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THE GEOENVIRONMENTAL IMPACT OF KLAIPĖDA GEOTHERMAL PLANT

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Abstract. A potential impact of geothermal energy exploitation on the underground of the Upper Phanerozoic following various schemes of thermal water extraction and injection to the productive aquifer and other aquifers was modelled on an example of Klaipėda demonstration geothermal plant (KDGP). The obtained results showed that: 1 – thermal energy resources in the productive Viešvilė aquifer are sufficient for operation of KDGP at project geothermal output 20.8 MW for 50 years; 2 – at a distance 0.2–0.5 km around the injection wells, the water level in the productive layer rises above the ground; 3 – the temperature in the productive complex falls down in an area of approximately 15 km^2; 4 – the spent mineralized (95 g/*l*) water of productive aquifer returned into the Upper Permian-Žagarė aquifer may reach the freshwater waterworks in 10 years; 5 – yet its short-lasting emergency injections represent no real hazard for waterworks; 6 – the interaction of groundwater of different temperature and chemical composition may slightly elevate the saturation of mixture with the ferrous minerals (hematite and magnetite) and allow their precipitation in the layer or well filters; 7 – the cooling of Viešvilė aquifer from 37–39 to 11 °C in the impact zone of injection wells during 50 years is an irreversible process; complete regeneration of temperature due to geothermal flux lasts for about 6000 years.

Keywords: hydrodynamics, mass and heat transport, modelling, West Lithuanian geothermal anomaly, geothermal energy, Klaipėda geothermal plant.

1. Introduction

Geothermal energy accumulated in aquifers or in hot dry rocks at a greater depth (2 km and deeper) is a widely used source of energy. The technological and economic achievements make it possible to use the underground energy which is extracted with the fluids. Extraction of energy from dry hot rocks is in the stage of technological development and experiments (Kaieda *et al*. 2005). Investigations of geothermal energy as especially promising and important for the future of humankind are supported by the European Union.

The geothermal energy of hot rocks was started to be used for production of electric power more than 100 years ago in Italy. At present, the capacity of geothermal plants of 20 countries in the zone of active volcanism reaches 7 million kW; seventy more countries including Lithuania use water from the lower temperature aquifers for production of thermal energy (Bičkus *et al*. 2004; Bertani 2005; Lund *et al.* 2005). The exploitation of geothermal energy as a local source of energy is provided for in the Lithuanian strategy for energy. The largest resources of energy of this kind are concentrated in the western part of Lithuania including the Klaipėda city. In the so-called West-Lithuanian geothermal anomaly occupying an area of more than 10 thousand km^2, the intensity of geothermal flux is about 0.09 Wm^{-2} or twice as high as in the adjoining territories (Kepežinskas *et al.* 1996). The neighbouring countries (Poland, Germany, etc.) having similar geothermal conditions successfully and effectively exploit geothermal systems, carry out full-scale investigations of geothermal energy sources (fluids, dry hot rocks, etc.) and develop new extraction technologies (Bujakowski 2005; Köhler 2005; Sanner *et al.* 2005; Seibt *et al.* 2005; Zinevicius *et al.* 2005).

Exploitation of geothermal energy includes solutions of three related problems: 1 – detection and exploration of energy sources and evaluation of their resources (geological structure, hydrogeological conditions, filtration–migration parameters, physical–chemical indices of rocks and fluids, etc.); 2 – selection (development) of effective energy exploitation technology; 3 – substantiation and monitoring of friendly for environment exploitation schemes.

The worldwide and Lithuanian researches mainly have been devoted to solutions of the first two problems (Kepežinskas *et al.* 1996; Bičkus *et al.* 2004; Calcagno 2008; Sliaupa *et al.* 2008; Zui *et al.* 2008). Meanwhile, the environmental effects of geothermal water exploitation, which so far have been evaluated only inasmuch as related with resources (maintenance of pressures and temperatures within permissible limits, etc.), is a new priority of the International Energy Agency (IEA) for the coming five years of the Geothermal Implementing Agreement (IGA) launched in 2007 (Rybach 2008).

A similar situation can be observed in the Klaipėda demonstration geothermal plant (KDGP), which has been built in 2001 and as a demonstration one has been designed not only for extraction of thermal energy but also for promotion of environment-friendly technologies. The project plant capacity of geothermal energy was 20.8 MW, planed geothermal water extraction 700 m^3/h. Unfortunately, at present the KDGP does not fulfil the mentioned functions: the project capacity has not been reached due to insufficient knowledge about the properties of the aquifer and fluids. Monitoring of its regime is absent.

At present, the situation of the aquifer can be evaluated only based on the indices of extracted water and operation of wells. As long as monitoring of the underground environment does not take place, mathematical modelling serves as the principal investigation method.

The injection of spent water into other aquifers (Upper Permian–Žagarė, Šventoji–Upninkai) for enhancing the capacity of the geothermal plant is related with the problem of maintaining pressure in the productive horizon and environmental problems. Moreover, the fact that after starting the plant inhibitors were not used its operation got complicated by precipitation of gypsum from the cold water in the pipe system.

Exploitation of geothermal plant following the present scheme when the geothermal water is extracted from and returned into the same aquifer, search for new spent water recipients and assessment of environmental consequences of emergency discharge of geothermal water into other aquifers urge solution of issues, which were insufficiently considered in the stages of projection, construction and exploitation of the plant:

- interaction of natural and cooled mineralized geothermal water from the productive aquifer with the water from other aquifers;
- parameters of the multi-layer stratum, hydrochemical and geothermal situation in it and substantiation of its adequate schematization for mathematical modelling;
- prognosis of short-lasting, long-lasting and geological impacts of geothermal energy extraction on the underground (geological) environment.

The required mathematical model of Klaipėda geothermal energy field should reflect migration of groundwater and contained chemical elements and heat fluxes in the aquifer under the conditions of operating extraction and injection wells, predict the groundwater pressure and temperature variations in the horizon, and simulate different plant operation scenarios (increase of the capacity, changing number of wells and their operation regimes, efficiency of spent water return to productive or other aquifers, etc.). Prediction of the mentioned processes is necessary for practical solutions of efficient and environmentally friendly exploitation of geothermal energy in the territory of West Lithuanian geothermal anomaly.

2. Methods

The present investigation included: 1 – analysis and generalization of available geological, hydrogeological and other kinds of related information, 2 – special hydrodynamic and thermal investigations in the wells of KDGP, 3 – mathematical modelling of hydrodynamic, hydrochemical and geothermal processes.

