The Use of Computer Modelling to Forecast the Sustainability in the Development of Geothermal waters Resource: Khankala Deposit Example

Anvar Farkhutdinov[1,3]‡, Patrick Goblet[1], Chantal de Fouquet[1], Rustem Ismagilov[2], Iskhak Farkhutdinov[2,3], Sergei Cherkasov[4]

[1]Geosciences Research Centre, Mines ParisTech, Fontainebleau, France, 77305

[2]Department of regional geology and tectonics, Institution of Russian Academy of Sciences Institute of geology of the Ufimian scientific centre, Ufa, Russia, 450077

[3]Department of Geology, Geographical Faculty, Bashkir State University, Ufa, Russia, 450076

[4]Vernadsky State Geological Museum, Moscow, Russia, 125009

(anvarfarh@mail.ru, patrick.goblet@mines-paristech.fr, chantal.de_fouquet@mines-paristech.fr, rustem_ismagilov@bk.ru, iskhakgeo@gmail.com, sergei_v_cherkasov@mail.ru)

‡ Corresponding Author; Anvar Farkhutdinov, Bashkir State University, Ufa, Russia, 450076, Tel: +79374774977, anvarfarh@mail.ru

Received: 26.07.2015 Accepted:13.09.2015

Abstract- In 2013 the Grozny State Oil Institute within the consortium ‘Geothermal resources’ started a pilot project to build a geothermal plant on the basis of the most promising XIII layer of the Khankala thermal waters deposit of Russia. Planned capacity of the projected facility is 5.45 Gcal/hour, which will heat a greenhouse complex. A “doublet” system is going to be applied which is represented by a closed loop of one production and one injection well with reinjection of all used water back into the layer. This technique allows maintaining the reservoir pressure and thus productive rates, and reducing the ecological effects of geothermal development to minimum. In order to predict the changes in the temperature of the resource (it goes down as a result of the injection of cold water) it is necessary to conduct a numerical simulation. Modelling permits to have general ideas on «doublet» system functioning in its hydrogeological environment, allows choosing best exploitation parameters and distance between production and injection wells bottoms in order to achieve sustainable use of the resource.

Keywords- geothermal waters; geothermal reservoirs; doublet; numerical modelling.

1. Introduction

At the present time, when thermal waters are no longer a little-known form of energy, many researchers put to the forefront the issue of “sustainability” of geothermal reservoir [1-5]. In order to detect the operation of its system in terms of the interaction between groundwater and water resources of the lithosphere, and the features of the development of the resource during the re-injection, computer technologies are used.

The Khankala deposit is situated in Russian southern Republic called Chechnya, 10 kilometers to the south-east from its capital – Grozny (Fig. 2). The deposit is represented by a multilayered system (22 productive layers) of sandstones containing geothermal waters, interlayered with clays, all related to Chocrack and Karagan horizons of middle Miocene.

It is planned to drill a "doublet" (Fig. 1) on the basis of the XIII productive layer reservoir, i.e. one production and one injection well with the reinjection of all water used for greenhouse heating [6,7] and in order to predict the changes in the temperature of the resource (it goes down as a result of the injection of cold water) it is necessary to conduct a numerical simulation.

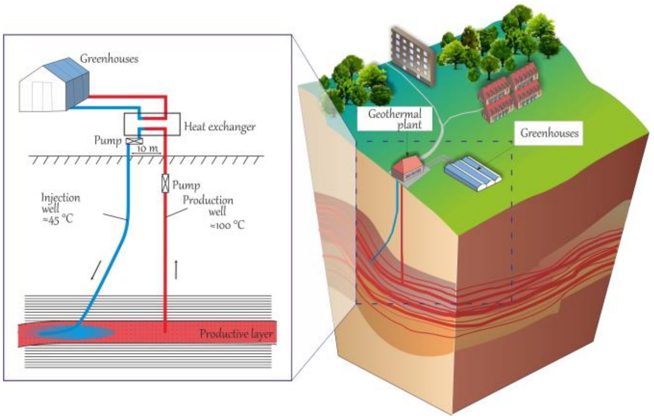

Fig. 1. The Khankala deposit "doublet" scheme.

