Δελτίο της Ελληνικής Γεωλογικής Εταιρίας, τομ. XLVII , 2013
Πρακτικά 13^{ου} Διεθνούς Συνεδρίου, Χανιά, Σεπτ. 2013

Bulletin of the Geological Society of Greece, vol. XLVII 2013
Proceedings of the 13th International Congress, Chania, Sept. 2013

GEOTHERMAL RESOURCE MANAGEMENT-A RESERVOIR SIMULATION APPROACH-THE PARIS BASIN CASE

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Abstract

Numerical modeling has become an indispensable part of geothermal resource management, especially when long-term production is involved, offering the ability to forecast the reservoir behavior under various exploitation scenarios. This paper illustrates the simulation results of the "Dogger" reservoir in Val de Marne region (south of Paris), where 16 doublets (production-injection wells) are still in operation today. The "Dogger" low enthalpy geothermal reservoir in Paris Basin is being under intensive and systematic exploitation since the early 1980's. Almost 40 years after the initiation of the heat mining project, the longevity of the reservoir and applications have become critical issues for achieving the exploitation system's sustainability. The simulation covers a period of 52 years (1984-2035), attempting to recreate the exploitation history and to provide an early estimation of the time-space variation of pressure and temperature inside the reservoir under future production/injection schemes and schedules. For the majority of the wells, the calculated production temperatures match quite well the field data up to the year 2011. The prediction models indicate that certain modifications in the development scheme could result in the stabilization of the fluids temperature, or at least in slower depletion rates.

Key words: *geothermal exploitation, Dogger, sustainability.*

Περίληψη

Οι αριθμητικές προσομοιώσεις αποτελούν ένα χρήσιμο εργαλείο διαχείρισης των γεωθερμικών ταμιευτήρων, ιδιαίτερα αυτών που βρίσκονται υπό μακροχρόνια εκμετάλλευση, παρέχοντας μεταξύ άλλων τη δυνατότητα πρόβλεψης της μελλοντικής συμπεριφοράς τους υπό διάφορα σενάρια αξιοποίησης. Η εργασία αυτή πραγματεύεται τα αποτελέσματα των προσομοιώσεων στο τμήμα του γεωθερμικού ταμιευτήρα Δογγέριου ηλικίας, που εκτείνεται στην περιοχή Val de Marne (νότια του Παρισιού), όπου λειτουργεί πυκνό δίκτυο γεωτρήσεων. Η εντατική εκμετάλλευση του γεωθερμικού δυναμικού στη λεκάνη του Παρισιού ξεκίνησε τη δεκαετία του 1980, με τη διάνοιξη πολλών γεωτρήσεων παραγωγής και επανεισαγωγής για την παροχή θέρμανσης και ζεστού νερού χρήσης. Αναπόφευκτα, περίπου τέσσερις δεκαετίες μετά, η βιωσιμότητα του συστήματος εκμετάλλευσης εξαρτάται άμεσα από την παράταση του χρόνου ζωής του ταμιευτήρα και των εφαρμογών. Η προσομοίωση καλύπτει περίοδο 52 ετών

(1984-2035), αναπαριστώντας το ιστορικό εκμετάλλευσης και παρέχοντας εκτιμήσεις για τη μελλοντική χωροχρονική μεταβολή της θερμοκρασίας και του υδραυλικού φορτίου μέσα στον ταμιευτήρα. Για την πλειονότητα των γεωτρήσεων, οι θερμοκρασίες που υπολογίστηκαν για το έτος 2011 είναι συγκρίσιμες με τα πραγματικά δεδομένα, ενώ τα μοντέλα πρόγνωσης έδειξαν ότι η τροποποίηση του σχήματος εκμετάλλευσης, μπορεί, υπό προϋποθέσεις, να οδηγήσει σε σταθεροποίηση της θερμοκρασίας των παραγόμενων ρευστών ή τουλάχιστον σε πιο αργούς ρυθμούς μείωσής της.

Λέξεις κλειδιά: *γεωθερμική εκμετάλλευση, Δογγέριος ταμιευτήρας, βιωσιμότητα.*

1. Introduction

Geothermal energy is an environmentally friendly energy source, which can be regarded as renewable, yet not inexhaustible at human time scale and under intensive exploitation. This is simply attributed to the fact that heat is abstracted faster from a geothermal system (via convection) that is naturally replaced by the terrestrial heat flow (via conduction) (Ungemach et al., 2005). Therefore, the crucial issue of achieving sustainability largely depends on creating a balance between the longevity of the resource and the demands of the heat mining project. An important factor for accomplishing sustainability is, among others, the effective geothermal field management, which in turn is based principally on the rational reservoir management. Ungemach and Antics (2003) have suggested an intergraded approach to sustainable reservoir management strategies as a combination of the exploitation system economics, the reservoir/well life, the offer/demand heat amounts, the reservoir engineering, certain externalities, etc.