The KDGP uses the energy of the Lower Devonian Viešvilė aquifer bedding at a depth of 980 m yet depending on the chosen spent water recipient aquifer its potential hydrodynamic, hydrochemical and thermal effects may embrace other aquifers in a rather large territory. The heat of deeper Devonian (D_2pr, D_2gr) and Silurian (S) layers also is transferred to productive aquifers. Therefore the available information about the bedding conditions, filtration, migration and thermal parameters of Viešvilė, Šventoji–Upninkai, Narva (D_1vš, D_2up-D_3šv, D_2nr), Upper Permian–Žagarė (P_2-D_3žg) aquifers and intermediate layers accumulated at the Lithuanian Geological Foundation and organizations exploiting geothermal energy and fresh groundwater (joint-stock companies "Geoterma" and "Klaipėdos vanduo") as well as the data about the chemical and physical properties and dynamics in the Klaipėda city environs (in an area of about 400 km^2) has been collected for modelling (Figs 1 and 2).

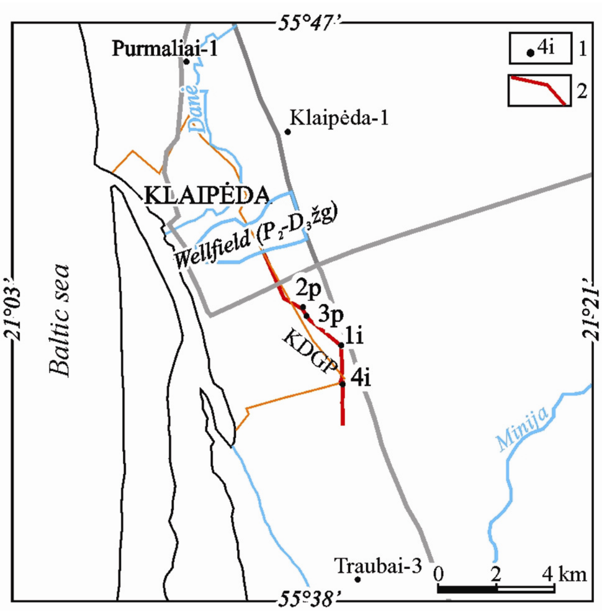

Fig. 1. Setting of Klaipėda demonstration geothermal plant (KDGP) and modelled area: 1 – well and its name; 2 – direction of model profiles

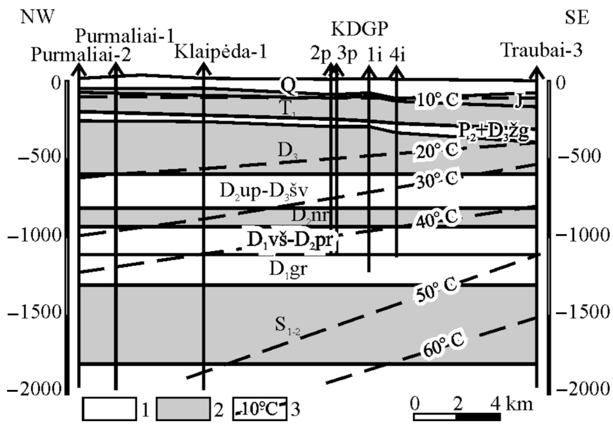

Fig. 2. Hydrogeological cross-section of KDGP: 1 – aquifers; 2 – aquicludes; 3 – isogeotherm (undisturbed)

The geothermal, hydrodynamic and hydrogeochemical investigations of the wells of KDGP were performed in projection, construction and exploitation stages in 1997–2008. Yet the natural vertical distribution of temperatures (i.e. before the exploitation) in the territory of the plant has not been determined. It is hypothetically estimated based on the data from the explored wells situated north (Klaipėda-1) and south (Traubai-3) of it.

The information about the volume of extracted-injected water, its distribution between the wells and temperature also bears a fragmentary character. Therefore, the operation regime of the wells was reconstructed with certain reservations.

Repeated hydrodynamic and hydrothermal investigations in the wells of KDGP were carried out by oil prospect specialists in 2008. The water from the Viešvilė aquifer was for a short while pumped out into injection wells 1i and 4i and water inflow from its various intervals and pressure variations also were measured. In well 1i, the temperature of rocks affected by injection was measured from top to bottom (up to a depth of 1100 m). The pressure and temperature measuring interval was 0.1 m. The measuring precision was: for pressure 0.0001 bar and for temperature 0.0001 °C.

Mathematical simulation of hydrodynamic, geothermal and hydrochemical processes. Extraction of geothermal energy following the technology applied in the KDGP not only entails drastic changes of water dynamics and thermal fluxes in the aquifer but also may change the natural hydrochemical processes. When the spent water from the productive aquifer is returned to other aquifers, the hydrochemical changes in the latter are inevitable.

At present, simulation of the mentioned processes through approximation of equations can be performed using many special or universal computer programs.

In the present study, calibration of filtration parameters of the upper (active) circulation zone was performed using the widely known MODFLOW (three-dimensional groundwater filtration modelling by the finite-difference method) (McDonald, Harbaugh 2000) and enterprise Groundwater Vistas 5.0 (Rumbaugh, Rumbaugh 2007), whereas for the general modelling of filtration and mass and heat transport in the underground of the environs of KDGP, FEFLOW software was used. It is designed for calculation of three-dimensional flow of fluids and dissolved chemical materials and heat transport by the finite-element method. The whole of the mentioned processes is roughly generalized in the Eq. (1) (Diersch 2002):

$$S_0 \frac{\partial h}{\partial t} + \frac{\partial q_i^f}{\partial x_i} = Q_\rho + Q_{EB}(C,T), \qquad (1)$$

where: S_0 – specific storage coefficient (compressibility); h – hydraulic head; q_i^f – Darcy velocity vector of fluid; Q_p – source/sink function; Q_{EB} – equations describing mass and heat transport (Boussinesq); C – concentration T – temperature.

Mathematical principles and premises of FEFLOW software are given in detail in methodical recommendations provided by the author (Diersch 2002, 2004). The software was successfully used for simulation of mass and heat transport problems (Sanner *et al.* 2005; Seibt *et al.* 2005; Jakimavičiūtė-Maselienė *et al.* 2006).

The Upper Permian–Žagarė, Šventoji–Upninkai and Viešvilė aquifers of the upper part of geological section in the environs of KDGP are of the highest productivity. They are spread in a large region and isolated from the earth surface by thick impermeable strata. Though there is almost no natural groundwater and chemical elements exchange between them and heat is transferred through conduction a joint model of the underground has been developed for planned or possible emergency redistribution of geothermal water between the aquifers. The model includes part of geological sequence from the upper layer with stable long-term temperatures (top of the Jurassic–Triassic clays) to the depth of 1 800 m (Silurian strata) in an area of 400 km^2. For modelling purposes, it was divided into 12 layers. The calculated triangular elements and their nodes are generated automatically by FEFLOW software to desirable detail. The total number of elements in the calibrated model used for prognostic calculations amounts to more than 30 000 and the number of nodes is over 60 000 (Fig. 3).

The productive Viešvilė (three layers of the model) and Šventoji–Upninkai (two layers of the models) aquifers are modelled in detail.

