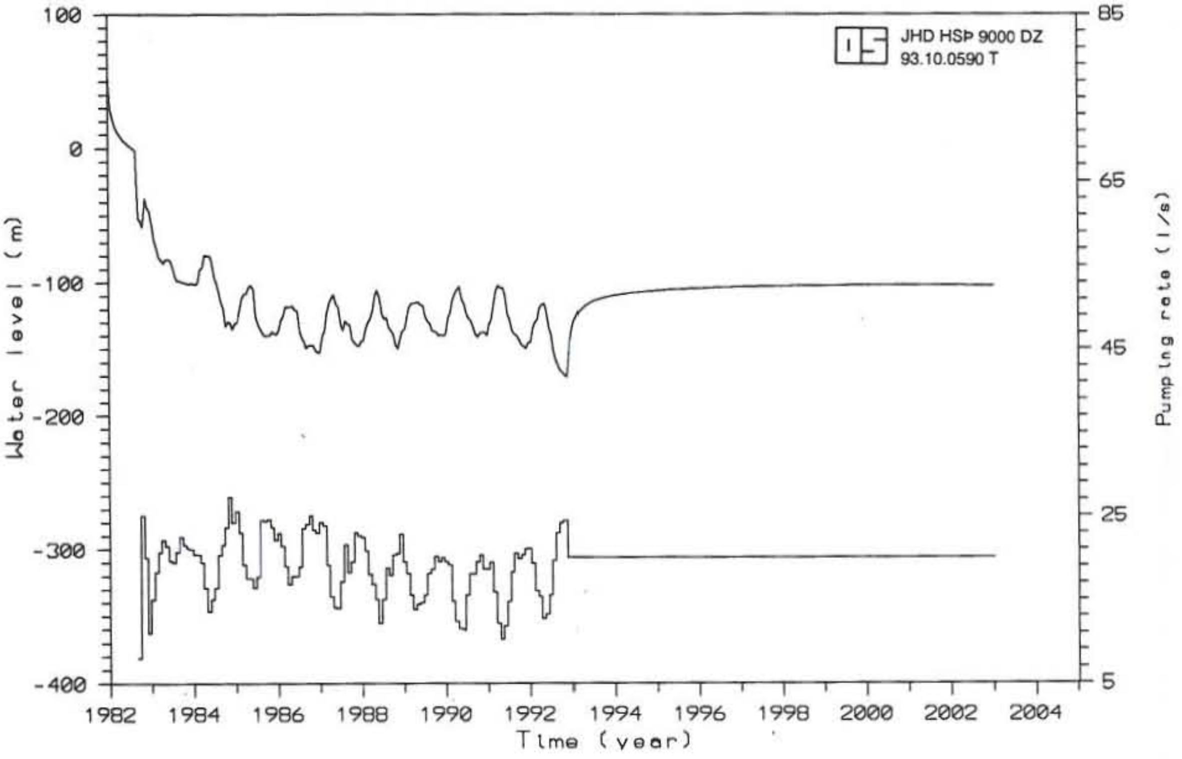

FIGURE 27: Prediction of water level in LWN-4 with the reinjection site 600 m away along the dyke

It is very clear that the production well LWN-4 has a quick response to reinjection. Water level in the reservoir has recovered 50-60 m in 100 days of reinjection and continues to go up steadily with time (Figure 27). Thermal breakthrough does not show up in LWN-4 after 10 years of reinjection, and temperature drops no more than 1°C within the predicted period (Figure 28). Silica concentration has been going down during 11 years of production because of low silica concentration inflow from the upper aquifer. After reinjection, silica concentration decline in LWN-4 will become gradual, as reinjection has decreased the leakage (Figure 29).