Numerical simulations constitute a very useful tool for reservoir engineering purposes by providing an early estimation of the temperature and pressure (or hydraulic head) space-time variations inside the reservoir, thus contributing to the better understanding of its response under long-term exploitation.

The aforementioned will be discussed for the well-documented low enthalpy reservoir of Dogger (Middle Jurassic) age in Paris basin. The geothermal exploitation of the Dogger reservoir started in the early 1970's and boosted in the 1980's with the construction of 55 doublets (110 production and injection wells) for district heating purposes. As for the year 2012, 71 geothermal wells have been in operation, supplying 27 district heating networks.

The area of Val de Marne is located south of Paris and includes a dense network of 32 geothermal wells, following the doublet (production-injection) concept (Figure 1). The simulations regard the past and future exploitation strategies over an entire period of 52 years and aim at investigating the behaviour of a relatively large part of the Dogger reservoir under a complex production scheme that was designed according to the anticipated well and reservoir lifetimes.

2. Geological-Geothermal Setting of the Study Area

Paris Basin is a stable intra-cratonic sedimentary basin that occupies the largest part of northern France, covering an area of 110.000 km^2 (Perodon and Zabek, 1990). Its basement consists of Palaeozoic igneous and metamorphic rocks (Pomerol, 1978), overlaid by a thick sequence of Mesozoic and Tertiary sedimentary rocks that gradually filled the basin. Their thickness reaches its maximum (3000 m) in the central part of the basin. The geothermal fluids are hosted by the Middle Jurassic (Dogger) marine carbonate sediments that lay between marls of Low Jurassic and Callovian age (Rojas et al., 1989; Perrodon and Zabek, 1990). The most productive layers are white oolithic limestones, typical of a warm-sea sedimentary environment. The salinity of the hot fluids is very high (5.8-35g/l), varying significantly from the southwest to the northeast of the basin (Rojas et al., 1989). The high salinity and the CO_2/H_2S gas phase of the fluids have made injection of the heat-depleted brine into the reservoir an environmental prerequisite, alongside pressure maintenance (Ungemach et al., 2005).

The detailed geothermal exploration in Paris basin (Rojas et al., 1987; 1989) revealed the high vertical and lateral heterogeneity of the reservoir, regarding both its structure and major features. The reservoir depths and formation temperatures range from 1400-2000 m and 56-80°C, respectively. The mean geothermal gradient is 35°C/km and increases to the east. The overall reservoir consists of several successive productive and interbedded impervious layers.

The reservoir top in Val de Marne region deepens from the west (1550 m below sea level) to the east (1720 m b.s.l.) and the fluids temperatures range from 70°C to 79-80°C accordingly. The first geothermal doublet was drilled in 1984; today 16 doublets are still in operation.

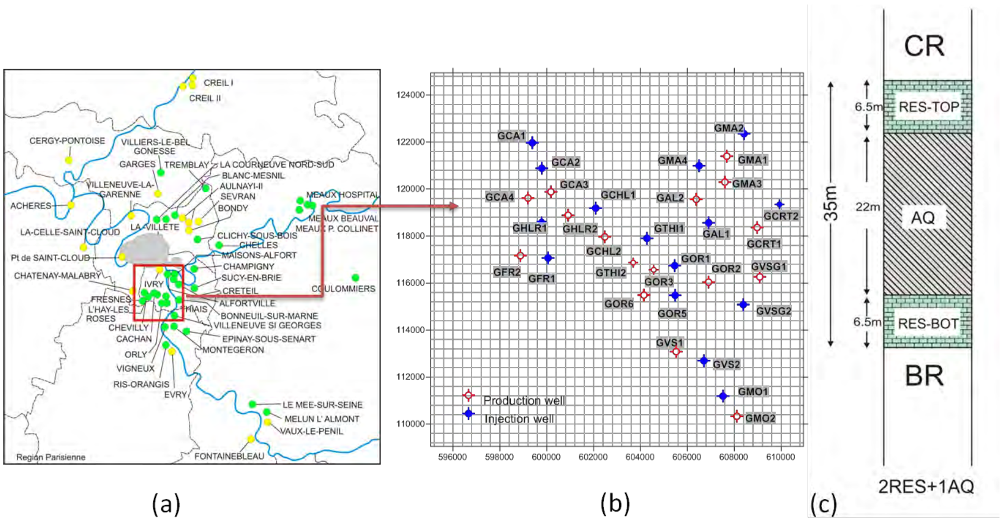
3. Simulation

3.1. Techniques and Methods

The transient processes that have been simulated are groundwater flow and heat transfer. The numerical simulator used is SHEMAT® (Clauser et al., 2003), which solves the 3-D coupled problem of flow and transport in fluid-saturated porous media, on a 3-D grid with x, y, z coordinates. It uses a finite difference method to approximate the partial differential equations that describe the internal processes. The spatial discretization of the advection term in the transport equation was made by the Il'in flux blending system (Il'in, 1969) and the resulting system of equations was solved implicitly by the strongly implicit procedure (SIP, Weinstein et al., 1969).