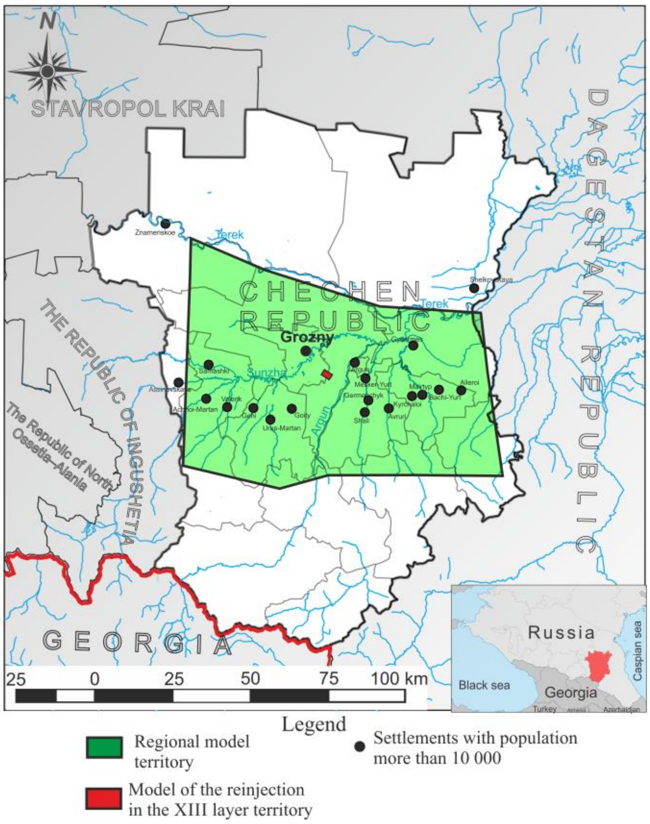

Fig. 2. The territory of regional and doublet models.

Necessity of the hydrogeological forecasts in connection with the creation of large hydraulic structures and water deposits exploitation determined rapid development of the theory of groundwater dynamics, and since the 1970s the numerical modelling using computers [8].

A large number of numerical codes were developed in order to model fluid and heat flow in aquifer systems (Comsol, Tough2 [9], Metis [10], Marthe [11], Opengeosys [12] among others), allowing to predict and select the right regime of exploitation of a thermal water resource, and in particular the effect of cooled water reinjection on the life span of the exploitation.

It should be noted that in Russia there is no large-scale application of thermal waters for heat and electricity production, and as a consequence poor development of computer technologies in this area, in contrast with countries where numerical modelling and GIS analysis has been used in the development of this resource for a long time now.

For example, in France after 20 years of exploitation of the Paris Basin geothermal waters, geothermal heat producers are faced with the problem of the cold front expansion because of reinjection. It has resulted a decrease of the temperature in one production well, and it is predicted, that a gradual reduction in temperature might show in another [13,14]. Different concepts were proposed to solve this problem, for example, the construction of reversed wells and the seasonal inversion (winter-summer) of the injection-production of the thermal water [15]. Thus modelling has been used for over 20 years to predict the duration of the thermal waters exploitation and the impact of installing new wells in the Paris basin [16].

In order to draw guidelines for achieving long-term sustainable exploitation of the Khankala deposits XIII layer and making a prognosis, a numerical modelling based on Metis code was used.

2. Methods

The computer code Metis developed at the Geosciences Department of Mines ParisTech [10], simulates liquid flow, heat and mass transport in fractured and porous medium in either steady or transient conditions. Mathematical equations describing the processes are converted into a form suitable for direct computer processing by the finite element method, which is one of the most efficient numerical methods for solving mathematical problems, describing the state of the physical systems of complex structure. It is a grid method: the region of interest is divided into distinct volumes (elements) and the model is defined by a system of differential equations with given boundary conditions. The equations are discretized in space according to the Galerkin formalism. Systems of linear equations are solved by conjugate gradient method [17].

2.1. Regional model

The initial stage of the work was the creation of a regional hydrological model for understanding the general water circulation in the XIII layer within the vast territory of the Chechen Republic. It is isolated from other layers by impermeable clay interlayers and a two-dimensional model was adopted for this case in regard of the big difference in horizontal and vertical extensions.