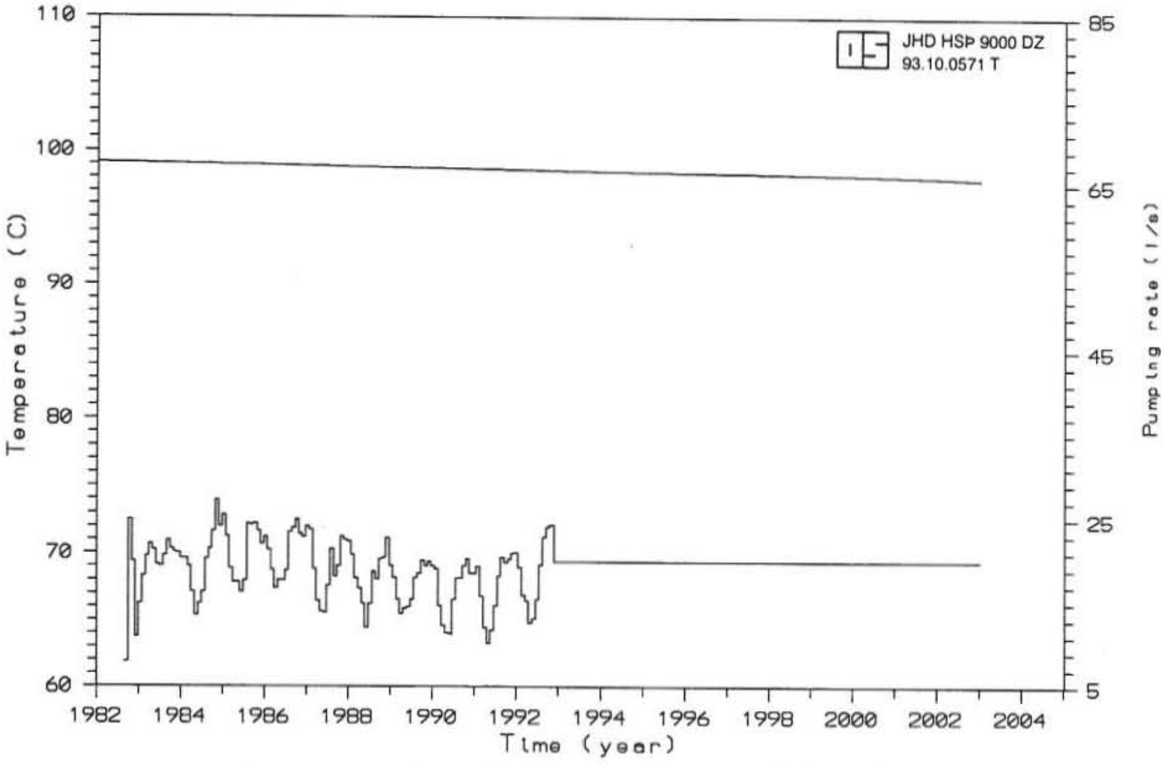

FIGURE 28: Prediction of temperature in LWN-4 with the reinjection site 600 m away along the dyke