3.2. Simulation Features

The simulated part of the reservoir covers an area of 256 km^2 (Figure 1a), which exhibits significant vertical and lateral heterogeneities. The model grid consists of 25600 cells (160 rows and 160 columns) with cell dimensions of 100 m x 100 m x z (z: the thickness -in m- of each layer).



(a) (b) (c)

Figure 1 - (a) Sketch map of the Val de Marne simulation domain, (b) doublets configuration (b) reservoir structure (RES: productive layers, AQ: aquitard, CR: cap rock, BR: bed rock).

The geometry of the multilayered reservoir is depicted by the so called "sandwich" configuration (Antics et al., 2005) (Figure 1b), which includes two symmetric (geometrically and hydraulically) productive units and an intermediate single aquitard (hydraulically impervious but thermally conductive layer). The reservoir is bounded by two confining layers, the cap (CR) and the bedrock

(BR). The simplified “sandwich” structure is used to meet the software constrains, regarding the thickness and depth variation of each layer in the model domain and the total amount of monitoring points (i.e. operating wells) taken into account.

Nevertheless, it should be mentioned that the sandwich configuration is regarded as a satisfactory substitute for the real, more complex geometry, especially for large simulation time scales, according to the sensitivity analysis of the cooling kinetics to various reservoir structure and settings for Paris Basin (Antics et al., 2005; Ungemach et al., 2007; Papachristou, 2011; Ungemach et al., 2011). The production temperature declines more rapidly for the first few years in the sandwich model than to a multi-layered model that corresponds the real stratigraphy of the reservoir. However, the depletion rate becomes slower and finally matches the multi-layer case for long simulation times.

The thickness of the reservoir layers (Figure 1b) has been calculated by averaging the correspondent thicknesses identified from flowmeter loggings in each well. The thickness of the cap and bedrock in the model are set to 200 m and 100 m respectively. The vertical boundary conditions consist of constant temperature, assigned for each cell midpoint according to the temperature gradient for the caprock, and constant heat flow (0.09 W/m^2) for the bedrock. The lateral boundary conditions are set as constant head and temperature.

The lateral reservoir heterogeneities have been assigned in the model by extrapolating, via Kriging, the available field data. The overall initial conditions regarding head, temperature, permeability and porosity are displayed in Figure 2. It is assumed that the three reservoir layers were in thermal equilibrium prior to exploitation.

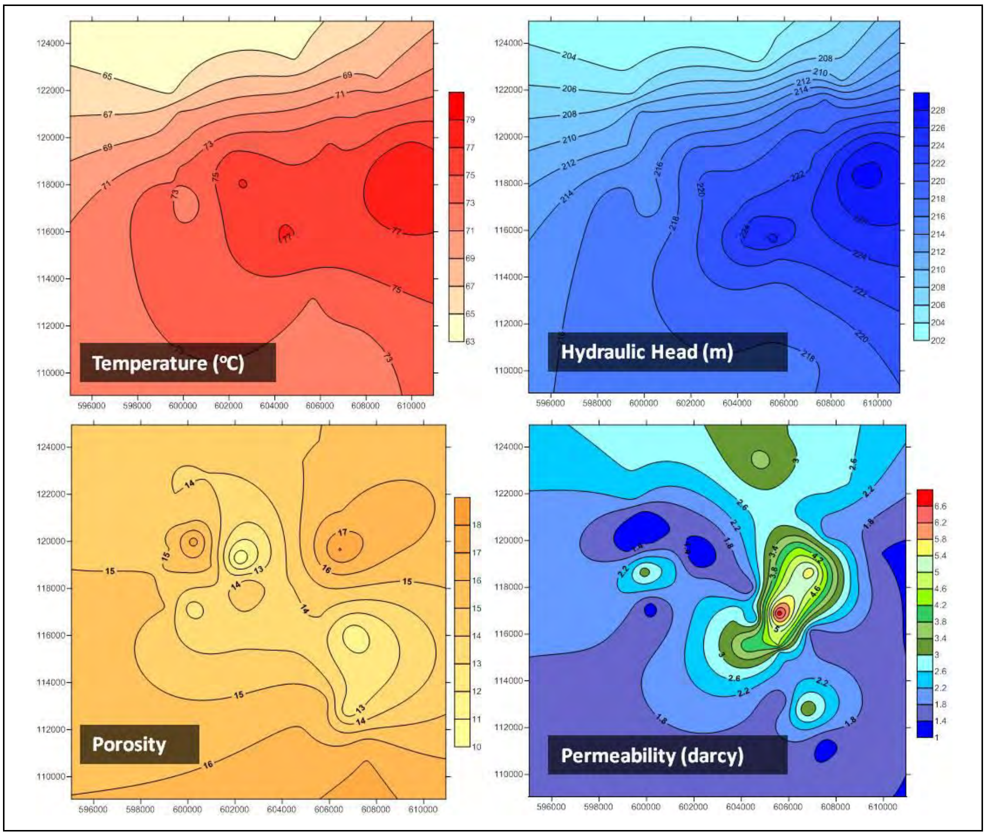


Figure 2 - Permeability and porosity distribution and initial head/temperature conditions in the Dogger reservoir of Val de Marne region.