The reservoir recharge zone is Karagan-Chokrak deposits outcrop in the south of Chechnya within the Black Mountains, which was chosen as the southern boundary of the modelled area. The northern border is carried out by the Terek River which is assumed to act as a regional drainage axis (Fig. 2). Waters move in north direction after infiltration.

The first step in modelling is discretization of the study area. This is done by covering it with the nodes and elements (in this case triangles) which are designated as a finite element mesh. Material properties of the reservoir (for example, hydraulic conductivity) must be defined for each element; each node and element is assigned a number.

The aim is to model groundwater flow (considering incompressible fluid) in a saturated porous medium in the case of the construction of the regional model within the Chechen Republic. Before modelling geometry parameters, initial and boundary conditions must be established.

Geometry and system parameters:

– Productive layers thickness equal to 40 m;

– Permeability of productive layer is 2.e-13 m^2;

Boundary conditions:

– Constant hydraulic head along southern and northern borders, in accordance with the average absolute elevations (Fig. 3). This condition means that water level is, at a regional scale, mostly governed by topography.

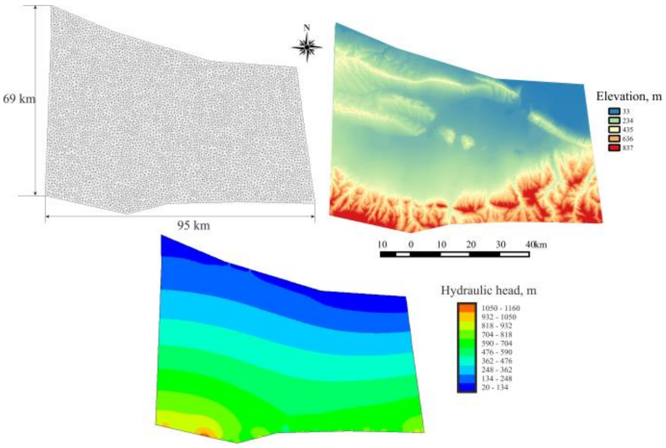

Fig. 3. Mesh, territory elevation and modelling results.

This regional model of groundwater flow within the XIII layer of the vast territory of the Chechen Republic shows that liquid flow through the southern border is equal to 0.62 m^3/s.

Gonsirovsky [18] has calculated the groundwater flow of the XIII layer by the formula, which is a regional application of Darcy's law:

$$Q = k \cdot m \cdot B \cdot i \quad (1)$$

Where k is filtration coefficient, m – layers thickness B – length of filtration front, i – piezometric slope. Taking k equal to 1,5 m/day, m = 47 m, B = 95 km, i = 6e-3 gives us groundwater flow thorough southern border equal to 0.47 m^3/s, which is relatively close to the results obtained by numerical modelling.

Results of regional groundwater flow modelling were taken into account in the simulation of doublet reinjection described in next part.

2.2. The Khankala deposit "doublet" model

More detailed modelling of used geothermal water reinjection in the reservoir of the XIII layer is conducted once identified the general features of groundwater movement within the Chechen Republic. This is based on a local, 3D model of the resource.

The results of temperature estimation and structural map of the XIII productive layer obtained after the application of geostatistical methods [19] are used to calculate the initial conditions of the system and as a basis for creating mesh, respectively. Different distances between productive and injection wells bottoms were taken into account while mesh creation (Fig. 4).

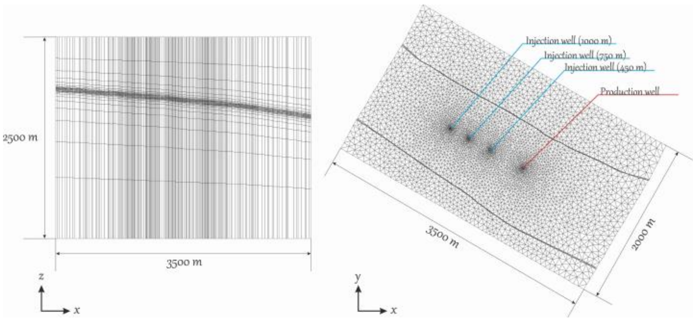

Fig. 4. Three dimensional mesh for geothermal doublet modelling.