In terms of hydrodynamic and mass transport, the upper boundary of the model coinciding with water (Q) and material (C) impermeable top of Jurassic–Triassic (J-T_1) clays is the type-II boundary (Q and C = const = 0) whereas in terms of heat it is stable temperature (T) limit (type-I limit – T = const = 10 °C). Analogous role also is played by the chosen lower boundary in the Silurian rocks at a depth of 1 800 m: Q, and C = const = 0, T = const = 60 °C.

The modelled territory is limited by lines drawn 10 km from the plant because the strata spread in a large territory beyond these lines have no appreciable influence on the precision of obtained results. It is taken that water, mass and heat (Q_h) transport does not take place through them (type-II boundary: Q, C and Q_h = const = 0).

The internal boundaries of the model are represented by extraction and injection wells and waterworks realized as type-II hydrodynamic boundary ($Q = f(t)$). Klaipėda waterworks 1 and 2 are exceptions in which type-I boundary is realized in the Upper Permian–Žagarė aquifer for prediction of the maximal possible flow of injected mineralized water in their direction (H = const = 35 m b. s. l. – minimal level beyond the impact zone of extraction wells recorded in 1985–1990. Mineralization and temperature of injected water are taken as (C and $T = f(t)$).

It is taken for prognostic calculations that the wells of the plant will be exploited for 50 years. The pattern of hydrodynamic, chemical and thermal processes is predicted for 10 000 years after the closure of the KDGP.

The height of groundwater column in the well depends on the density of captured horizon predetermined by water mineralization. For this reason, hydrodynamic calculations included recalculation of the water levels of different layers and densities for respective freshwater

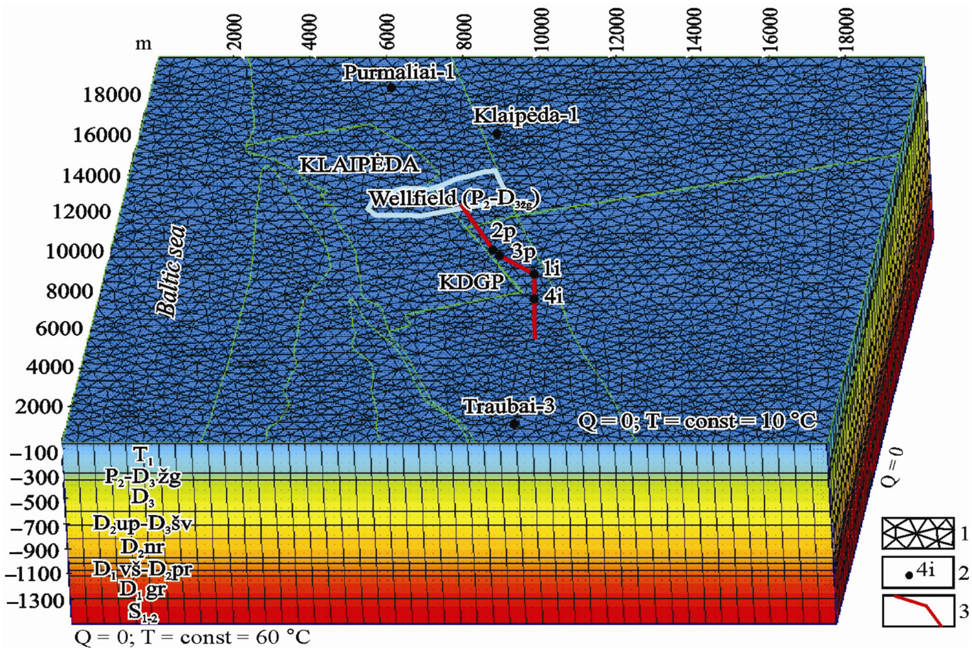

Fig. 3. Scheme of mathematical model of the upper part of Phanerozoic in the KDGP environs: 1 – model elements in layers; 2 – wells and their names; 3 – direction of the section

levels. Thus the level of Šventoji–Upninkai aquifer (bedded at a depth of 600 m; water mineralization and density are 30 g/*l* and 1016 g/*l* respectively) in the well is by about 10 m and the level of Viešvilė aquifer (bedding depth 980 m; water mineralization and density 95 g/*l* and 1046 g/*l* respectively) by 40 m lower than the freshwater level.

The initial conditions of the model were: water levels, water mineralization and water and rock temperatures undisturbed by extraction.

The additional drawdown or elevation of the water level in wells due to peculiarities of construction and colmatation of filter ("skin effect") should be evaluated separately basing on the exploitation experience.

The sensitivity of hydrodynamic, chemical and thermal processes to parameters of geological medium is rather variable. For evaluation of the maximal possible migration distance of chemical materials, it is taken that they are inert, i.e. do not decay, precipitate or react with rocks and are not absorbed by them.

Migration forms of chemical elements and groundwater saturation with minerals were predicted using the WATEQ4F software (Ball, Nordstrom 2001).

The saturation index of water by mineral (SI) is expressed by Eq. (2):

$$SI = \lg\left(\frac{IAP}{Ksp}\right), \tag{2}$$

where: *IAP* – ion activity product; *Ksp* – solubility constant.

It shows the water and the analysed mineral state: zero – they are in the state of equilibrium; above zero – the analysed mineral tends towards precipitation; below zero – the analysed mineral tends towards dissolution in the water.

3. Geology and hydrogeology

Klaipėda environs belong to the central part of the West Lithuanian geothermal anomaly. The temperature of rocks of crystalline basement bedded at a depth of 2200 m reaches 80 °C and the intensity of geothermal heat flow is 0.08–0.09 Wm^{-2}. The temperature of groundwater of different mineralization contained in the Phanerozoic section ranges from 70 (Cambrian sandstone) to 35–40 (Lower Devonian Viešvilė sand and sandstone, clay) and 25–30 °C (Upper-Middle Devonian Šventoji–Upninkai sand and sandstone) (Kepežinskas *et al.* 1996; Bičkus *et al.* 2004).

The structure and properties of the productive Viešvilė complex aquifer determined according to the well data are given in Table 1.

Table 1. Indices of the Lower Devonian Viešvilė complex (aquifer) in wells of the plant

Indice	Value
Bedding depth (interval), m	980–1116
Thickness, m	131–136
Thickness of permeable sandy layers, m	71–92
Porosity of permeable layers	0.25–0.26
Conductivity of permeable layers, mD	400–2000
Conductivity of impermeable layers, mD	0.001
Undisturbed pressure within the interval 1010–1113 m, bar	103–114
Undisturbed temperature within the interval 1010–1113 m, °C	38.2–40.6
Water mineralization, g/*l*	95

Characteristics of dynamic, filtration, hydrochemical and thermal parameters of the upper part of Phanerozoic in the environs of KDGP generalized based on abundant geological survey, water and oil prospecting, and special investigation data (Dortman 1992; Kepežinskas *et al.* 1996; Bičkus *et al.* 2004; Sliaupa *et al.* 2008; Zuzevičius 2000, 2003; Zuzevičius *et al.* 2007, Zuzevičius, Rastenienė 2001), and from geothermal plant wells.

