A PRELIMINARY 3-D NUMERICAL MODELLING OF THE WARSAW SYNCLINORIUM EARLY CRETACEOUS RESERVOIR

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ABSTRACT

The Early Cretaceous aquifer is a large sedimentary structure in the Great Poland depression, covering about 108,000 km^2. In the Warsaw synclinorium, the depth to the Early Cretaceous layer varies from a few dozens metres to about 1500 m u.s.l. The thickness of this formation ranges from a few metres to 200 m maximum. Stratigraphically, the Early Cretaceous sediments are divided into two permeable sandstone layers separated by near-impermeable mudstone and clay layers. Permeability varies from 1.5 D in the deep part of the synclinorium to 8 D in the outcrops. The lower sandstone layer is of less permeability than the upper one. Regional flow in the reservoir is mainly from southeast to northwest. The static water level in wells drilled into the Early Cretaceous layer is at 50 m. The reservoir temperature varies from about 10-15°C in the southwestern outcrops to about 40-45°C in the deepest part. With the aid of the TOUGH2 simulator, a simple numerical reservoir model was set up for the Early Cretaceous reservoir. A 60 m^3/hr production from one well, and the same re-injection rate to one or two other wells was simulated. No cooling is predicted for this well configuration, partly because of the long distance between the wells, and partly because of regional flow in the reservoir.

1. INTRODUCTION

In recent years, interest for geothermal development in Poland has grown. This interest is driven by the rich geothermal resources present in Poland and by environmental pressure to reduce CO_2 emissions from the current coal-fueled thermal plants. In the Polish territory three main European geotectonic elements occur, the East-European Precambrian platform, the West-European Palaeozoic platform and the Alpine orogenic area (Figure 1). Heat flow is low to moderate and its value is 40-90 mW/m^2 while geothermal gradients amount to 2-3°C/100 m (Kepinska 1998). Over 80% of the Polish territory is built of Mesozoic-Tertiary sedimentary basins with numerous aquifers. This is often called the Great Poland depression.

Among the numerous sedimentary layers of the Great Poland depression, the so-called Early Cretaceous aquifer is of special interest. It covers about 108,000 km^2 and is almost entirely bounded by outcrops. Only the northwestern and eastern edges extend beyond state borders (Figure 2). The Early Cretaceous

aquifer layers (permeable sandy and sandy-muddy sediments) belong mainly to the Valanginian, Hauterivian, Middle Barremian - Aptian and, locally, to the Albian stages in geological time. The variable lithology of the Early Cretaceous strata and local incorporation of permeable Upper Albian and Cenomanian sediments, result in highly irregular thickness of the permeable horizon.

The Warsaw synclinorium is located in central Poland (Figure 2). Several cities in the central part of the synclinorium may benefit from the utilization of geothermal water from the Early Cretaceous aquifer. The Warsaw synclinorium is the south part of the Marginal Pomorze - Warsaw synclinorium, situated in the Great Poland depression. To the east, the Warsaw synclinorium is limited by a Precambrian platform, and to the west by the Pomorze - Kujawy anticlinorium. A few geothermal research projects and thermal plant construction phases are presently being conducted in order to utilize the deep geothermal water for district heating. Among them is a geothermal project in the town of Mszczonow in Central Poland. It concerns hot water production from Early Cretaceous sandstones, containing high quality drinking water of 43-45°C temperature. Water will be produced from an abandoned well, for both space heating and drinking. It is also possible to utilize geothermal water from this reservoir in several other towns, in particular the towns of Zyrardow and Sochaczew (Figure 3).

In this report, the Early Cretaceous reservoir in the Warsaw synclinorium is briefly described. A conceptual reservoir model with temperature distribution and reservoir

FIGURE 1: Tectonic subdivision of Poland (Sokolowski, 1992); A. Pre-Cambrian platform area; B. Great Poland depression; C. The fold-block area; D. Carpathian Mts. (Alpides); E. Neogene Carpathian foredeep
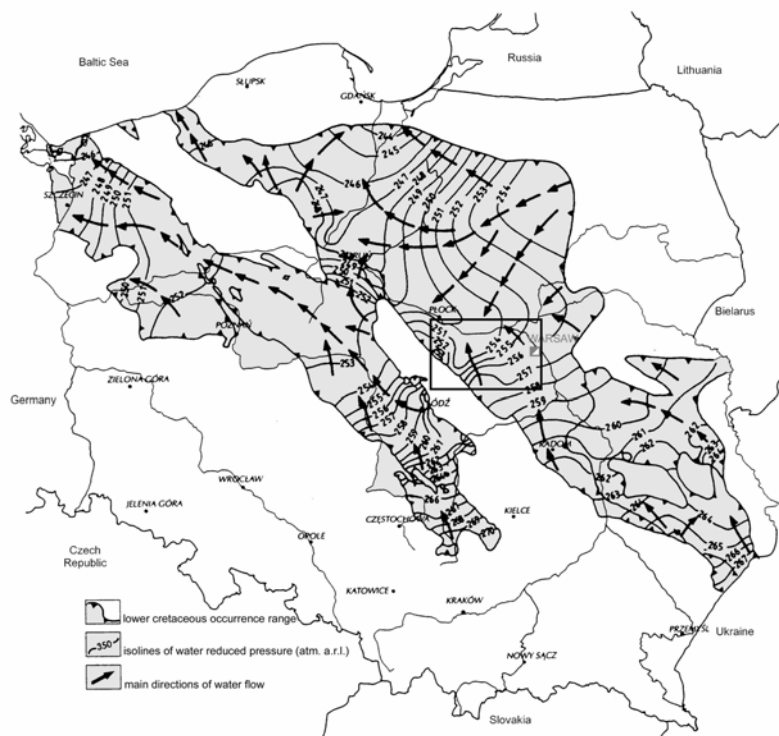

FIGURE 2: Lower Cretaceous occurence range and main directions of regional groundwater flow (Gorecki et al., 1995); the rectangle shows the part of the Warsaw synclinorium to be studied here

geometry is presented. On the basis of the conceptual model, a three-dimensional numerical model was developed. Finally, a few cases of production and injection scenarios were simulated in order to obtain a preliminary production capacity estimate for this specific layer in the ground.

2. DATA SOURCES

2.1 Geological investigation of the Warsaw synclinorium

Information on the hydraulic parameters of permeable and semi-permeable rocks is rather limited, as the Early Cretaceous reservoir has not been a subject of interest and large scale exploitation. Exceptions are, however, found in the outcrops at the northeast margins of the Lodz synclinorium, at the southwest margin of the Warsaw synclinonium and, to some extent, in other sedimentary units where fresh groundwater is exploited. Hydraulic parameters have, therefore, mostly been measured close to the outcrops, for shallower parts of the aquifer. In these, the reservoir temperatures are naturally too low for any substantial geothermal applications.   The geothermal aquifer hosted in the

FIGURE 3:   Location of wells and towns in the Warsaw synclinorium

Early Cretaceous sedimentary unit is at confined conditions throughout almost the whole area. Unconfined conditions occur only in the outcrops and incrops under the Cainozoic (mostly Quaternary) deposits. Pressure in deep wells suggests the existence of regional flow within the Early Cretaceous aquifer with the flow direction generally from southeast to northwest (Gorecki et al., 1995). This is shown schematically in Figure 2.