Table 1: Production/Injection Schedule.

Doublet/Triplet	Operation Period	Prod/Inj rate (m^3/h)	T_{in} (°C)	$T_{inj.}$ (°C)
GFR1(i)+GFR2(p)	1987-2010	137	74.30	48.0
	2011	145		48.0
	2012-2013	177		48.0
	2014-2015	100		50.0
	2016-2020	116		50.0
	2021-2035	149		50.0
GFR4(i)+GFR3(p)	2014-2015	118	73.90*	50.0
	2016-2020	136		50.0
	2021-2035	210		50.0
GTHI1(i)+GTHI2(p)	1987-2015	160	76.60	50.0
GTHI1(i)+GTHI2(i)+GTHI3(p)	2016-2035	125	76.72*	46.0
GCA1(i)+GCA3 (p)	1986-2015	110	71.00	48.0
GCA1(i)+GCA3(i)+GCA5(p)	2016-2035	110	71.37*	46.0
GCA2(i)+GCA4 (p)	1986-2015	125	70.00	48.0
GCA2(i)+GCA4(i)+GCA6(p)	2016-2035	125	69.00*	46.0
GCHL1(i)+GCHL2(p)	1986-2015	170	77.20	48.0
GCHL1(i)+GCHL2(i)+GCHL3(p)	2016-2035	180	75.73*	45.0
GHLR1(i)+GHLR2(p)	1986-2015	165	74.10	47.0
GHLR1(i)+GHLR2(i)+GHLR3(p)	2016-2035	175	73.30	45.0
GMA2(i)+GMA1(p)	1986-2010	160	73.30	52.0
	2011-2016	185		53.0
GMA2(i)+GMA1(i)+GMA5(p)	2021-2035	200	75.72	52.0
GMA4(i)+GMA3 (p)	1986-2010	180	75.2	58.0
	2011-2020	140		57.0
GMA4(i)+GMA3(i)+GMA6(p)	2016-2035	200	73.56*	52.0
GAL1 (i)+GAL2 (p)	1988-2015	180	75.20	45.0
GAL1(i)+GAL2(i)+GAL3(p)	2016-2035	200	75.89*	40.0
GVS2(i) +GVS1(p)	1988-2015	137 (1986-1995)	72.9	44.0
		147 (1996-2005)		46.0
		117 (2006-2015)		47.0
GVS2(i)+GVS1(i)+GVS3(p)	2016-2035	150	75.02*	44.0
GOR1(i)+GOR2(p)	1984-2015	75	76.0	45.0
	2016-2035	125		42.0
GOR4(i)+GOR3(p)	1987-2005	177	76.9	45.0
GOR5(i)+GOR6(p)	2009-2010	190	77.0	42.0
	2011-2035	200		42.0
GMO1(i)+GMO2(p)	1986-2010	100	72.5	50.0
GVSG2(i)+GVSG1(p)	1988-2015	170 (1988-2005)	77.9	45.0
		135 (2005-2015)		47.0
GVSG2(i)+GVSG1(i)+GVSG3(p)	2016-2035	150	77.16*	43.0
GCRT2(i)+GCRT1(p)	1986-2010	180	78.9	45.0
	2011-2015	190		42.0
GCRT2(i)+GCRT1(i)+GCRT3(p)	2016-2035	200	78.15*	45.0
IADP(i)+PADP(p)	2011-2015	180	75.0	42.0
IADP(i)+PADP(p)	2016-2035	190	75.05*	42.0

T_{in}=initial production temperature, T_{inj}=injection temperature, * =simulation result.

The total simulation time is 52 years, divided into three periods: 1984-2010, 2011-2015 and 2016-2035 (Table 1). The first represents the exploitation history and the others the future production/injection schemes and schedules, with the construction of new wells and the triplet array substituting, in many cases, for the former doublet configuration (Figure 3). The head and temperature time-space distribution at the end of the first simulation period provide the necessary information for planning the future exploitation scenarios and new well locations.