4. Actual and possible regimes of the geothermal plant

The energy in the KDGP is extracted from Viešvilė aquifer groundwater using heat pumps. The designed system is composed of 2 extraction (productive) wells, heat pumps, where the heat from the mineralized geothermal water is transferred to fresh water rising its temperature to the 70 °C, and 2 injection wells for return of spent cooled to 11 °C water to the aquifer for maintaining the necessary pressure.

The productive wells (2p and 3p) spaced 300 m and injection wells (1i and 4i) situated at distances 1200 and 2850 m from the well 3p (Fig. 1). The filters of all wells are installed at an approximate depth interval 980–1116 m.

The project yield of extracted water was 700 m^3/h (16.8 thousand m^3/d), capacity of geothermal energy was 20.8 MW. As the conductivity parameters of the aquifer turned out to be worse than expected and efficiency of injection wells is insufficient, the accepted actual yield is 450 m^3/h (10.8 thousand m^3/d) (geothermal capacity 13.6 MV).

The plant was started in 2001. In 2001–2007, it operated for about 1550 days and extracted almost 8 million m^3 of geothermal water (37.5 °C), which cooled down to 16–18 °C and was returned to the same aquifer. This means that about 7×10^5 GJ thermal energy was extracted what equals to the amount of energy produced by 17 thousand t of oil. The plant operated for 220 days per year (except the years 2001 and 2008 when short-lasting exploitation experiments were carried out) at an average yield of 210 m^3/h or approximate thermal capacity of 6 MW.

As it is, neither the project nor accepted for exploitation capacities of water and geothermal energy extraction were reached. The insufficient and reducing efficiency of injection wells is the main cause of failure. Solution of this problem would allow increasing the plant capacity to the project values. For this reason, it is expedient to evaluate the possibilities of spent water return to other aquifers (Šventoji–Upninkai and Upper Permian–Žagarė) and the possible impacts of this exploitation scheme on them.

Different possible scenarios of geothermal energy extraction from the Viešvilė aquifer and impacts on the underground environment were modelled on the example of KDGP (Table 2).

Reconstruction of the actual operation of Klaipėda geothermal plant. Objective information, which could be used for calibration of model parameters includes: investigation data about parameters of aquifers, initial temperature of aquifers, amount and temperature of extracted and returned water, and distribution of underground temperature in well 1i measured instrumentally on 14 May 2008, i.e. about 350 days after the stoppage of the plant at the beginning of June 2007.

Geothermal plant operation at project and accepted capacities. A permanent operation (50 years) of plant at project (700 m^3/h) and accepted (450 m^3/h) geothermal water extraction capacities were modelled.

The water is extracted in equal amounts from two wells (2p and 3p) and cooled to 11 °C it is in equal amounts returned through two wells (improved 1i and 4i) to the productive aquifer.

Operation of typical geothermal plant with two wells. The Viešvilė aquifer is a promising source of thermal energy in a large part of West Lithuania (Kepežinskas *et al.* 1996).

A typical plant with 1 productive and 1 injection wells in its underground part is able to extract 250 m^3/h of geothermal water. The spent water after cooling by 20 °C is returned into the productive aquifer. In case of lowest temperatures in the periphery of West Lithuanian geothermal anomaly would be 30 °C and the temperature of returned water 10 °C.

The return of all water extracted from the Viešvilė aquifer and cooled to 11 °C to Šventoji–Upninkai or Upper Permian–Žagarė aquifers is irrational in terms of maintaining pressure in the productive aquifer yet it is modelled for evaluation of the maximal possible hydrodynamic, chemical and thermal impacts in the underground environment.

Table 2. Modelled geothermal plant operation scenarios and their objectives

Operation regime	Temperature of extracted/ returned water, °C	Objective
Scenario 1. Extraction and spent water return from/to Viešvilė aquifer		
1. Reconstruction of 2001–2007	38/16–18	Calibration of conductivity, migration and heat parameters
2. Project capacity (water yield 700 m^3/h)	37.5/11	Prognosis of the impact on the dynamics of productive aquifer (pressures and levels), prognosis of heat and material distribution
3. Accepted capacity (water yield 450 m^3/h)	37.5/11	
4. Typical plant capacity (water yield 250 m^3/h)	37.5/16.5	Evaluation of potential heat resources and establishment of permissible distance between neighbouring users
Scenario 2. Extraction water from Viešvilė aquifer; return to Viešvilė, Upper Permian–Žagarė or Šventoji–Upninkai aquifers		
Project capacity (water yield 700 m^3/h)	37.5/11	1. Evaluation of the impacts of the maximal extraction of thermal energy from the productive aquifer, using other aquifers for accumulation of cooled water, on the underground environment. 2. Evaluation of the consequences of injections (including the emergency ones) of spent water into other aquifers.

In both variants, the operation time is 50 years. Groundwater level, mineralization and temperature dynamics is predicted (modelled) for 10 000 years.

For evaluation of the outcomes of emergency situations, it is taken that an accident is a single one-day lasting penetration of 8400 m^3 spent cooled (11 °C), mineralized (95 g/*l*) water into the Šventoji–Upninkai or Upper Permian–Žagarė aquifer from injection well 1i situated in the closest proximity to the Klaipėda waterworks.

5. Results and discussion

Model analysis of geothermal energy extraction scenarios allowed evaluating its possible environmental impacts on hydrodynamic, hydrochemical and thermal regimes of productive and other aquifers.

Modelling of the operation regime of the plant in 2001–2007 and the following standing period which lasted until repeated temperature measurements in 2008 was used for calibration of parameters.

It should be noted that due to inertness of thermal processes, the measurements carried out in the injection well 1i in May 2008, recorded the temperature of rocks close to the well walls cooled by the returned spent water. The difference between the measured and initial (unchanged by returned water) temperatures in the top of Viešvilė complex may reach 4–5 °C. Therefore, the calibration criterion of parameters was possibly the closest comparability of really modelled and measured water temperatures in the Viešvilė aquifer (Fig. 4).

The present yields of the wells entail no marked changes of groundwater head. Moreover, there is an obvious reciprocal stabilizing impact of extraction– injection. The most marked elevation of water head takes place in injection well 4i situated farthest from the extraction wells. Yet even in this area, the level of mineralized (95 g/*l*) water remains below the earth surface.

There is no available factual information about the impacts of Klaipėda geothermal plant on the distribution of groundwater levels, temperatures and injected water in the Viešvilė aquifer in 2001–2007. The model reconstruction results are given in Figs 5 and 6.