Information available on the Early Cretaceous geothermal aquifer comes mostly from oil and geological exploration drilling made by both the local petroleum industry and the State Geological Institute.   Figure 3 and Table 1 show the location of these wells and their intercepts with the Early Cretaceous aquifer.   The irregular borehole pattern, limited range of measurements and core sampling result in limited hydrogeological characterization of the reservoir. Well tests have been performed in a fraction of the boreholes, mainly in shallow wells at outcrops and incrops, but also in the most recent deep wells.   In some cases parameters like open porosity and specific surface have been determined in laboratories from core samples.

Figure 4 shows temperature profiles collected in the Warsaw synclinorium wells. Although the graph is heavily crowded by temperature logs, a dominant feature is seen in all of them, namely, a linear temperature gradient in the range of 0.016-0.032°C/m. From this data alone, one would expect minor vertical fluid movement and hence low vertical permeability.
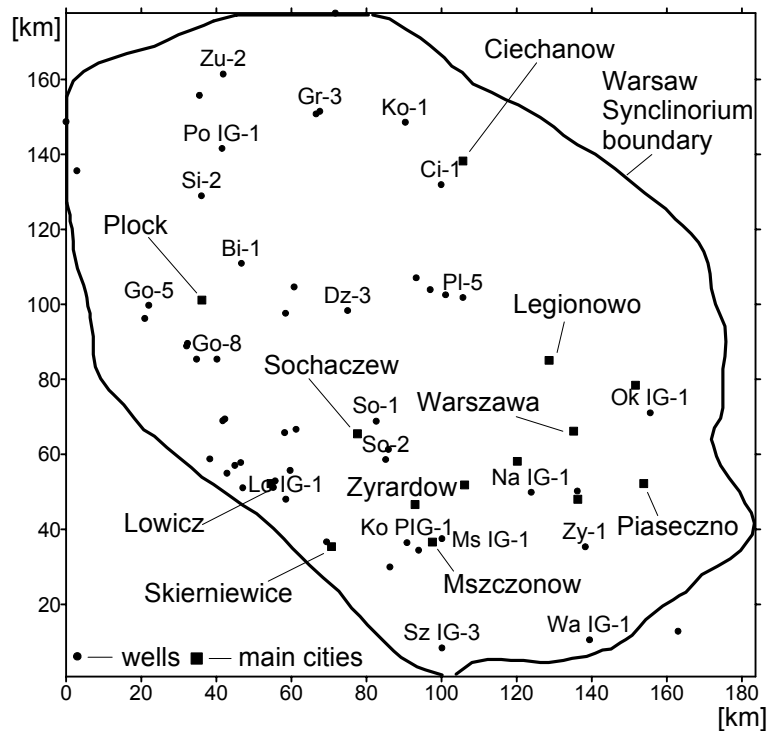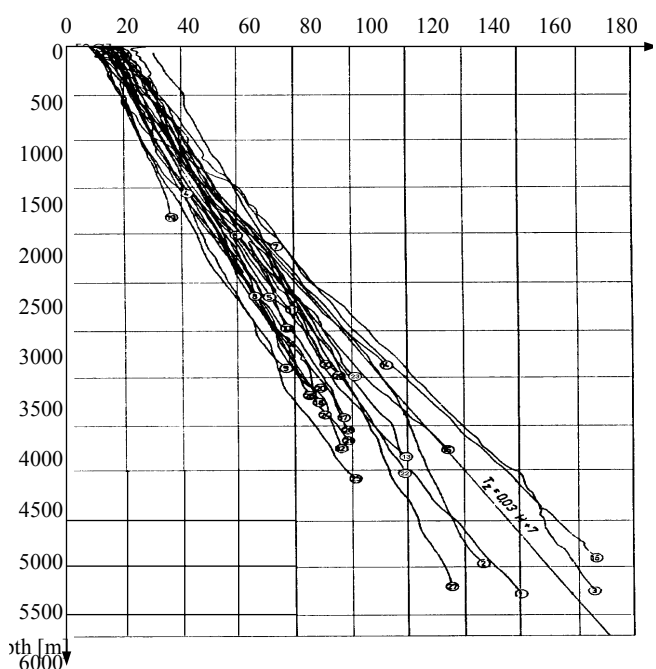

FIGURE 4:   Temperature profiles from wells completed in the Warsaw synclinorium (Sokolowska, 1991)

TABLE 1: Overview of wells drilled into the Warsaw synclinorium; top and bottom column names
refer to upper and lower boundaries of the Early Cretaceous aquifer

Town	Well no.	Latitude	Longitu.	Elev. (m a.s.l.)	Top (m u.s.l.)	Bottom (m u.s.l.)	Town	Well no.	Latitude	Longitu.	Elev. (m a.s.l.)	Top (m u.s.l.)	Bottom (m u.s.l.)
Bakow	Ba-240	52°09'58"	19°42'51"	96	11.6	41	Magnuszew	Ma IG-1	51°45'10"	21°23'21"	102	992	996.5
Bielsk	Bi-1	52°38'7"	19°49'38"	140	1024	1258	Mszczonow	Ms IG-1	51°58'30"	20°32'40"	171.33	1431.17	1563.7
Bochen	Bo-277	52°05'49"	19°49'55"	91	59	71.9	Mszczonow	Ms IG-2	51°56'50"	20°27'40"	180	1240.5	1359
Bodzanow	Bo-1	52°34'43"	20°00'56"	140	884	1105.6	Nadarzyn	Na IG-1	52°05'10"	20°51'50"	111	1072	1146
Bodzanow	Bo IG-1	52°30'56"	19°59'7"	119.7	1336.3	1556.3	Okuniew	Ok IG-1	52°16'36"	21°17'23"	100	786	812
Ciechanow	Ci-1	52°49'26"	20°32'30"	105	988	1045	Plonsk	Pl-4	52°34'20"	20°30'09"	100	990	1092.5
Dzialdowo	Dz-1	53°14'08"	20°09'47"	165	902	985	Plonsk	Pl-5	52°33'12"	20°37'11"	100	933.5	1096
Dzierzanowo	Dz-3	52°31'19"	20°12'26"	130	952.5	1138	Plonsk	Pl-7	52°33'35"	20°33'28"	107.5	969.5	1067.5
Gostynin	Go-5	52°32'05"	19°29'45"	75	380	643	Plonsk	Pl IG-2	52°36'02"	20°27'08"	120	929	1122
Gostynin	Go-6	52°30'11"	19°28'54"	75	321	629	Polik	Po IG-1	52°54'39"	19°45'28"	118.5	1097	1271
Gostynin	Go-7	52°24'20"	19°40'00"	103	703	935	Raducz	Ra IG-1	51°54'25"	20°21'30"	141.6	943.4	1081.9
Gostynin	Go-8	52°27'55"	19°44'22"	70	1146	1427	Rozyce	Ro IG-2	52°13'45"	19°58'55"	100	1260	1422.5
Gostynin	Go IG-1	52°26'36"	19°38'04"	112.3	626.7	898.2	Rozyce	Ro-1	52°14'14"	20°01'21"	99	1320	1487
Gradzanowo	Gr-2	52°59'37"	20°05'39"	110	989	1097	Sierpc	Si-2	52°47'50"	19°41'03"	120	952.5	1159.5
Gradzanowo	Gr-3	53°00'00"	20°06'28"	115	1006	1109	Skierniewice	Sk-445	51°58'02"	20°07'55"	124.5	331.5	493.5
Iwiczna	Iw IG-1	52°05'21"	21°01'44"	110	999.35	1056.4	Sochaczew	So-1	52°15'24"	20°18'33"	60	1106.5	1139
Karnkowo	Ka IG-1	52°51'26"	19°14'20"	110	1369	1641	Sochaczew	So-2	52°09'53"	20°20'36"	87.5	1330.5	1366
Kolce Step.	Ko-39	52°15'43"	19°46'05"	90	512	845	Sochaczew	So-3	52°11'20"	20°21'11"	90	1151	1181.5
Kompina	Ko-2	52°08'19"	20°00'05"	90	963	1137.5	Stugienice	St-278	52°07'55"	19°46'32"	90	12.8	60
Konopki	Ko-1	52°58'25"	20°24'49"	158	951	1005	Szczawno	Sz-1	53°02'18"	19°40'37"	130	1050	1191
Korabiewice	KoPIG1	51°57'55"	20°25'10"	164.4	1333.1	1453.1	Szwejki	Sz IG-3	51°42'46"	20°32'40"	178.8	215.2	335.7
Korzen Krol.	Ko-187	52°26'13"	19°37'52"	115	625.3	900	Warka	WaIG-1	51°43'56"	21°04'21"	112	1017	1075
Lipno	Li-4	52°58'30"	19°12'00"	100	1158	1219.5	Zduny	Zd-279	52°09'02"	19°48'13"	95	58.4	85.2
Lowicz	Lo IG-1	52°04'10"	19°59'10"	92	202	271.5	Zduny	Zd-310	52°09'27"	19°49'29"	95	96.9	165.5
Lowicz	Lo-7	52°05'55"	19°56'18"	86.2	191.8	263.8	Zuromin	Zu-2	53°05'21"	19°45'43"	133.5	991.5	1295
Lowicz	Lo-82	52°05'53"	19°56'29"	85.6	189.9	264.4	Zychlin	Zy IG-3	52°15'28"	19°45'37"	90	512.5	848
Lowicz	Lo-83	52°06'48"	19°56'52"	84.5	374	447.5	Zyrów	Zy-1	51°57'19"	21°03'27"	130	1076	1144