Geometry and system parameters:

– Productive layers thickness 47 m;

– Permeability: 1.4e-12 m^2;

– Longitudinal and transverse thermal dispersivity: 10 × 2 m;

– Volumetric heat capacity of water 4.18 $MJ/m^3/°C$;

– Volumetric heat capacity of the aquifer 2.75 $MJ/m^3/°C$, in calculation of which parameters of reservoir rocks and water are taken into account [20]:

$$\rho'' C'' = \omega \rho C + (1-\omega)\rho' C' \quad (2)$$

Where ρ'' – reservoir density, C'' – reservoir heat capacity, ω – rock porosity, ρ – rock density, C – rock specific heat capacity, ρ' – water density, C' – water specific heat capacity;

– Volumetric heat capacity of the surrounding formations 2.09 $MJ/m^3/°C$;

– Conductivity of the aquifer 1.45 W/(m·K);

– Conductivity of the surrounding formations 1.3 W/(m·K);

Boundary conditions:

– Imposed liquid flow of 200 m^3/h at the injection well point with a constant heat flow of 10051 MW, which corresponds to water temperature of 45 °C;

– Imposed liquid flow through north-west and north-east borders, according to regional modelling results (in case of taking it into account);

– Geothermal flux imposed at the base of the model. This flux is calculated according to Fourier's law:

$$\vec{q} = -k\nabla T \tag{3}$$

Where $\vec{q}$ is geothermal flux, k is thermal conductivity coefficient, T is temperature. Average thermal conductivity coefficient of the deposits laying in-between the XIII layer and the surface which is equal to 1.4 W/(m·K), depth of the XIII layer, temperature of the XIII layer and at the surface were taken into account to calculate geothermal flux. The fairly high average heat flow (110 mW/m^2) can be explained by «overthrust-nappe theory» as caused by tectonic movements, considering the North Caucasus as a mobile tectonic zone [21].

The Khankala geothermal waters deposit "doublet" model is shown in Fig. 5.

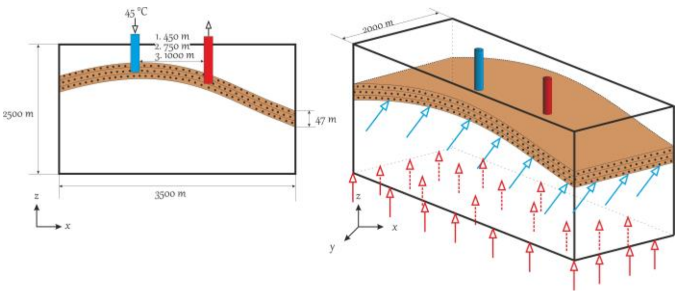

Fig. 5. Schematic representation of geothermal doublet modelling.

Change in liquid viscosity in Metis code is expressed by Bingham equation [20]. Laboratory analysis of the Khankala deposit geothermal waters were conducted in 1988, including study of viscosity dependence of the temperature [22]. It is very well correlated with equations used in Metis (Fig. 6), which could be explained by the low salinity of the Khankala deposit geothermal waters (0,5–2 g/l), justifying that thermo-hydraulic modelling is fair enough without taking into account chemical components.

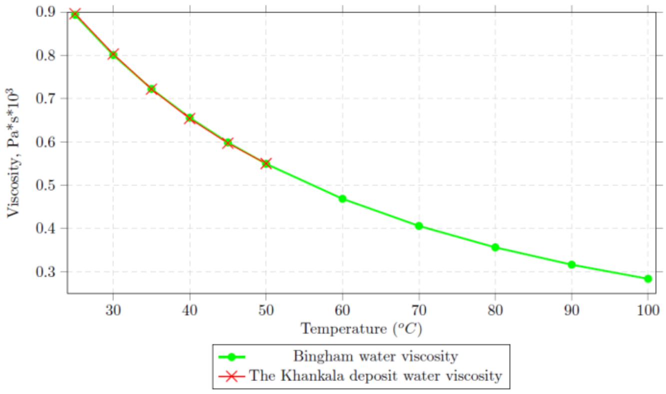

Fig. 6. Change in water viscosity depending on temperature according to Bingham and laboratory analysis.

Processes of liquid flow and thermal transport are coupled: at each time step the program conducts an alternate resolution of their equations. Simulation time is equal to 50 years.