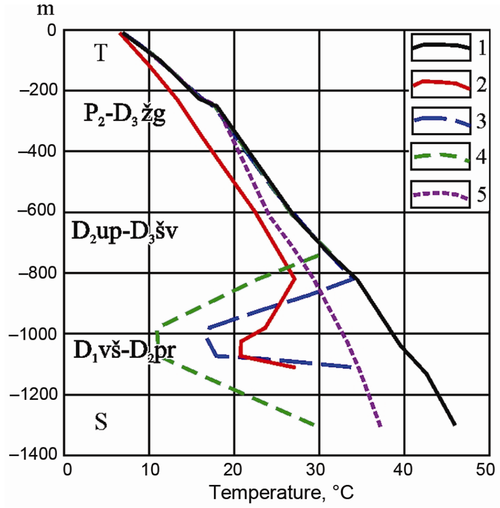

Fig. 4. Temperature of the underground in the injection well 1i: 1 – undisturbed; in 2008: 2 – measured; 3 – modelled; predicted: 4 – after 50 years of exploitation plant at project capacity; 5 – 6000 years after it stoppage

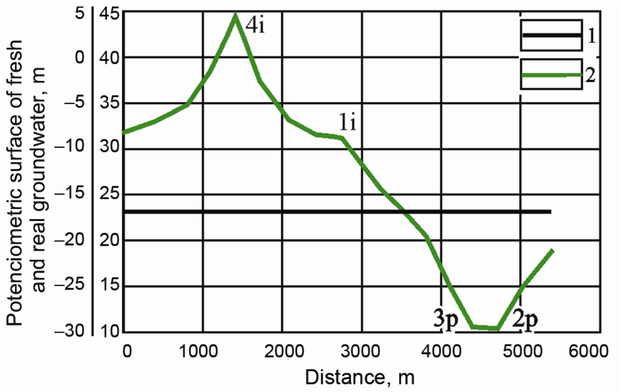

Fig. 5. Piezometric surface of groundwater in the Viešvilė aquifer in the direction of section A–A: 1 – initial; 2 – before the stoppage of the plant in 2007

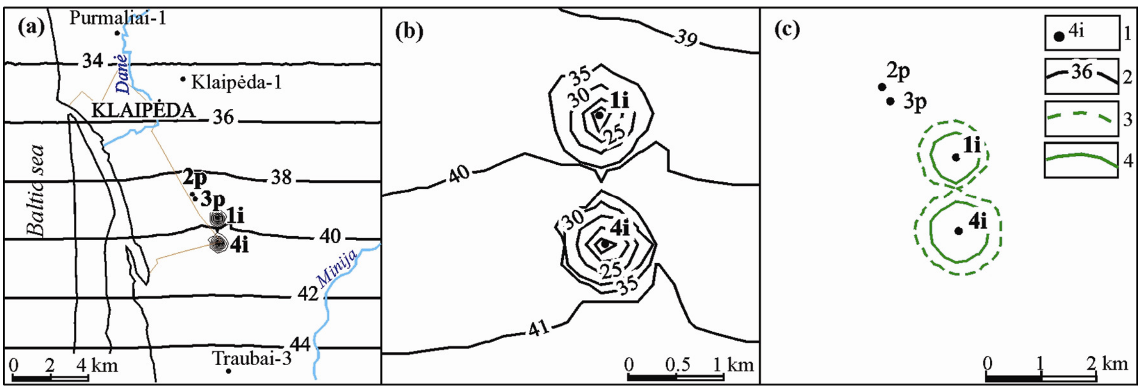

Fig. 6. Schemes of isogeotherms (a), (b) and injected materials migration (c) in Viešvilė aquifer before the stoppage of KDGP in 2007 (model data): 1 – well and its name; 2 – isogeotherm, °C; per cent of the initial concentration of injected material: 3–1%; 4–10%

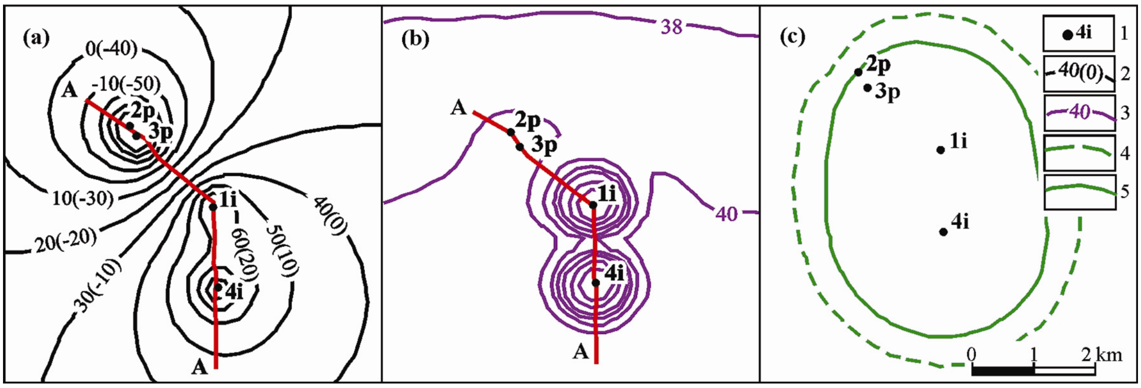

Fig. 7. Schemes of piezometric surface of fresh and real (in parentheses) water (a), isogeotherms (b) and injected material migration (c) after 50 of exploitation of KDGP wells at project capacity (model data): 1 – well and its name; 2 – isopotential line; 3 – isogeotherm, °C; per cent of the initial concentration of injected material: 4 – 1%; 5 – 10%

In 2001–2007, the zone of cooled water impact on the temperature of Viešvilė aquifer extended for 0.5 km from injection wells. The distance of maximal dispersion of injected water in the aquifer is about 1 km. I.e., the injected water remains within 0.5 km from the closest extraction well (3p) (Fig. 6[b,c]).

Geothermal plant operation at project capacity. As the impact of project geothermal water extraction (700 m^3/h) on the underground would have been the strongest, we will concentrate on description of its modelling results bearing in mind that this capacity can be reached by installation of one or two additional injection wells.

The predicted temperature changes in the Viešvilė aquifer occurring due to cooled water injection are shown in Fig. 7[b] and the possible dispersion pattern of injected materials is shown in Fig. 7[c].

In 50 years, the zone of lowered temperatures would include a territory of about 15 km^2 around the injection wells, but the temperature of extracted water would remain unchanged. This means that extraction of geothermal energy at project capacity (20.8 MW) would be possible in the territory of KDGP even after 50 years.

After stoppage of thermal water extraction and cooled water injection, the variations of underground temperature occur mainly through heat conduction. According to model prediction, in 500 years after the stoppage of plant, the temperature of Viešvilė aquifer would increase due to heat fluxes only by 8–9 °C. As the initial temperature (37–40 °C) of Viešvilė aquifer would regenerate in more than 6000 years its cooling should be regarded as an irreversible process in the historic time (Fig. 4).