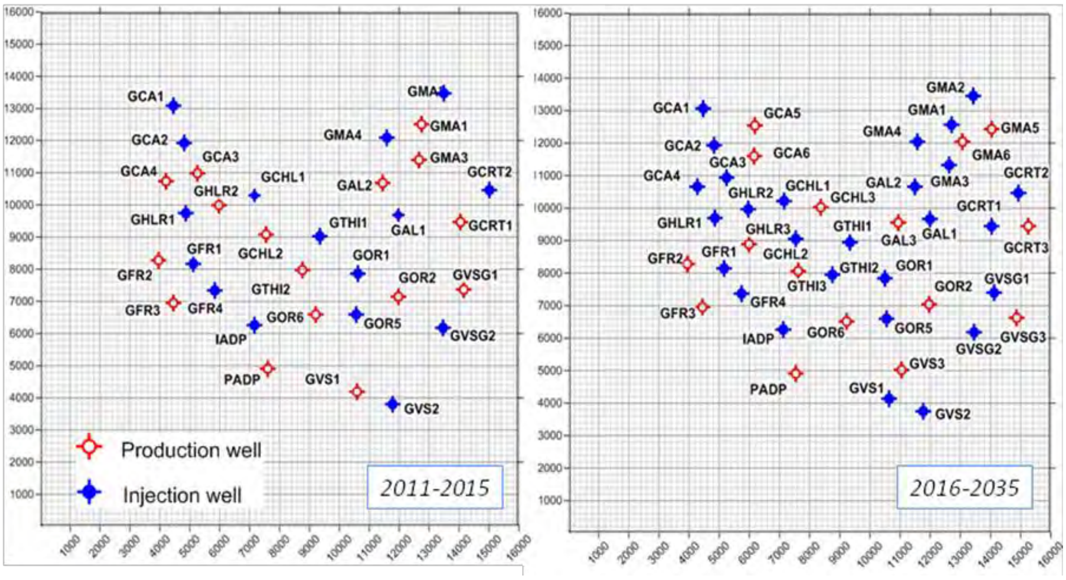


Figure 3 - Well network in 2011-2015 and 2016-2035 periods.

4. Results-Discussion

The temperature depletion results ($T_{initial}$-T_{final}) for each simulation period are as follows:

- 1984-2010: **GFR2** (-1.09), **GCA3** (-1.03), **GCA4** (-0.30), **GCHL2** (-1.33), **GHLR2** (-2.58), **GVS1** (-1.12), **GOR2** (+0.54), **GOR3** (-2.57), **GTHI2** (-1.45), **GVGS1** (-1.00), **GAL2** (-2.68), **GMA1** (-2.78), **GMO2** (-0.75), **GMA3** (+0.76), **GCRT1** (-1.44)
- 2011-2015: **GFR2** (-0.36), **GCA3** (-0.28), **GCA4** (-0.33), **GCHL2** (-0.47), **GHLR2** (-0.69), **GVS1** (-0.43), **GOR2** (+0.00), **GTHI2** (-0.88), **GVGS1** (-0.18), **GAL2** (-0.60), **GMA1**(-0.52), **GMA3** (-0.10), **GOR6** (-1.48), **GCRT1** (-0.46), **PADP** (0.00), **GFR3** (+0.06)
- 2016-2035: **GFR2** (-1.99), **GCA5** (-0.74), **GCA6** (-0.63), **GCHL3** (-2.10), **GHLR3** (-3.50), **GVS3** (-2.21), **GOR2** (-0.65), **GTHI3** (-2.13), **GVGS1** (-1.89), **GAL2** (-6.16), **GMA3**(-0.07), **GMA5** (-1.89), **GMA6** (-7.73), **GOR6** (-2.79), **GCRT3** (-4.11), **PADP** (-1.97), **GFR3** (-3.54)

4.1. Simulation Period 1984-2010

Between the years 1984 and 2010, 16 doublets were gradually set in operation. After the year 2005, the GOR3-GOR4 doublet was abandoned due to serious technical problems. For the majority of the wells, the calculated temperature and the thermal breakthrough time (t_b), which is assumed equal to a 1°C temperature drop, match well or slightly differ from the actual data (year 2011), given the inevitable simplifications of the reservoir geometry previously discussed.

The most important temperature decrease occurs in the GAL2, GMA1, GHLR2 and GOR3 wells. An average drop of 2-3°C has been indeed recorded for the GAL2 well (Lopez et al., 2010; Le Brun et al., 2011); therefore the simulation result is considered reliable. On the contrary, there are not any available recorded temperature data for the problematic GOR3 well. The difference between calculated and actual data for the GHLR2 and GMA1 wells could be explained by the simplified reservoir structure in the model, which affects more the wells that are located at sites with much more complicated layering. However, the case of the GMA doublet should be further commented. According to the drilling data, the depth of the reservoir top between the production (GMA3) and the injection (GMA4) wells is notably different (-1628 and -1531 m, respectively). This important lateral depth variation has not been accounted for in the simulation due to software limitations, according to which it is assumed that all wells operate in the same depth inside the reservoir. Therefore, neither the time delay of the thermal/hydraulic front arrival nor the thermal exchanges for this depth interval are calculated.

4.2. Simulation Period 2011-2015

During this period, 15 doublets are in operation according to the exploitation schedule. In 2011, the PADP-IADP wells have been completed and set in operation in the ORLY Airport of Paris.