3. Results

Different hypotheses were checked during numerical modelling (table 1):

– Influence of distance between production and injection well (450, 750, 1000 m);

– Permeability of two general faults;

– Influence of natural groundwater flow;

Results were compared with Gringarten and Sauty analytical solution for "doublet" water reinjection thermal breakthrough [23].

Table 1. The modelling results

Case	$\Delta T = 1^o C$, Year	ΔT , °C (50 years)
Distance 450 m		
No liquid flow, no faults influence	7.42	18.35 °C
Impermeable faults	7.25	20.17 °C
Groundwater flow	10.08	9.92 °C
Analytical solution	≈6.5	25.56 °C
Distance 750 m		
No liquid flow, no faults influence	22.00	8.60 °C
Faults influence	20.25	10.63 °C
Groundwater flow	45.08	1.33 °C
Analytical solution	≈20	13.72 °C
Distance 1000 m		
No liquid flow, no	39.42	2.76 °C

faults influence		
Impermeable faults	35.08	4.41 °C
Groundwater flow	–	0.62 °C
Analytical solution	≈38	4.73 °C

Thermal breakthrough occurs earlier and temperature decrease faster in case of analytical solution (Table 1., Fig. 7) because temperature of reservoir, cap rock and bedrock are the same and in numerical simulation temperature obtained after geostatistical estimation was used, which is distributed unequally with higher temperatures deeper and to the south from the prediction well (Fig. 8).

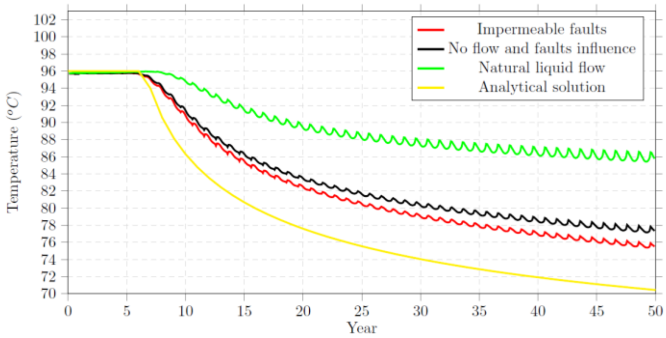

Fig. 7. Temperature in production well change in the case of 450 m distance between production and injection well bottoms.

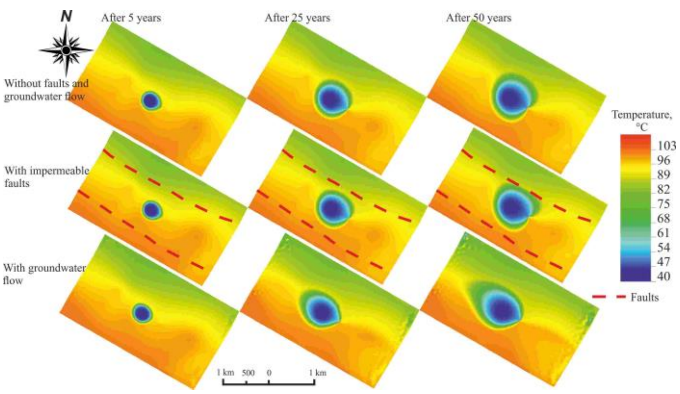

Fig. 8. Results of the modelisation: temperature evolution in layer XIII (450 m distance).

Our further study was to simulate the recovery behavior of the Khankala XIII productive layer resource. The reservoir was assumed to be exploited for 50 years (distance between wells equal to 450 m) and then shut in (Fig. 9).

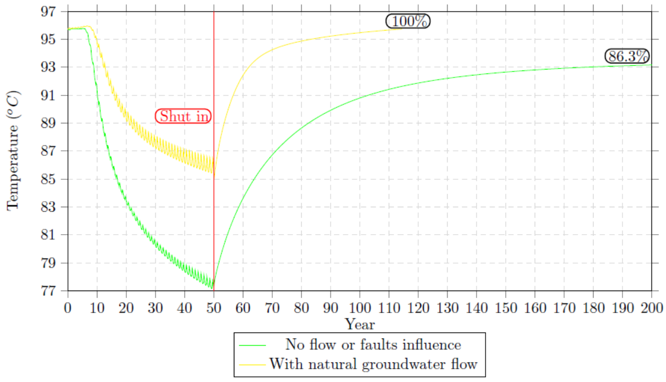

Fig. 9. Production well temperature for 50 year exploitation and then shut-in scenario.