The technology of energy extraction in the KDGP provides for cooled water treatment with inhibitors before return to the aquifer in order to prevent gypsum precipitation. Calculation results showed that the injected water would reach the closest productive well in 15–20 years yet after 50 years its amount in the extracted water would not exceed 10%. Accordingly, the maximal concentration of injected material in the extracted water would not exceed 10% of the initial one (Fig. 7[c]).

The depression and dome of piezometric surface in the Viešvilė aquifer formed by groundwater extraction and injection are almost symmetrical due to similar rates and comparable aquifer conditions. The water level is above the ground (altitude 10–15 m) only between the injection wells and 0.2–0.5 km from them. Drawdown is 80–90 m outside the casing of productive wells (to a depth of 120–130 m below the ground) (Fig. 8).

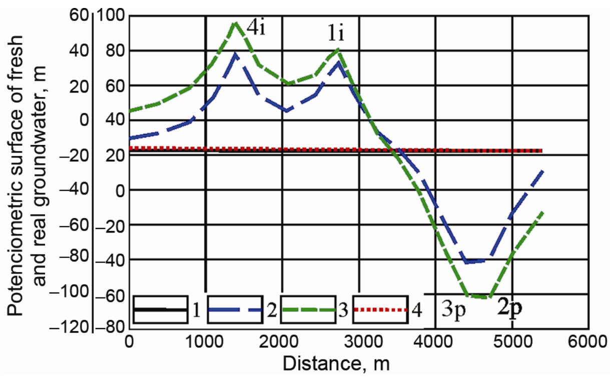

Fig. 8. Variation of piezometric surface of Viešvilė aquifer: 1 – initial; 2 – after 1 year; 3 – after 50 years of exploitations of wells at project rate; 4 – 100 year after plant stoppage (in the direction of A-A section)

As mentioned above, the accepted exploitation capacity (and amount of extracted water) of KDGP is lower than the project one. The predicted impacts are similar in character yet slightly weaker. As the lower capacity of the plant offers no obvious environmental advantages, their detailed discussion seems irrelevant.

A typical plant exploiting the geothermal energy from the Viešvilė aquifer would include one productive and one injection wells operating at a rate of 250 m^3/h (6000 m^3/d). Model results showed that with wells spaced at 750–850 m, the plant would operate at full capacity for 50 years.

The predicted water level change in the Viešvilė aquifer around the wells would range within 20–30 m. In the surroundings of injection wells, the water level usually does not reach the ground.

The temperature variations embrace a small ellipse-shaped area. Thus, in case of required greater amount of energy, another pair of wells can be installed at a similar distance. Beside, the extraction wells should be installed in the zone of higher temperatures (closer to the centre of the geothermal anomaly).

The return of part or whole of the spent water from the Viešvilė productive aquifer to other aquifers affects the water dynamics, chemistry and thermal regime of the latter.

When all spent water is returned to the Šventoji–Upninkai aquifer, the drawdown in the productive aquifer is by 40–50 m higher than in the project variant (up to an altitude of -140 m). Due to comparatively good filtration parameters, the rise of water level in the Šventoji–Upninkai aquifer near the injection wells is small (12–15 m). After the stoppage of extraction or injection, the levels of Viešvilė and Šventoji–Upninkai aquifers do not take long to reach the initial position.

The injection of the whole water cooled to 11 °C from the Viešvilė productive aquifer into the Šventoji–Upninkai aquifer changes the temperature of the latter due to almost analogous heat capacity in a similar area as in the Viešvilė aquifer in the case of the project variant.

The return of cooled water into two aquifers changes the dynamics of Viešvilė and Šventoji–Upninkai complexes minimally if compared with the previous variant.

The rise of water mineralization (dispersion of injected water) in the Šventoji–Upninkai aquifer entailed by injection is expected at a distance up to 1.5–2 km from the wells.

In the case of injections of the whole project spent water into the Upper Permian–Žagarė aquifer, the mineralized water would reach the wells of Klapėda 2 waterworks situated approximately 3 km north-west of the geothermal plant in 10 years and in 25 years the mineralization of the extracted water would rise to 7–10 g/*l* (Fig. 9).

Evaluation of the outcomes of emergency events. The emergency penetration of the spent geothermal water with mineralization of 95 g/*l* and temperature of 11 °C can be expected through injection wells into the Šventoji– Upninkai (mineralization 30 g/*l*, temperature 25–28 °C) or Upper Permian–Žagarė (mineralization 0.5–5 g/*l*, temperature 10–15 °C) aquifers. The water of Šventoji–Upninkai aquifer is practically not used due to its mineralization and low temperature. The emergency (short-lasting) injections of the water from the Viešvilė aquifer, which is of similar chemical type, represent no hazard for it.

The fresh Upper Permian–Žagarė water is used for Klaipėda city water supply. A single one day-lasting injection of cooled spent water into this aquifer from the closest injection well (1i) presents no hazard to the fresh water quality in the waterworks. The consequences of emergency injection to the Upper Permian–Žagarė aquifer would disappear in 25 years (Fig. 10).

The thermodynamic calculations of the consequences of mixing of the waters with different temperature and chemical composition included: 1 – mixing of natural temperature (37.5 °C) and the cooled water (11 °C) of Viešvilė aquifer; 2 – the Upper Permian–Žagarė and Šventoji–Upninkai aquifers-recipients water mixing with the cooled (11 °C) injected Viešvilė aquifer water (at proportions 20%, 40%, 60%, and 80%). Calculations were based on the average values of indices in Viešvilė, Šventoji–Upninkai and Upper Permian–Žagarė aquifers.

The percentage of migration forms of the main chemical elements in the groundwater changes but little in different calculations. Calcium, magnesium, sodium, potassium and iron mainly migrate as ions (86.4–99.7% of the total content of each element) and in the forms of carbonates and sulphates: up to 9%.

Water saturation by minerals is more variable. In all estimated cases, the water is saturated with iron oxides: hematite, magnetite, goethite. Saturation with calcium and magnesium carbonates (aragonite, calcite and dolomite) is characteristic only of Šventoji–Upninkai water. It remains highly saturated until the portion of cooled water from the productive aquifer reaches 50%. Similar pattern is followed by iron oxide maghemite.