2.2 Geostatistical analysis of well data

Aquifer parameters like permeability, thickness and temperature vary in space. Initially, only well test parameters are known; between wells, these values are naturally not known. Here some geostatistical methods can be applied to fill in the gaps. In geostatistics, these parameters are treated as a random function, dependent on the spatial co-ordinates. A study of the Warsaw synclinorium spatial distribution of reservoir parameters, using geostatistical methods has been done (Stopa and Wojnarowski, 1999). First, empirical semivariograms were calculated using the Matheron formula and analysed to fit theoretical models. Next, modelling of parameter distribution was performed using 3D conditional stochastic simulation methods. A suite of conditionally simulated maps provided a measure of uncertainty about the parameter spatial distribution. These geostatistical analyses were performed using computer programs based on GSLIB procedures (Deutsch and Journel, 1992). The studies resulted in maps of depth to aquifer, its thickness, permeability and temperature. These maps are used here as a basis for a numerical simulation study (Chapter 4).

3. A CONCEPTUAL RESERVOIR MODEL

A conceptual reservoir model is the initial and most crucial step in modelling a geothermal reservoir. This model incorporates the most essential features of a geothermal system. It is constructed on the basis of geological, geochemical and geophysical data gathered from the system in question.

The Early Cretaceous reservoir in the Warsaw synclinorium is part of a wide permeable structure, found in a considerable area of Poland (Figure 2). It has the shape of a long syncline striking SE-NW. The

deepest part of the aquifer is near the city of Mszczonow, in the southern part of the reservoir (Figure 3). The depth is about 1500 m u.s.l. Figure 5 shows depth to the top surface of the Lower Cretaceous aquifer in the Warsaw synclinorium and its temperature distribution. The temperature varies from about 10-15°C at the southwestern outcrops to about 40-45°C in the deepest part of the reservoir. Thickness of the aquifer is variable. It changes from a few metres to about 200 m maximum.
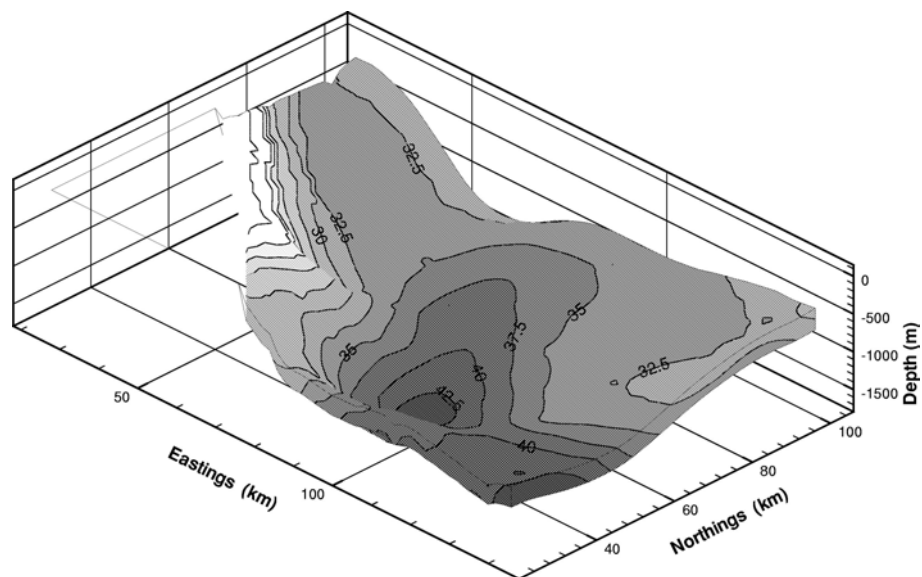

FIGURE 5: A 3-D map of depth to the Lower Cretaceous reservoir and its temperature distribution; the study area is shown by a rectangle in Figure 2

In vertical profile, the Early Cretaceous permeable sandstones are separated by impermeable mudstone and clay layers. The upper sandstone layer has higher permeability than the lower one. The western side of the synclinorium is steep and the Early Cretaceous deposits come to the surface in this part of the study area. The eastern side, however, passes softly into a platform slope. Fluid recharge is believed to come mainly from south and south-southeast where the Early Cretaceous formation makes contact directly with Quaternary deposits. A topographically driven pressure gradient from the Poland highlands in the south to the lowlands in the north results in a regional flow (Figure 2). Water outflow from the Early Cretaceous reservoir follows a northerly and northwesterly direction, parallel to the strike of the Pomorze-Kujawy Antyclinorium (Gorecki et al., 1995).

4. NUMERICAL MODEL

In order to better understand the Early Cretaceous reservoir in the Warsaw synclinorium, a numerical reservoir study was carried out. Numerical models consider the often complex geometry of reservoirs, variable properties of rocks and the physical state of geothermal systems. With a conceptual model at hand, the first step in a numerical simulation study is to build a natural state model, showing the physical state of the system before exploitation. After that an exploitation model is constructed, based on the former and on collected production data. Finally, the future reservoir performance under different production scenarios is predicted. In the present work, the TOUGH2, multiphase, multicomponent simulator was applied (Pruess et al., 1999).