In case of taking natural groundwater flow into account, total recovery of the temperature in the production well occurs after about 65 years of shut-in, if not taking it into account temperature will recover on 86.3% after 150 years of shut-in scenario.

4. Discussion

Taking into account the influence of impermeable faults has no big influence on the temperature in the production well because they are situated far enough and the cold front does not reach them too soon. Natural groundwater flow in the XIII layer significantly delays the production temperature decrease. So it should be noted that at the Khankala deposit site it is very important to place wells parallel to these two faults with production well bottom in the south part and injection well in the north part.

According to results obtained by numerical modelling it is highly recommended to choose distance between injection and production wells equal to 750 m and more. In such case temperature in production well will not go down drastically after 25-30 years, the usual period of wells equipment lifetime after which it is advisable to drill new ones. After drilling the “doublet” numerical model should be calibrated with new data obtained from hydrogeological tests, well logs, etc.

5. Conclusions

Numerical modelling allows understanding general features of the Khankala deposit XIII layer groundwater flow within the vast territory of the Chechen Republic and also predicting the evolution of the resource as a result of the recycling of the reinjected cold water. It is a powerful tool for drawing guidelines in geothermal waters use and for choosing an optimal exploitation regime.

One of the main advantages of the Khankala deposit of geothermal waters is that it is represented by a multilayer system and in case of significant drop in production well temperature after some period of the XIII layer exploitation, there is a possibility to drill a new “doublet” at the same territory on the resource of highly perspective XVI or XXII layer so the geothermal station could continue working. The resource of the XIII layer could be used again in case of shut-in after some period of time taking into account relatively high speed of temperature recovery. In perspective, periodic use from different layers could be organized for sustainable use of geothermal waters at the Khankala deposit site.

Acknowledgements

The research has been executed with support of the Ministry of Education and Science of Russian Federation, contract № 02.G25.31.0056.

References

[1] M. Antics, M. Papachristou, P. Ungemach, “Sustainable heat mining. A reservoir engineering approach”, Proceedings of the 30th Workshop on Geothermal Reservoir Engineering, January 31-February 2, 2005, Stanford University, Stanford, California. (Conference Paper)

[2] G. Axelsson, “Sustainable geothermal utilization – Case histories, definitions, research issues and modelling”, Geothermics, No. 39, pp. 283-291, 2010. (Article)

[3] P. Ungemach, M. Antics, M. Papachristou, “Sustainable Geothermal Reservoir Management. World Geothermal Congress”, Antalya, Turkey. 2005. (Conference Paper)

[4] P. Ungemach, M. Papachristou, M. Antics, “Renewability Versus Sustainability. A Reservoir Management Approach”, European Geothermal Conference, Unterhaching, Germany, 2007. (Conference Paper)

[5] P. Ungemach, M. Antics, P. Lalos, “Sustainable geothermal reservoir management – a modelling suite”, Australian Geothermal Energy Conference, 16-18th Nov. 2011, Melbourne, Geoscience Australia Record 2011/43, pp. 267-275. (Conference Paper)

[6] A.M. Gareev, A.M. Farkhutdinov, I.M. Farkhutdinov, S.V. Cherkasov, “Current state and prospects of use of geothermal waters in Russia (on the example of the Khankala deposit)” (in Russian), Bulletin of Bashkir University, Vol. 19, No 3, pp. 887-892, 2014. (Article)

[7] A.M. Farkhutdinov, I.M. Farkhutdinov, R.A. Ismagilov, “History of discovery and development of the Khankala thermal waters deposit” (in Russian), Bulletin of Bashkir University, Vol. 19, No 1, pp. 93-97, 2014. (Article)

[8] V.A. Vsevolozhsky, “Basics of Hydrogeology”, 2nd edition, M .: MGU, 448 p., 2007. (Book)

[9] K. Pruess, C.M. Oldenburg, G.J. Moridis, “TOUGH2 User’s Guide version 2.0”, Lawrence Berkeley National Laboratory, Report LBNL-43134, Berkeley, CA, USA, 1999. (Standards and Reports)