The significant temperature decrease of the GOR6 fluids is mostly attributed to the intensification of heat production (high production/injection rates in combination to low injection temperatures). Additional simulation runs show that the final production temperature is not affected by the increase of injection temperature by 2°C. In contrast, lower production/injection rates (by 30m^3/h) result in a significantly lower temperature depletion (0.5°C).

4.3. Simulation Period 2016-2035

Many of the existing production and injection wells are recompleted and converted into injectors between the years 2016 and 2035. New, large diameter, production wells are constructed at selected sites, changing the array from doublet to triplet. The heat generation is maximized to meet higher future demands.

The simulation results show fast temperature depletion rates in five wells: GFR3, GHLR3, GAL3, GMA6 and GCRT3. In all cases, these results are related to the wells' location. Clearly, as it can been seen at the temperature and head pattern maps of Figure 4, these wells are affected by the neighboring injectors and the development of a high pressure (head) zone that cause faster flow of the (colder) fluids towards the lower pressure areas.

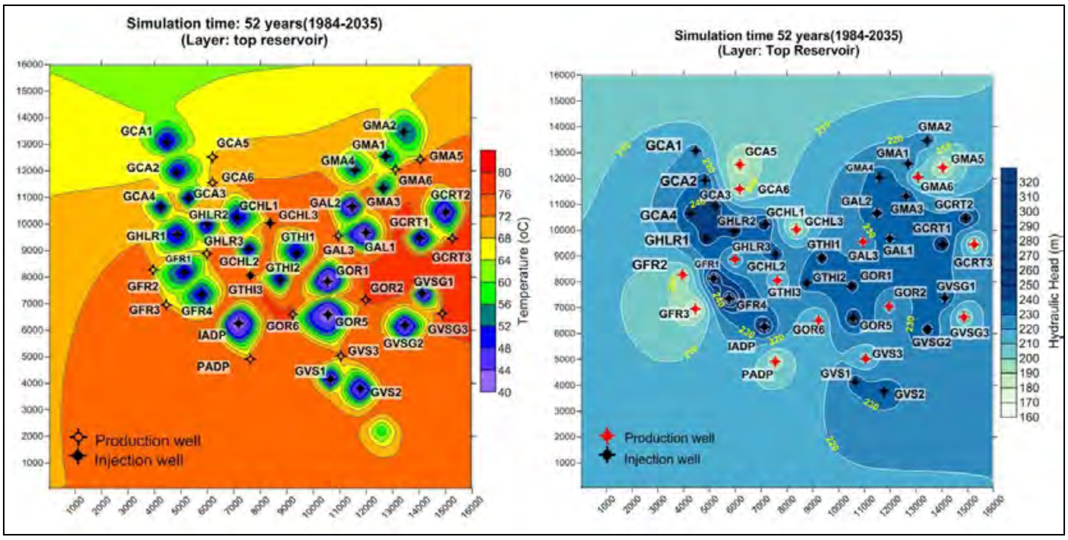


Figure 4 - Temperature and head distribution (31.12.2035).

Certainly, the significantly lower temperature is more or less expected for the GHLR3 case, given that in this specific area the effect of the simplified stratigraphy is more obvious, as discussed in Chapter 4.1. Nevertheless, modifying the GHLR3 well location (at reservoir depth) by 200 m, the temperature drops by 2.45°C (opposite to 3.50°C), with no changes in pressure.

The case of GAL3 and GMA6 wells, which show the most important temperature drop (-6.16 and -7.73°C respectively), need further investigation in order to find the proper combination of tolerable temperature depletion and reasonable head decrease.

By re-locating the GAL3 well around 400m to the northwest (Figure 5a), the temperature reduction becomes significantly smaller (-3°C). Similarly, by moving GMA6 800 m towards the east-southeast (Figure 5a), the temperature drops by 1.5°C only. However, in this new GMA6 location the pressure becomes an issue as a result of the long distance between the production well and its injectors (GMA3-GMA4) on one hand, and the operation of the nearby GMA5 production well that causes an additional head drop on the other. To avoid this, GMA6 is placed 200 m further to the south, whereas GMA3 operates as the only injector, in order to maintain adequate pressure levels (Figure 5b). In this case, the temperature reduces 2.5°C and the hydraulic head are higher. The system operates a doublet instead of a triplet.