4.1 Overview of the TOUGH2 simulator

TOUGH2 is a numerical simulator for nonisothermal flow of multicomponent, multiphase fluids in one-, two-, and three-dimensional porous and fractured media (Pruess et al., 1999). The basic mass and energy balance equations solved by TOUGH2 have the general form

$$\frac{d}{dt} \iiint_{V_n} M^\kappa dV_n = \iint_{\Gamma_n} F^\kappa \bullet n \, d\Gamma_n + \iiint_{V_n} q^\kappa dV_n \tag{1}$$

where V_n = Subdomain of analysed flow system;
Γ_n = Surface of the subdomain;
M = Mass or energy content;
κ = Mass component indicator;
F = Mass or heat flux;
q = Sink and sources;
n = Normal vector on surface element $d\Gamma_n$, pointing inward into V_n.

A general form of the mass accumulation term is

$$M^\kappa = \phi \sum_\beta S_\beta \, \rho_\beta \, X_\beta^\kappa \tag{2}$$

where ϕ = Porosity;
S = Saturation;
ρ = Density;
β = Phase indicator;
X = Mass fraction.

Phase fluxes are described by a multiphase version of the Darcy's law:

$$F_\beta = \rho_\beta \times u_\beta = -k \frac{k_{r\beta} \, \rho_\beta}{\mu_\beta} \times (\nabla P_\beta - \rho \times \beta \, g) \tag{3}$$

where u_β = Darcy velocity in phase β;
k = Absolute permeability;
$k_{r\beta}$ = Relative permeability of phase β;
μ_β = Dynamic viscosity of phase β;
P_β = $P + P_{c\beta}$ = fluid pressure in phase β;
$P_{c\beta}$ = Capillary pressure of phase β.

Continuum equations are discretized in space using the integral finite difference method (Narasimhan and Witherspoon, 1976). The time discretization results in a set of coupled non-linear, algebraic equations, which are solved by the Newton/Raphson iteration.

4.2 The model grid

To build a numerical model of the deepest part of the Early Cretaceous reservoir, a 3-D Cartesian rectangular grid was made by applying the meshmaker feature of TOUGH2. The computational mesh consists of 9672 elements of variable volumes. Figure 6 shows the model grid.

The smallest increment in the x and y directions is 50 m, assigned to well elements. The largest increment in those directions is 1500 m at the model boundaries. Each of the two permeable sandstone layers in the reservoir was divided into three horizontal layers; their thickness ranges from 14 to 17 m. The low-permeability clays and mudstones which separate these were divided into two layers with a thickness of 10 m each (Figure 6). The upper permeable zone is between 1431-1473 m u.s.l., and the deeper one at 1493-1544 m u.s.l. Note that the vertical depth span of the model is only between 1200 and 2100 m. At these two depths, the model is bounded by inactive elements. This was done in order to reduce the number of grid elements and, hence, computer time.
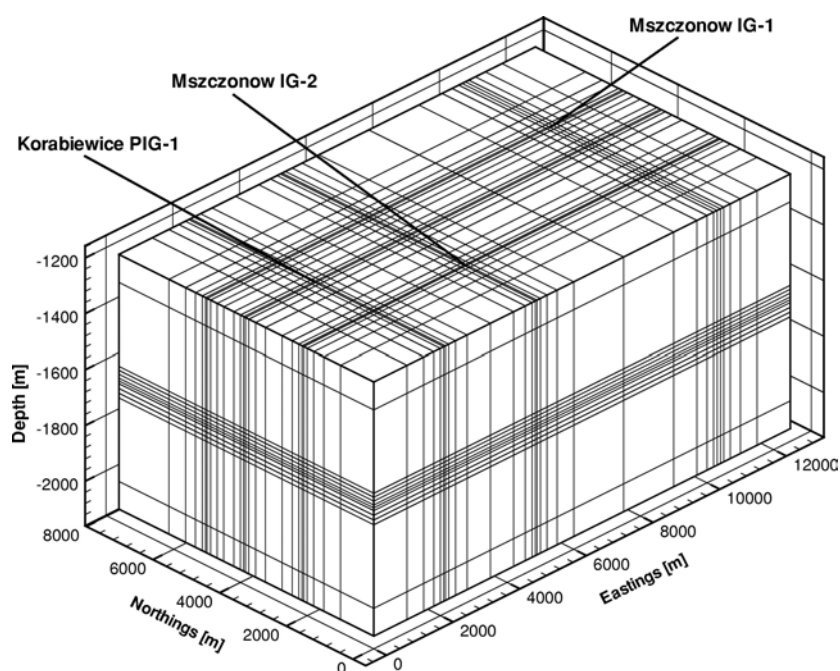
FIGURE 6:   The model grid used for the simulation study; highest density of grid elements is at wells PIG-1, IG-1 and IG-2. The Early Cretaceous reservoir is at approximately 1600 m depth below surface

4.3 Natural state simulation

A natural state model should match the observed thermodynamic conditions of a reservoir prior to exploitation. The main data utilized in natural state modelling come from the conceptual model and from initial temperatures and pressures in wells. Natural state simulation for the Early Cretaceous reservoir proceeded by estimating the model boundary conditions and properties of rocks to obtain hydraulic and thermal state, consistent with natural flow in the reservoir and with values measured in the wells. The reservoir pressure is in accordance with a static water level of 121 m a.s.l. in well Mszczonow IG-1.   A geothermal gradient of 0.028°C/m was assumed for that same location.

The top and bottom layers of the model were defined as inactive, i.e. all the elements are of constant pressure and temperature at all times. Furthermore, the outermost grid elements in each layer were also defined as inactive, but of slightly varying pressure and temperature in order to induce the regional flow observed from southeast to northwest (Figure 2).   Initially, the model is at constant temperature and pressure in all elements except for the inactive ones.   Temperatures are identical to what has been determined from the geostatistical analysis (Stopa and Wojnarowski, 1999). Table 2 gives an overview of the hydraulic reservoir rock properties, also estimated by geostatistical analysis. Due to the limited reservoir data available to constrain the model, no sensitivity analysis was performed. It should, however, be mentioned that vertical permeability must be low (in the order of few milli-Darcies) in order to prevent vertical fluid convection, which then greatly disturbs model temperature.   This conclusion is also supported by the linear type temperature profiles shown in Figure 4.

Layers 2 and 4 are the permeable parts of the reservoir. Layer 3 describes surrounding rocks and impermeable mudstones and clays between permeable sandstones. Layers 1 (top) and 5 (bottom) are inactive and only used to obtain the desired steady-state conditions. Steady-state conditions were then

TABLE 2:   Overview of rock properties in the numerical model; formation heat conductivity was presumed to be 2.4 W/m°C, and rock grain specific heat as 1000 J/kg°C for all layers

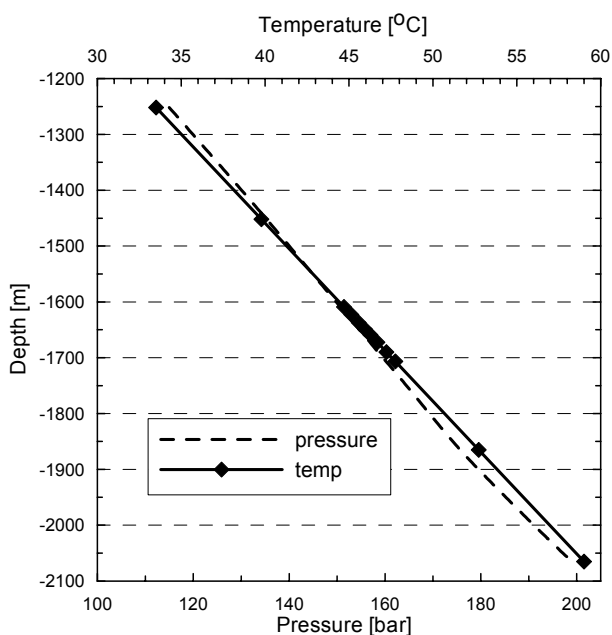| Name of layer	Porosity	Permeability, k_x [mD]	Permeability, k_y [mD]	Permeability, k_z [mD]
LAY 1	0.20	2500	2500	$2.5 \cdot 10^{-5}$
LAY 2	0.20	1600	1600	16
LAY 3	0.05	0	0	0
LAY 4	0.20	150	150	1.5
LAY 5	0.01	0	0	0