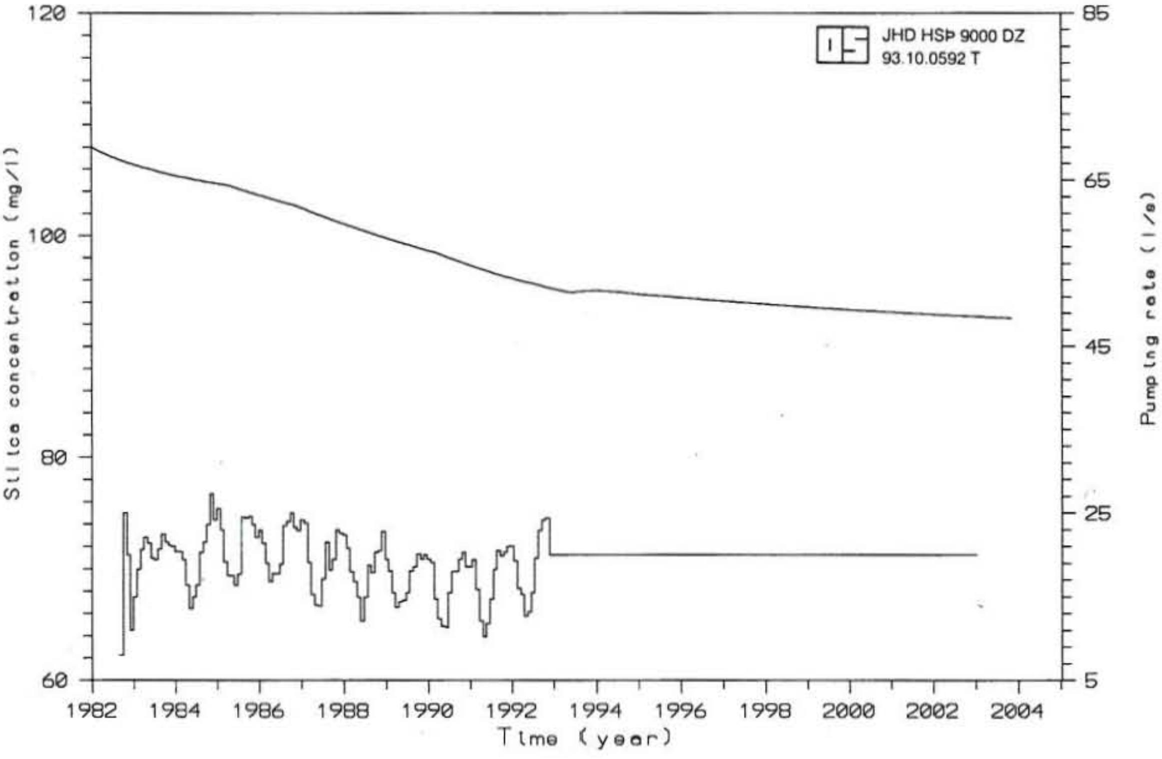

FIGURE 29: Prediction of silica concentration in LWN-4 with the reinjection site 600 m away along the dyke

## 5. CONCLUSIONS

During the past 11 years, hot water has been continuously produced from well LWN-4 with the pumping rate ranging from 10 l/s to 25 l/s depending on the seasons. A great drawdown occurred in the first two years. Afterwards it reached a relatively steady state with seasonal variations, because the leakage from upper aquifers began to have an important influence on the reservoir.

If the present production rate continues without reinjection, the water level in LWN-4 will gradually go down with an annual drawdown of about 1 meter. And there will be nearly no cooling occurring within the predicted period of the next 10 years.

To extract more energy from and prolong the lifetime of the Laugaland geothermal field, reinjection is a good alternative. The best calculated location of the reinjection well is 600 m away from LWN-4 along the dyke to the north. A 50-60 m water level recovery in LWN-4 would be achieved in 200 days after the start of reinjection. If the reinjection rate is kept at 10 l/s and the injected water temperature remains 40°C, thermal breakthrough will not reach LWN-4 in 10 years and the temperature decline would be only 2-3°C.

Another possible site for the reinjection well is 180 m away from LWN-4, perpendicular to the dyke to the east. Because it has a shorter distance to the production well, this is an advantage from an economical point of view.

## 6. RECOMMENDATIONS AND COMMENTS ON GEOTHERMAL DEVELOPMENT AND MANAGEMENT IN TIANJIN, CHINA

Modelling studies of geothermal reservoirs are essential to optimize the development of a resource (Bodvarsson et al., 1986) The purposes of modelling are:

1. To obtain information on the conditions in a system as well as the nature and properties of the system;
2. To predict the response of the system to future production, and to estimate the production potential of the system (Axelsson, 1990);
3. To choose the best reinjection well sites and to study the influence of reinjection to the future behaviour of the reservoir and the production wells.