[10] P. Goblet. “Modélisation des transferts de masse et d’énergie en aquifère [Modelling mass and energy transfers in aquifers]”, PhD Thesis, Ecole Nationale Supérieure des Mines de Paris, University Pierre and Marie Curie, Paris, France, 200 p., 1980. (Book)

[11] D. Thiéry, ”Software MARTHE. Modelling of Aquifers with a Rectangular Grid in Transient state for Hydrodynamic calculations of heads and flows. Release 4.3”, Report BRGM 4S/EAU n° R32548, 1990. (Standards and Reports)

[12] O. Kolditz, S. Bauer, L. Bilke, N. Böttcher, J.O. Delfs, T. Fischer, U.J. Görke, T. Kalbacher, G. Kosakowski, C.I. McDermott, C.H. Park, F. Radu, K. Rink, H. Shao, H.B. Shao, F. Sun, Y.Y. Sun, A.K. Singh, J. Taron, M. Walther, W. Wang, N. Watanabe, Y. Wu, M. Xie, W. Xu, B. Zehner, “OpenGeoSys: an open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes in porous media”, Environ, Earth Sci. http://dx.doi.org/10.1007/s12665-012-1546-x, 2012. (Book)

[13] M. Le Brun, V. Hamm, S. Lopez, P. Ungemach, M. Antics, J. Ausseur, E. Cordier, E. Giuglaris, P. Goblet, P. Lalos, “Hydraulic and Thermal Impact Modelling at the Scale of Geothermal Heating Doublets in the Paris Basin, France”, Proceedings of the 36 Workshop on Geothermal Reservoir Engineer, January 31 - February 2, 2011, Stanford, California, USA. (Conference Paper)

[14] S. Lopez, S. Hamm, O. Goyeneche, “Optimal and sustainable use of the Dogger aquifer geothermal resource: long-term management and new technologies”, SIMS The 53rd Scandinavian Conference on Simulation and Modelling, 2012. (Conference Paper)

[15] A. Réveillère, V. Hamm, H. Lesueur, E. Cordier, P. Goblet, “Geothermal contribution to the energy mix of a heating network when using Aquifer Thermal Energy Storage: modeling and application to the Paris basin”, Geothermics, No. 47, pp. 69-79, 2013. (Article)

[16] S. Lopez, V. Hamm, M. Le Brun, L. Schaper, F. Boissier, C. Cotiche, E. Giuglaris, “40 years of Dogger aquifer management in Ile-de-France, Paris Basin, France”, Geothermics, No. 39, pp. 339-356, 2010. (Article)

[17] M.R. Hestenes, E. Steifel, (December 1952) “Methods of Conjugate Gradients for Solving Linear Systems”, Journal of Research of the National Bureau of Standards, Vol. 49, No. 6, pp. 409-436, 1952. (Article)

[18] D.G. Gonsirovsky, L.I. Sudeiko “ Evaluation of natural resources of thermal waters of the southern districts of East Ciscaucasia of Pliocene, Upper Pliocene, Karagan and Chokrak aquifer complexes” (in Russian), Essentuki, 1966. (Standards and Reports)

[19] A.M. Farkhutdinov, de F. Chantal, M. Sh. Mintsaev, S.V. Cherkasov “Application of geostatistics for analysis of the prospects for the exploitation of the Khankala geothermal waters deposit” (in Russian), Geoinformatics, No. 1, pp. 60-67, 2015. (Article)

[20] G. Marsily, “Quantitative Hydrogeology: Groundwater Hydrology for Engineers”, Academic Press, New York, 440 p., 1986. (Book)

[21] M.A. Kamaletdinov, T.T. Kazantseva, Yu. V. Kazantsev, D.V. Postnikov. “Nappe-thrust tectonics of lithosphere” (in Russian), M.: Nauka, 256 p., 1991. (Book)

[22] V. Krilov “Complex investigations of wells and evaluation of exploitation reserves of geothermal waters in terms of geothermal circulation system on Khankala deposit of CHIASSR” (in Russian), 1988. (Standards and Reports)

[23] A.C. Gringarten, J.P. Sauty, “A theoretical study of heat extraction from aquifers with uniform regional flow”, Journal of Geophysical Research 80, pp. 4956-4962, 1975. (Article)