FIGURE 7: Calculated pressure and temperature
profiles with depth in well IG-1

reached after 35,000 simulated years. After this
period, equilibrium was established. Figure 7
shows the simulated pressure and temperature
with depth in well IG-1. The simulated steady-
state pressure and temperature distribution in the
upper permeable sandstone LAY 2 is shown in
Figure 8. Natural flow in the reservoir mainly
occurs to the southeast and northwest as a
consequence of the 1 bar pressure difference
between the model boundaries. Figure 8 shows
regional flow direction and temperature
distribution at the top of the aquifer.
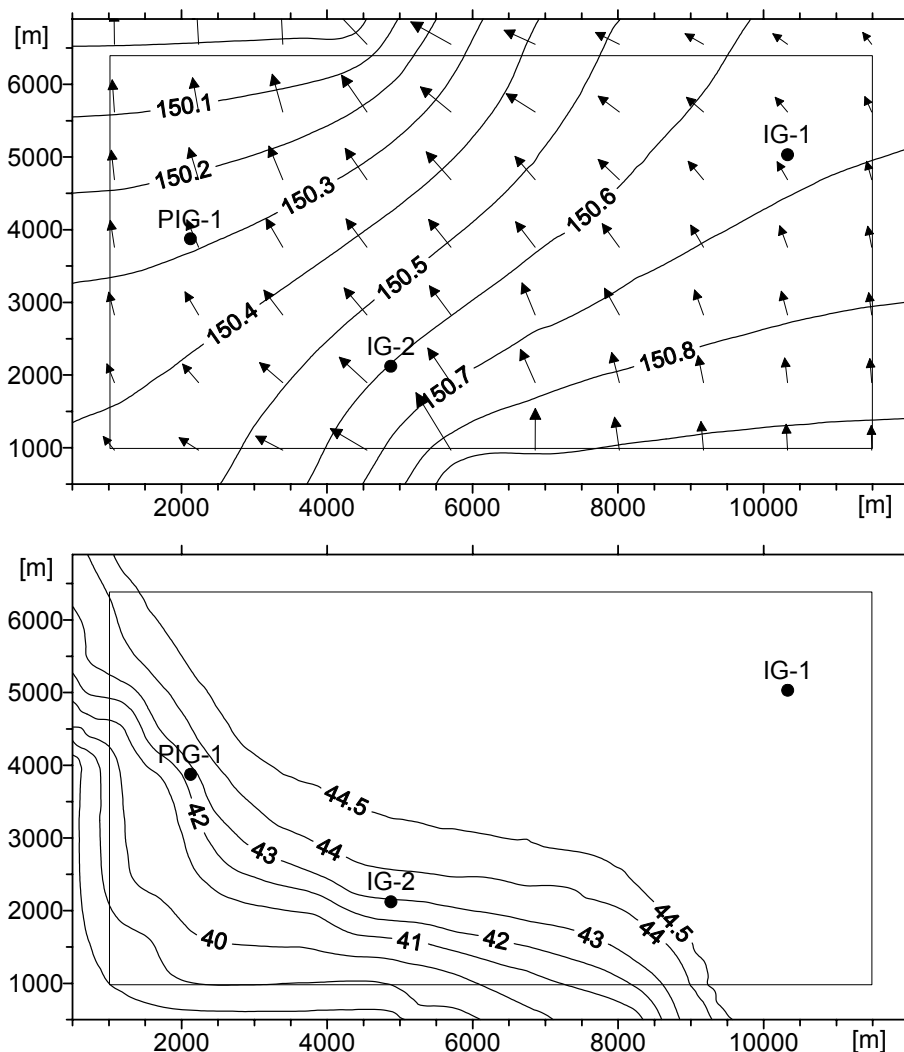
FIGURE 8: Simulated steady-state pressure (bars) and temperature (°C)
distribution in layer 2; model elements outside the rectangle,
shown on both graphs, are inactive (at steady-state)

5. RESERVOIR PERFORMANCE STUDIES

Well IG-1 is situated in the town of Mszczonow in the central part of the Warsaw synclinorium. On the basis of this well, a geothermal plant has already been built. Exploitation of water for central heating and domestic use in Mszczonow will start in winter 2000 as a single well system. Water with temperature of 41°C will be exploited with a flowrate of 60 m^3/hr. Due to environmental concerns and reservoir management purposes, some or all of the produced fluid may be re-injected at 10˚C temperature. In the vicinity of Mszczonow are situated two old wells, IG-2 and PIG-1, which can be used for injection (Figure 3). The natural state numerical model presented here can now be used as a tool for providing a preliminary estimate for the future performance of this reservoir. In order to do this, four production scenarios were considered:

Case 1: Production from well IG-1 only (60 m^3/hr);
Case 2: Production from well IG-1 (60 m^3/hr) with re-injection into well IG-2 (60 m^3/hr);
Case 3: Production from well IG-1 (60 m^3/hr) with re-injection into well PIG-1 (60 m^3/hr);
Case 4: Production from well IG-1 (60 m^3/hr) with re-injection into wells IG-1 and PIG-1 (30 m^3/hr for each).

Simulation time of 300 years was assigned for each case to predict future reservoir status. This long simulation period was selected due to the considerable distance between the wells in question. As shown earlier, the Lower Cretaceous reservoir is modelled here by two separate layers. It is assumed, however, that the 3 wells only intersect the upper layer (LAY 2), and that the injection/production only takes place in this layer.

Figure 9 shows simulated pressure at several locations away from well IG-1 to the west, for production case 1. Due to high reservoir permeability, fast pressure stabilisation is predicted (a few days). The greatest pressure change occurs in the well element of IG-1. Farther away, the pressure changes are very small. No temperature changes are predicted for this case during the 300 years of production.
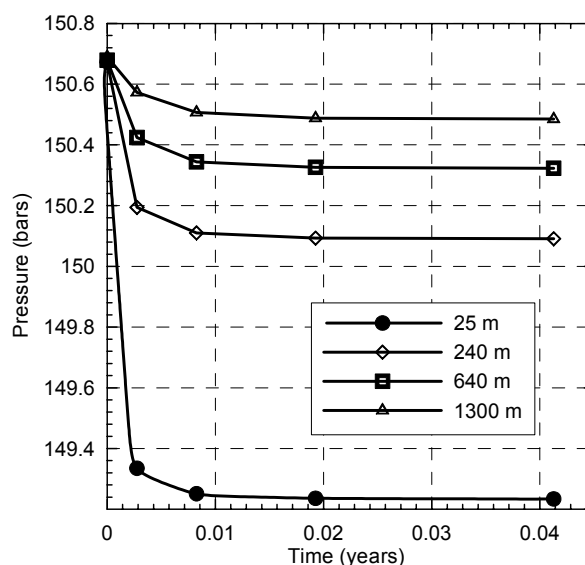
FIGURE 9: Predicted model pressures for production case 1 at a few different distances from production well IG-1

Case 2 considers the production-injection dipole IG-1/IG-2. Figure 10 shows the predicted pressure at a few different distances from the injection element of well IG-2. Similar to case 1, the pressure change is greatest in the injection well and then rapidly recovers with distance to the natural state pressure. The slower stabilisation time and almost doubled pressure changes, compared to that of the production well (Figure 9), are easily explained by cooling effects. Cooling by injection leads to increased viscosity of injected water, which then both elevates the pressure and extends the time constants of reservoir parameter changes.