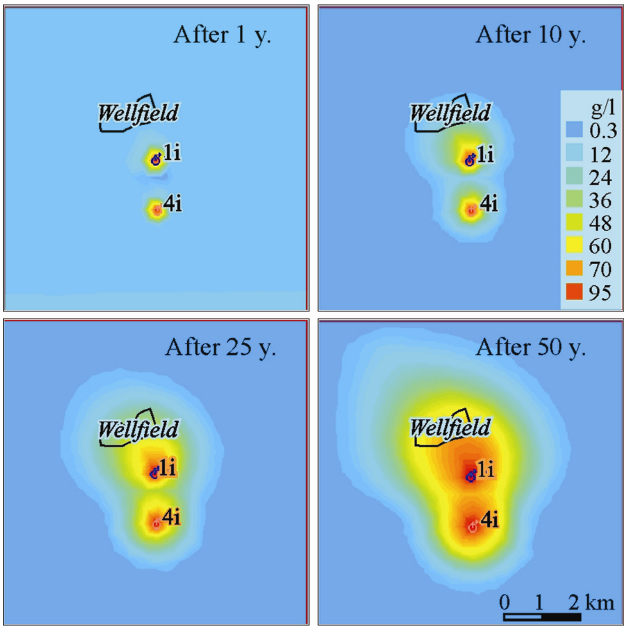

Fig. 9. Mineralization of Upper Permian–Žagarė aquifer water after 1, 10, 25 and 50 years of spent water injection with project yield

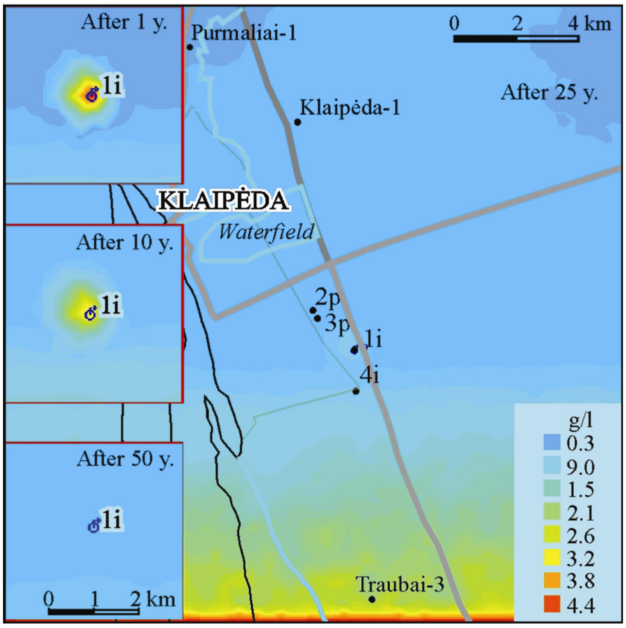

Fig. 10. Mineralization of Upper Permian–Žagarė aquifer water after 1, 10, 25 and 50 years a potential emergency in the injection well 1i

The water of the Upper Permian–Žagarė aquifer is slightly saturated with iron carbonate siderite. The spent water injection reduces the saturation index. In all analysed cases, the groundwater is not saturated with calcium sulphate anhydrite and magnesium carbonate magnesite.

The total amount of chemicals in the water of Viešvilė aquifer able to precipitate remain the same (up to 2 g/*l*): sulphates account for about 65% and oxides for about 25%. The portion of carbonates does not exceed 10%. The temperature and composition variations fractionally change the saturation indices.

Therefore, precipitation of gypsum and other materials on the pipe walls and well filters presumably is predetermined by other technogenic reasons (exposure to oxygen, etc.). During the exploitation of geothermal energy from the Viešvilė aquifer, it is necessary to prevent the groundwater evaporation and emission of carbon dioxide from it.

The composition of mixture and the calculated migration forms of chemical elements and the variation of the saturation indices with minerals is given in Fig. 11.

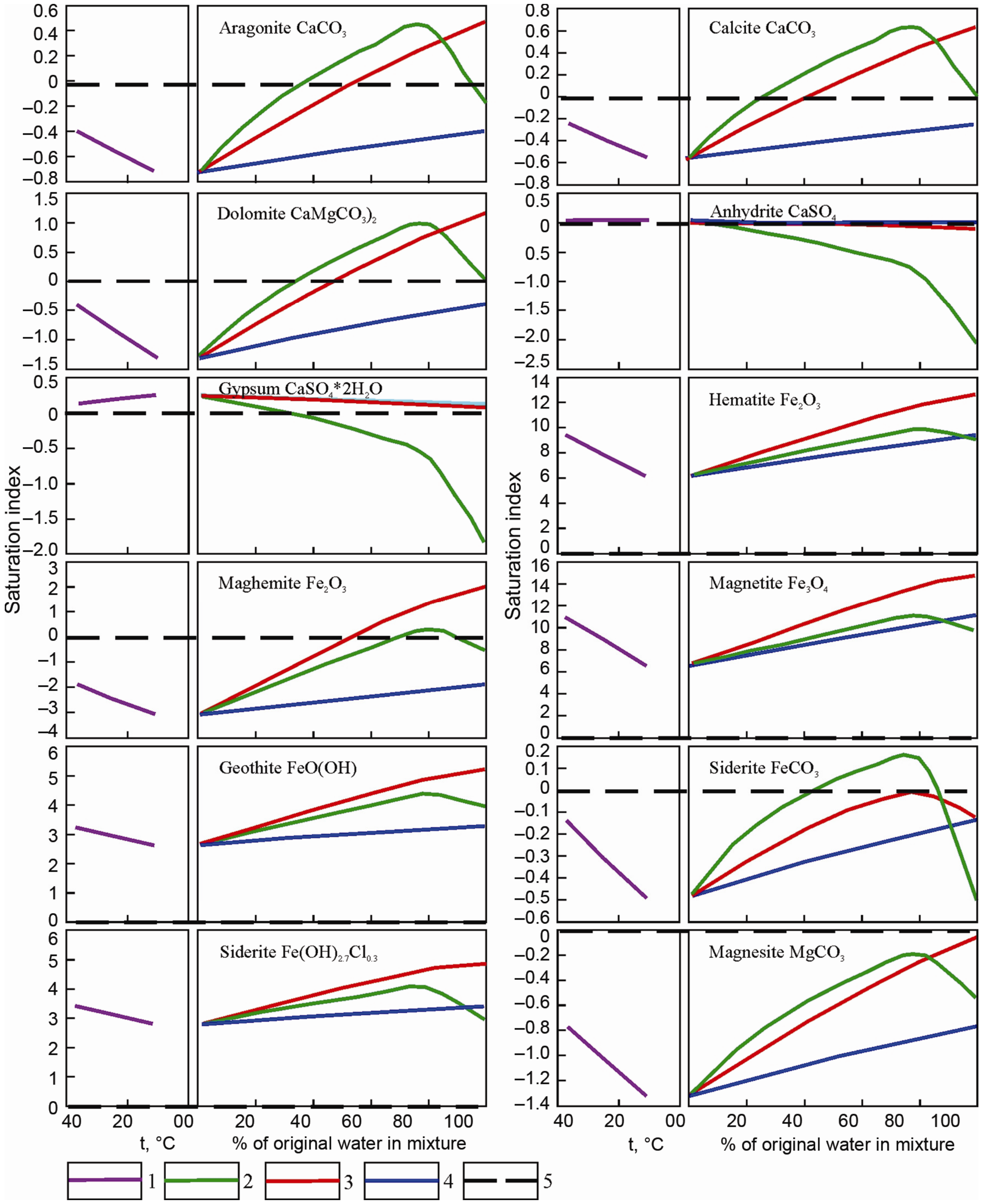

Fig. 11. Predicted saturation of groundwater with minerals: 1 – in the water of Viešvilė aquifer at temperature fall from 37.5 to 11°C; 2–4 – in the Upper Permian–Žagarė, Šventoji–Upninkai and Viešvilė aquifers (respectively) after injection of cold (11 °C) spent geothermal water

The operation experience of KDGP showed that in the projection stage of analogous geothermal plants, it is necessary: to carry out detailed investigations of chemical composition and physical properties of the water from the productive and other aquifers where geothermal water may be purposefully or accidentally injected and to predict the possible reactions entailed by changing temperatures and pressure. Bearing in mind the costliness of errors, not only mathematical but also physical modelling and development of special technologies are expedient.