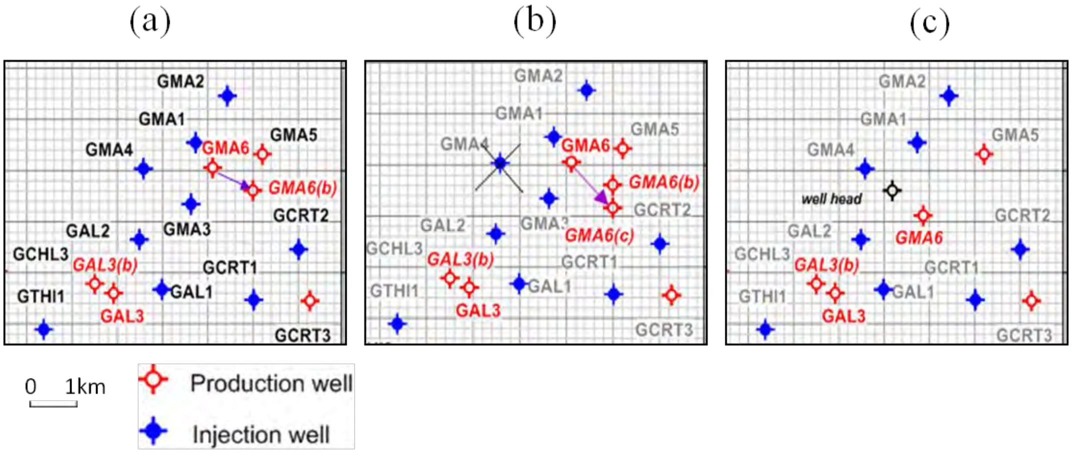


Figure 5 - GAL3 and GMA6 various well locations.

Nonetheless, when dealing with well placement, the well architecture should not be ignored. Especially for Paris basin, the production and injection wells are routinely drilled from the same platform on surface, with an average 30-35°C angle securing a well spacing in top reservoir depth varying from 900-1200 m (Ungemach et al., 2011). This condition is not satisfied by the last tested scenario, due to the platform position in surface ("well head" in Figure 5c). Subsequently, the optimal setting for the GMA wells that takes into consideration both technical and thermodynamic issues, regard as most "realistic" the case of the new production well (GMA6) encountering the top reservoir very close to the former production well GMA3. The latter is abandoned and the new well system remains as a doublet, with only one injector, the GMA4 well (Figure 5c). This simulation results in lower temperature decrease (-1.76°C) and significantly smaller head drop. Such scenarios were not examined for GCRT3 well, since its vicinity to the model domain boundary would cause boundary effect and distort the simulation results.

One more observation that should be mentioned is the progressive reservoir temperature built-up at the abandoned injection well sites, which indicates the gradual reservoir thermal replenishment (due to the natural head flow) and confirms the renewability of the source. The top reservoir head and temperature spatial variation at the end of simulation time, after defining the final well locations is presented in Figure 6.

5. Conclusions

The detailed sensitivity analysis described in Antics et al. (2005) and Papachristou (2011), provi-

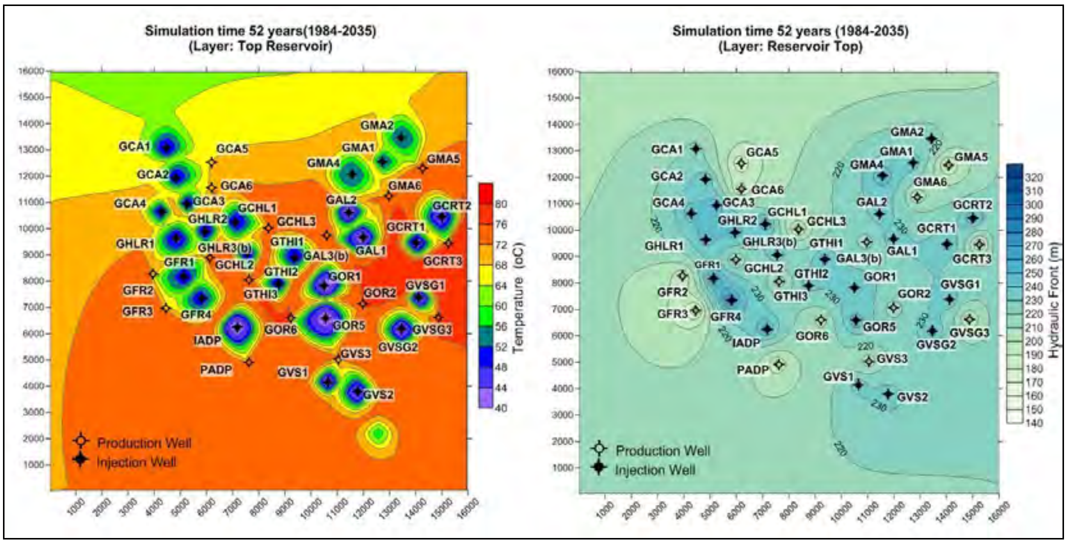


Figure 6 - Final temperature and head distribution (31.12.2035).

ded useful clues on the reservoir structure applied in the model, as well as on the assignment of the bedrock/caprock thermal boundary conditions. The geostatistical interpolation of the available data, regarding initial reservoir parameters, contributed to the more realistic representation of the lateral heterogeneities.