Figure 11 shows predicted model temperatures with distance from injection well IG-2 for case 2. The reservoir cooling appears to be local and is hardly noticeable at 1000 m distance from the injection well.

Similarly shaped local perturbations in model temperatures and pressure are predicted for case 3. Figures 12 and 13 show this for increasing distance to the east from well PIG-1. Again a distance of 1000 m appears safe in terms of negligible reservoir cooling.
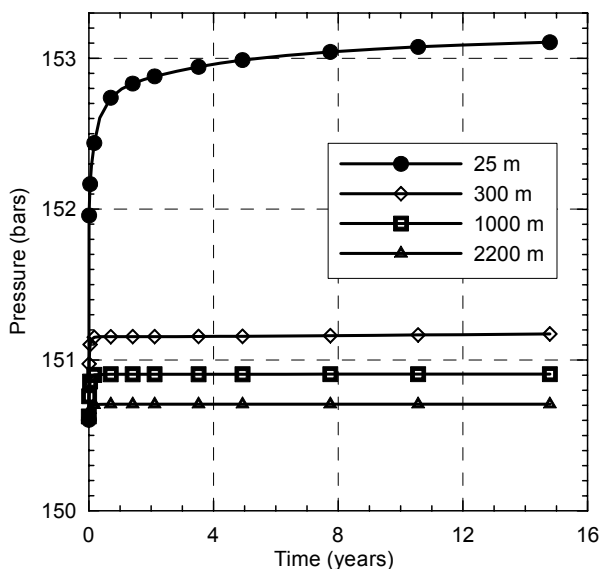
FIGURE 10: Predicted model pressures for
production case 2 at a few different distances
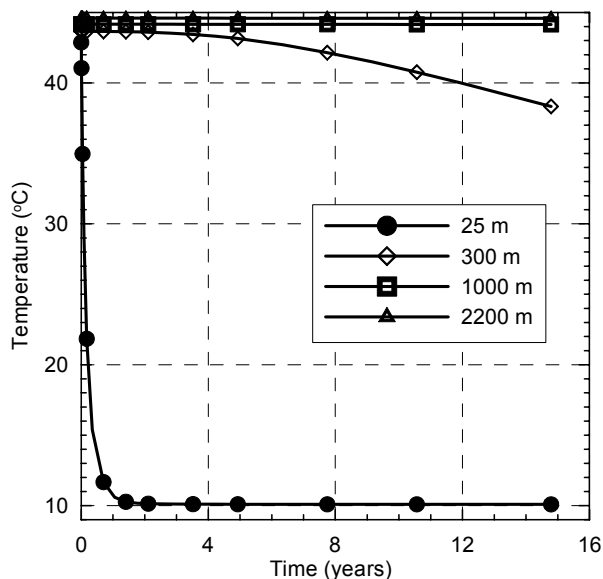from injection well IG-2 during injection

FIGURE 11: Predicted model temperatures for
production case 2 at a few different distances
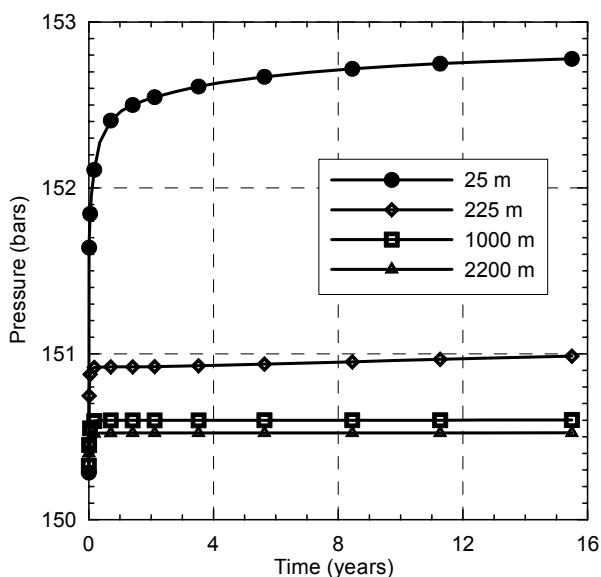from injection well IG-2

FIGURE 12: Predicted model pressures for
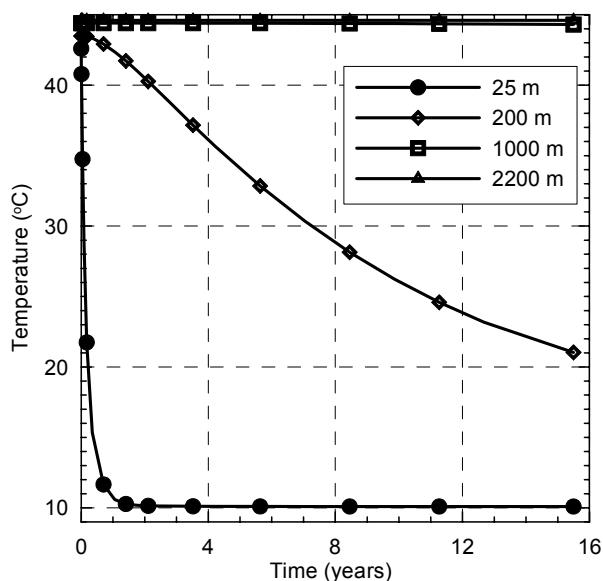production case 3 at a few different distances
from injection well PIG-2

FIGURE 13: Predicted model temperatures for
production case 3 at a few different distances
from injection well PIG-1

Somewhat different pressure and temperature distribution are predicted when water is injected into two
wells at a flowrate of 30 m^3/hr for each well (case 4). The range of the pressure disturbances is smaller
and more gentle. Pressures of the injection wells are also substantially lower than in the previous cases.
Furthermore, reservoir cooling of the area surrounding the injection wells is slower and more gentle than
in cases 2-3. Figures 14 and 15 show these predicted pressures and temperatures away from injection well
IG-2. A 1000 m distance between production and injection wells appears absolutely safe here, and even
300 m distance may prove to be adequate.
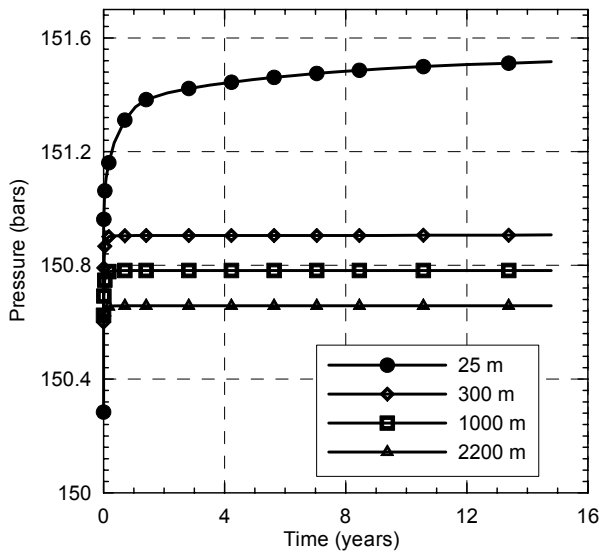
FIGURE 14: Predicted model pressures for a few different distances from injection well IG-2 for production case 4
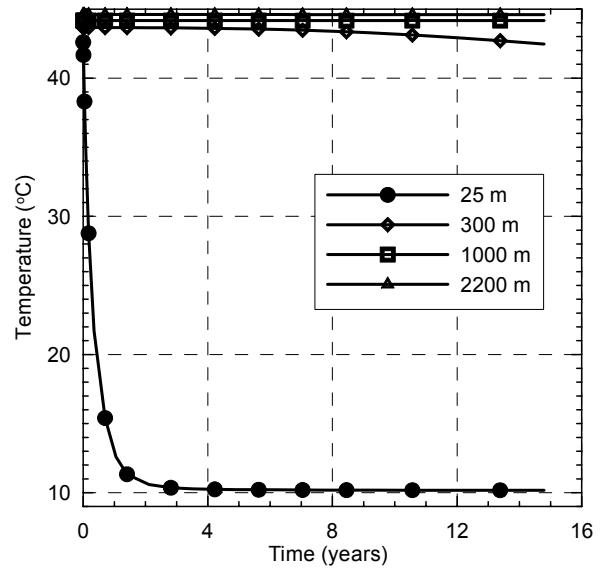
FIGURE 15: Predicted model temperature for a few different distances from injection well IG-2 for production case 4