To set up a successful model, a comprehensive programme of data collection during exploration and careful monitoring of geothermal system during production are very important (Axelsson, 1990). Long term production histories are being obtained at many geothermal fields worldwide, as in this case of the Laugaland geothermal field.

Tianjin geothermal system is located in China's northeastern coastal area, including nine geothermal fields. Out of them four have been developed. Many production wells have been drilled and a great amount of hot water produced every year. But long term monitoring of those fields has to be improved. Geothermal modelling of the field is important, because the results from the model give clear indication what data is most needed.

With the completion of two reinjection wells in the Tianjin geothermal system, the establishment of a long term monitoring programme is becoming increasingly urgent. According to the experience gained in Iceland and at other places throughout the world, reinjection of cold water into geothermal reservoirs will greatly change the behaviour of the system and affect production wells (Bodvarsson et al., 1986). Based on the reasons mentioned above, the following recommendations are brought forward for the geothermal development and management in Tianjin area:

1. To set up a long term geothermal monitoring programme as soon as possible, all geothermal fields and wells should be included in the programme. Items, frequencies and sensitivities are as follows:

| Parameter | Frequency | Sensitivity |
|---|---|---|
| Production from each well | 1 - 2/week | 2% |
| Instantaneous flow | 1 - 2/week | 2% |
| Total production | 1 - 2/week | 1 $m^3$ |
| Water level | 1 - 2/week | 0.1 m |
| Temperature | 1 - 2/week | 0.1°C |
| Chemical content | complete 1/year<br>simple 1/month | |
| Temperature logs | every 1 - 5 year | 0.1°C |

2. To organize a team in charge of long-term monitoring and modelling. Well trained personnel should be included; high quality computers, supporting equipment and relevant

software are also needed.

3. In order to obtain valuable information on the properties of the geothermal system, hydrological tests should be conducted before long term reinjection operation starts, including interference tests and build-up tests.

4. Tracer tests should be performed during the reinjection operation to calculate tracer break through time as it is closely related to thermal break through time.

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## NOMENCLATURE

$a_L$ - longitudinal dispersivity [m]
$a_T$ - transversal dispersivity [m]
$b$ - aquifer thickness [m]
$c$ - solute concentration [kg/m$^3$]
$c_o$ - solute concentration of vertical inflow [kg/m$^3$]
$c_W$ - solute concentration of injected water [kg/m$^3$]
$C_l$ - specific heat capacity of the liquid [kJ/kg°C]
$C_s$ - specific heat capacity of the porous media [kJ/kg°C]
$D_m$ - molecular diffusivity [m$^2$/s]
$D_{xx}$ - dispersion coefficient in x direction
$D_{yy}$ - dispersion coefficient in y direction
$h$ - groundwater level [m]
$h_o$ - water level in upper aquifer [m]
$k$ - permeability of the semipermeable layer [m/s]
$K_d$ - distribution coefficient
$m$ - aquitard thickness [m]
$R$ - infiltration [mm/year]
$R_d$ - retardation coefficient
$S$ - storage coefficient
$t$ - time [s]
$T$ - temperature [°C]
$T_o$ - temperature of vertical inflow [°C]
$T_{xx}$ - transmissivity in x direction [m$^2$/s]
$T_{yy}$ - transmissivity in y direction [m$^2$/s]
$Q$ - pumping/injection rate [m$^3$/s]
$v$ - velocity [m/s]
$v_x$ - velocity vector [m/s]
$v_y$ - velocity vector [m/s]

Greek symbols:

$\beta_c$ - retardation constant [mass transport]
$\beta_h$ - retardation constant [heat transport]
$\gamma$ - leakage [m/s]
$\kappa$ - time constant [s]
$\lambda$ - decay constant [1/s]
$\rho_l$ - density of the liquid [kg/m$^3$]
$\rho_s$ - density of the porous media [kg/m$^3$]
$\varphi$ - porosity

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