The simulation of the Val de Marne region addressed the 1984-2010 period, in order to calibrate the model by reconciling the simulation outputs with factual evidence. It also accounted for a 25 year (2011-2035) well and reservoir life sequence, an assumption that is considered reasonable, based on the particularities of the geothermal conditions and exploitation in the Paris Basin.

In most cases (10 out of 15 production wells), the simulation results match well the recorded data, given that no temperature drop more than 1°C has been yet observed, except for the GAL2 case. Despite the more “pessimistic” figures, the overall results are consistent and reliable. As expected, the simplification of the reservoir layering affected more the sites of complicated structure and resulted in higher temperature depletion rates. The latter should not be overlooked.

The reservoir temperature and head distribution at the end of 2010 offered important information on positioning the new wells for the period 2011-2035. It was clearly shown that, whereas temperature is the most decisive factor in selecting well locations, pressure (or head) should not be ignored either, because it may affect significantly the cooling kinetics.

All things considered, the validity of the simulation results should not merely rely on absolute figures, but mainly on the general observed trends. From this perspective, it is reasonable to regard the simulations as an interesting and reliable tool for establishing the characteristics of a long-term sustainable geothermal development, as in the case of Paris basin. Specifically for the Dogger reservoir, it was proven that sustainable exploitation can significantly extend the reservoir life, even if the mined heat is maximized.

6. References

Antics M., Papachristou M. and Ungemach P. 2005. Sustainable heat mining. A reservoir engineering approach, *Proceedings 30th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, USA, January 2005.

Bartels J., Cheng L.Z., Ranalli G., Pape, H., Hurter S., Kuhn M., Schneider W., Stofen H., Meyen V. and Pribnow D. 2003. Numerical Simulation of Reactive Flow in Hot Aquifers-SHEMAT and Processing SHEMAT, Ed. Clauser CH., Springer, New York. 332 pp.

Il'in, V.P. 1969. On an integral inequality, Mat. Zametki, 6(2), 139–148.

Lopez S., Hamm V., Le Brun M., Schaper L., Boissier F., Cotiche C. and Giouglaris, E. 2010. 40 years of Dogger aquifer management in Ile-de-France, Paris Basin, France, *Geothermics*, 39, 339-356.

Le Brun M., Hamn V., Lopez S., Ungemach P., Antics M., Ausseur J.Y., Cordier E., Giuglaris E., Goblet P. and Lalos, P. 2011. Hydraulic and thermal impact modelling at the scale of the geothermal heating doublet in the Paris basin, France, *Proceedings 36th Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, California, Jan. 31-Febr. 2.

Papachristou M. 2011. Contribution to the low enthalpy geothermal reservoir management by using numerical simulations-The Paris basin case, *PhD Thesis*, Aristotle University of Thessaloniki, Dept. of Geology, 282 pp.

Perrodon A. and Zabeck J. 1990. Paris Basin, In: Leighton M.W., Kolata D.R., Oltz D.F. Eidel J.J., (eds), *Interior Cratonic Basins,* American Association of Petroleum Geologists*,* 51*,* 633 679

Pomerol Ch. 1978. Paleogeographic and structural evolution of the Paris Basin, from the Precambrian to the present day, in relation to neighbouring regions*, Geologie En Mijnbouw,* 57(4), 533-543.

Rojas J. Menjoz A., Martin J., Criaud A. and Fouillac C. 1987. Development and exploitation of low enthalpy geothermal systems: example of the “Dogger” in the Paris basin, France, *Proceedings 12th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, January 20-22 1987.

Rojas J., Giot D., Le Nindre Y.M., Criaud A., Fouillac C., Brach M., Menjoz A., Martin J.C. and Lambert M. 1989. Caractérisation et modélisation du réservoir géothermique du Dogger, Bassin Parisien, France*, Final Report,* EUR 12636 FR, European Community Commission-DG XII, 240 pp.

Ungemach P. and Antics M. 2003. Inside into Modern Geothermal Reservoir Management Practice, *Text Book, International Geothermal Days*, Turkey, 2003.

Ungemach P., Papachristou M. and Antics M. 2005. Sustainable geothermal reservoir management. *Proceedings World Geothermal Congress*, Antalya, Turkey, 24-29 April 2005.

Ungemach P., Papachristou M. and Antics M. 2007. Renewability versus sustainability. A rerervoir management approach, *Proceedings European Geothermal Congress 2007*, Unterhaching, Germany, 30 May-1 June 2007, paper 216.

Ungemach P., Antics M., Lalos P., Borozdina O., Foulquier L. and Papachristou M. 2011. Geomodelling and well architecture, key issues to sustainable reservoir development, *Proceedings 36th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, January 31-February 2, 2011.

Weinstein H.G., Stone H.L. and Kwan T.V. 1969. Iterative procedure for solution of systems of parabolic and elliptic equations in three dimensions*, Industrial and Engineering Chemistry Fundamentals* 8(2), 281-287.