Figures 16-23 show finally the predicted pressure and temperature distribution in the upper permeable aquifer (LAY 2) after 300 years of continuous production and injection. In all 4 prediction cases one can observe similar pressure changes and no temperature change around production well IG-1. Injection of water with a flowrate of 60 m³/hr causes local cooling, and large local pressure rise in the injection wells. Injecting into two wells at a flowrate of 30 m³/hr for each results in lower injection pressure compared to cases 2 and 3. Finally, locating the production well to the east of the injection wells appears favourable because of the regional flow which may counteract invasion of the colder injectate into the production
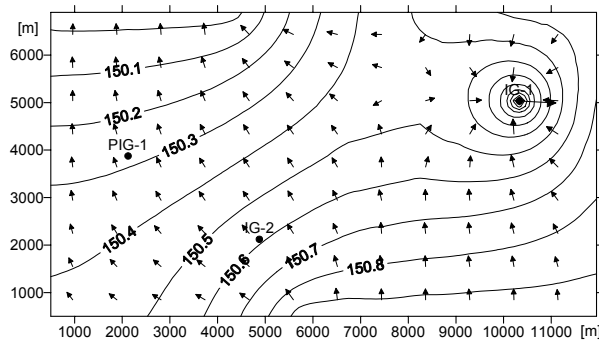
FIGURE 16: Pressure distribution for case 1 after 300 years of production from well IG-1
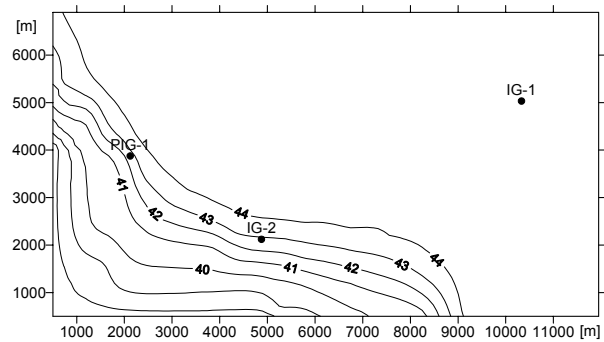
FIGURE 17: Temperature distribution for case 1 after 300 years of production from well IG-1
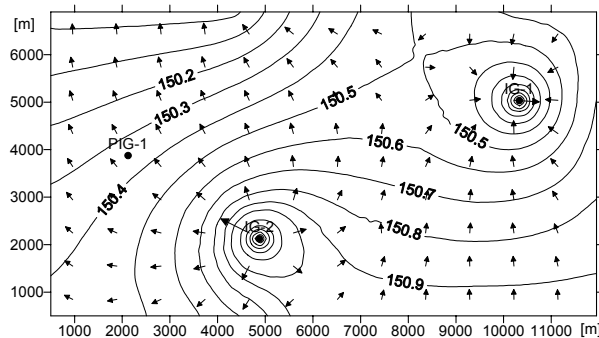
FIGURE 18: Pressure distribution for case 2 after 300 years of production from well IG-1 and injection into well IG-2
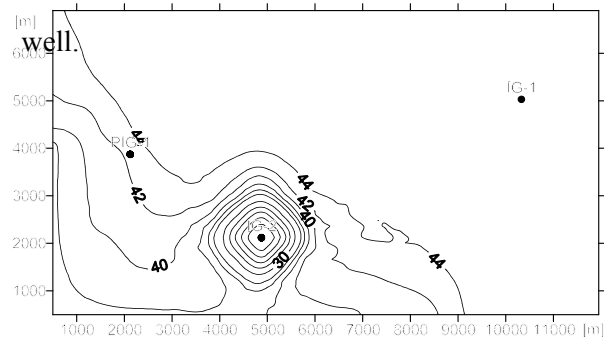

FIGURE 19: Temperature distribution for case 2 after 300 years of production from well IG-1 and injection into well IG-2
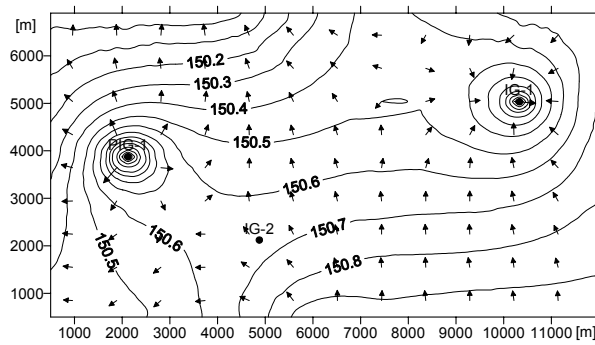
FIGURE 20:   Pressure distribution for case 3
after 300 years of production from well IG-1
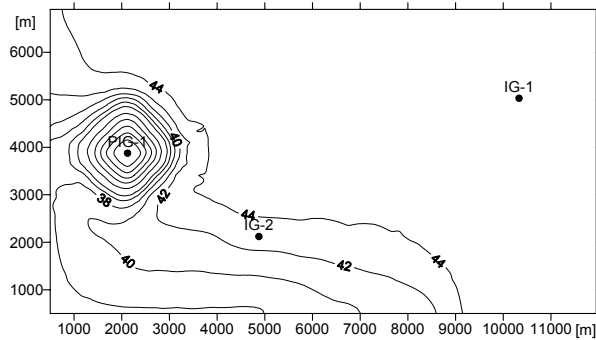and injection into well PIG-1

FIGURE 21:   Temperature distribution for case 3
after 300 years of production from well IG-1
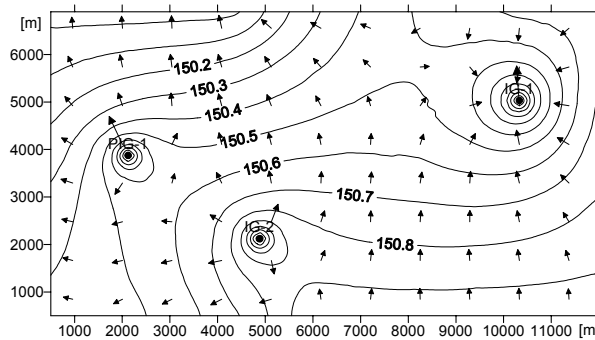and injection into well PIG-1

FIGURE 22:   Pressure distribution for case 4
after 300 years of production from well IG-1
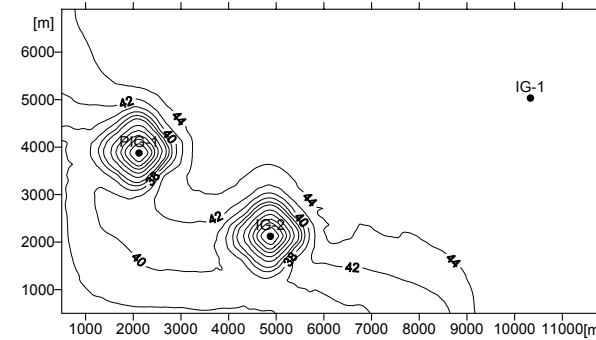and injection into wells PIG-1 and IG-2

FIGURE 23:   Temperature distribution for case
4 after 300 years of production from well IG-1
and injection into wells PIG-1 and IG-2

6. REGIONAL FLOW AND TRACER TEST

The preliminary modelling exercise presented in the Chapter 5 suggests that the Lower Cretaceous reservoir is of excellent production capacity, both in terms of pressure changes and cooling. Also, it appears that as short a distance as 1000-1500 m is sufficient for a production-injection well dipole and flowrates in the vicinity of 60 m^3/hr. The regional groundwater flow presumed in the reservoir is, however, of concern and may lead to overly optimistic predictions with regards to future reservoir cooling.

In order to check the influence of the regional flow, a single time step forward run was executed for the steady-state reservoir model. This time the flow across all connections was sought. Then, all the sum of flows through the upstream south and east model boundaries and also through the downstream west and north boundaries were computed. This resulted in a 9-10 kg/s flowrate through the upper model layer (LAY 2). This flowrate was then compared with the 17 kg/s assumed for the production/injection.

Secondly, the two-water option of TOUGH2 was used to estimate the mass fraction of the injectate in the reservoir layer, LAY 2. In order to obtain a pessimistic prediction, 60 m^3/hr were produced from well PIG-2 and injected to the upstream well IG-2, 3 km to the southeast. Figure 24 shows how the mass fraction of the injected fluid changes with time at a few downstream distances from the injection point.

The graph clearly shows that regional flowrates are very slow. For example, it may take more than 50 years to have a chemical breakthrough at 2800 m distance from the injection well (a chemical front velocity of approximately 50 m/year).

The overall conclusion from these 4 model cases is, therefore, that even with sizeable regional flow in our reservoir layer, the flow velocity is too slow to greatly influence the predictions. Much more important here is the conductive heat flow from the rock volume adjacent to the Lower Cretaceous reservoir layers.
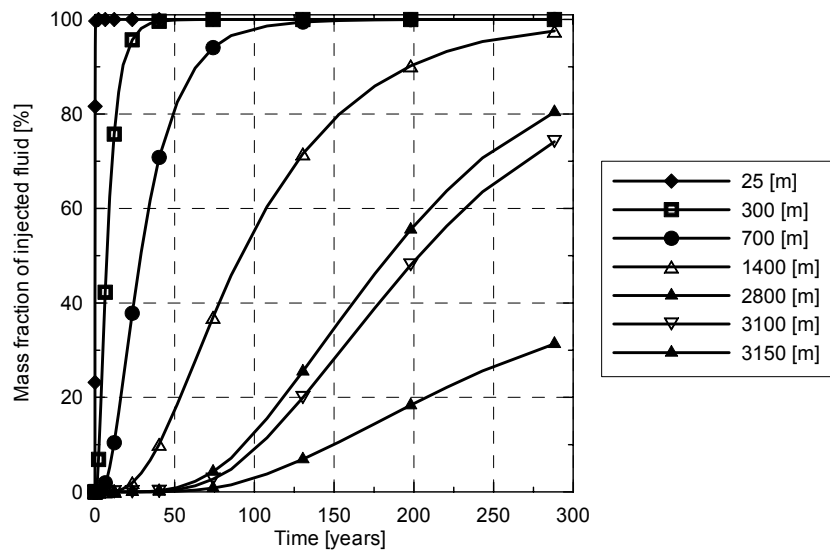

FIGURE 24: Predicted mass fraction of injectate with distance from injection point; 60 m³/hr are injected into well IG-2 and produced from well PIG-1; well PIG-1 is at 3150 m distance from IG-2

7. CONCLUSIONS

The main conclusions of this report are the following:

1. The Early Cretaceous reservoir in the central part of the Warsaw synclinorium can be used as a source of 45°C low-temperature geothermal water, utilized for central heating.

2. Production of 60 m³/hr from well Mszczonow IG-1, causes only local perturbations in the field pressure distribution.

3. Injecting water into wells Mszczonow IG-2 and Korabiewice PIG-1 does not affect the temperature of production well IG-1, even after 300 years of continuous injection.

4. Cooling effect is negligible because of the long distance between the wells and the regional flow in the reservoir.

5. Using two wells for re-injection appears favourable in order to reduce wellhead pressures of injection wells and for allowing less distance between injection and production sites.

6. It appears feasible to utilize old boreholes located in the study area as exploitation and injection wells.

7. Very slow chemical breakthrough times are predicted. Chemical front velocities may be as low as 50 m/year.

8. Because of favourable production characteristics, this reservoir appears to sustain considerably higher production rates than the 60 m³/hr studied here. Re-injection of cooled return water also seems a safe reservoir management strategy. For the time being, a minimum distance of 1000 m between injection and production well dipoles is recommended.

ACKNOWLEDGMENTS

REFERENCES

Deutsch C., and Journel A., 1992: *GSLIB geostatistical software library and user's guide*. Oxford University Press, New York.

Gorecki W., Kuzniak T., Lapinkiewicz A., Mackowski T., Strzetelski W., and Szklarczyk T., 1995: *Atlas of geothermal energy resources in the Polish Lowlands* (in Polish*)*. Towarzystwo Geosynoptykow GEOS, Krakow.

Kepinska B., 1998: Geothermal energy in Poland: the state-of-the-art in 1998 and future prospects. In Georgsson, L.S., (ed.), *Geothermal Training in Iceland, 20th Anniversary Workshop.* UNU, G.T.P., Iceland, 53-65.

Narasimhan T., and Witherspoon P., 1976: An integrated finite difference method for analyzing fluid flow in porous media. *Water Resources Research, 12-1*, 57-64.

Pruess K., Oldenburg C., and Moridis G., 1999: *TOUGH2 user's guide*. Lawrence Berkeley Laboratory, University of California.

Sokolowska, J., 1991: *Methodology of fluid resources exploration* (in Polish). Wydawnictwo CPPGSMiE PAN, Kraków.

Sokolowski J., 1992: *Geosynoptical atlas of Poland*. Wydawnictwo CPPGSMiE PAN, Krakow.

Stopa J., and Wojnarowski P., 1999: Uncertainty analysis for productivity of the geothermal wells in the area of Warsaw synclinorium using geostatistical simulation (in Polish, English abstract). Presented at the *10th International Scientific and Technical Conference „New Methods and Technologies in Petroleum Geology, Drilling and Reservoir Engineering",Krakow.*