Installation of special network of deep (over 1000 m in depth) wells designed for monitoring of temperatures, pressures and chemical composition of productive aquifer in operating plants is economically unrealizable. Nevertheless, detailed measurements of pressures, yields, water temperatures and chemical composition in the productive and injection wells of operating KDGP are essential. Mathematical modelling as an instrument of assessment of underground responses to geothermal energy extraction would be the best solution. The mathematical model of filtration, migration and heat processes in the Upper Phanerozoic complex of Klaipėda environs (software and database) should be upgraded and used for interpretation of monitoring data and for prediction of the resources of projected and operating plants and their possible environmental impacts.

6. Conclusions

The Klaipėda demonstration geothermal plant started in 2001 has two productive and two injection wells. The total project amount of water extracted and returned back to the same Viešvilė aquifer after cooling from 37.5 to 11 °C equals to 700 m^3/h. Due to low productivity the number of injection wells is insufficient for achievement of the project capacity of the power plant. Increase of the capacity to the project one by injection of the spent water to other aquifers (Šventoji–Upninkai and Upper Permian–Žagarė) is associated with the problems of maintaining pressures in the productive aquifer and protection problems of the underground embracing the larger part of Phanerozoic, which were evaluated by mathematical modelling.

Analysis included a few variants of geothermal energy extraction in the KDGP (factual operation regime in 2001–2007, operation at project, accepted and minimal cost-effective capacities, return of the spent water from the Viešvilė aquifer and emergency injections into the Upper Permian–Žagarė or Šventoji–Upninkai aquifers) and probability of precipitation of minerals under the conditions of mixing of waters of different chemical composition and temperature.

The model analysis showed that:

1. The geothermal energy resources in the productive Viešvilė aquifer are sufficient for 50 years of operation of KDGP at capacity 20.8 MW (water extraction 700 m^3/h or 16.8 thousand m^3/d); the drawdown (or elevation) of the water level in the aquifer near the productive (injection) wells would be about 80–90 m and within the distance of 0.2–0.5 km from the injection wells it would rise above the ground.

2. The water injected at project capacity would reach the extraction wells in 10–15 years yet after 50 years its portion in the yield would not exceed 10%. The temperature in the productive about 130 m thick aquifer would fall in an area of about 15 km^2.

3. The cooling (from 37–39 to 11 °C) of the Viešvilė aquifer entailed by geothermal energy extraction in the impact zone of injection wells is an irreversible process in historic time. In case of stoppage of injections, the geothermal energy flux would rise the aquifer temperature only by a few degrees in 500 years. The initial temperature could be reached only in 6000 years;

4. The geothermal energy of Viešvilė aquifer could be exploited in an area of almost 10 thousand km^2; it is sufficient to space the productive and injection wells at 750–850 m what would safeguard the operation of such plant for 50 years at the capacity of 5–6 MW (water extraction 250 m^3/h).

5. The return of the spent water into the Šventoji–Upninkai aquifer produces no adverse effects on hydrodynamic and hydrochemical regime of the latter.

6. In the case of permanent injection at project capacity into the Upper Permian–Žagarė aquifer, the mineralized spent water would reach the Klaipėda waterworks in 10 years. In 25 years, the groundwater mineralization in the waterworks would reach 10 g/*l*.

7. Short-lasting emergency penetration of spent water from the injection wells represents no hazard for the water quality of Šventoji–Upninkai aquifer; in the case of such penetration into the Upper Permian–Žagarė aquifer, the mineralized water also would not reach the waterworks situated at a distance of 3 km.

8. The interaction of the waters of different temperatures and chemical composition may slightly increase the saturation of the mixture with iron minerals (hematite and magnetite) and favour their precipitation in the aquifer or well filters, i.e. may deteriorate the conductivity of the aquifer in the filter zone and adjacent area.

Acknowledgements

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KLAIPĖDOS GEOTERMINĖS JĖGAINĖS POVEIKIS GEOLOGINEI APLINKAI

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S a n t r a u k a

Potencialus geoterminės energijos gavybos poveikis viršutinei fanerozojaus daliai, taikant įvairias terminio vandens gavybos ir grąžinimo į produktyvųjį ir kitus vandeninguosius sluoksnius schemas, vertintas Klaipėdos parodomosios jėgainės pavyzdžiu. Atlikus modelinius tyrimus nustatyta: 1 – išsprendus injektavimo problemą, produktyvaus Viešvilės komplekso šiluminės energijos ištekliai yra pakankami 50 metų jėgainei veikti planuotu 20,8 MW geoterminiu galingumu; 2 – injektuotas vanduo gavybinius gręžinius pasiekia per 10–15 metų, tačiau jo dalis debite po 50 metų neviršija 10 %; per 50 metų produktyviame komplekse temperatūros pažemėjo maždaug 15 km^2 plote; 3 – panaudoto mineralizuoto (apie 95 g/*l*) vandens grąžinimas į Šventosios – Upninkų kompleksą esminio neigiamo poveikio jo hidrodinamikai, hidrochemijai ir šiluminiam režimui nedaro; analogiškai injektavus į viršutinio permo – Žagarės horizontą, gėlo vandens vandenvietes grąžintas vanduo pasiektų per 10 metų; 4 – įvairių temperatūrų ir cheminės sudėties požeminio vandens sąveika gali nežymiai padidinti mišinio įsotinimą geležies mineralais (hematitu ir magnetitu) ir sukelti jų nusėdimą sluoksnyje ar gręžinių filtruose; Viešvilės komplekso atšalimas poveikio zonoje nuo 37–39 °C iki 11 °C, kurį lėmė 5–50 metų trukmės injektavimas, yra istoriškai negrįžtamo pobūdžio. Sustabdžius injektavimą kompleksas iki pradinės temperatūros įšiltų daugiau kaip per 6000 metų.

Reikšminiai žodžiai: Vakarų Lietuvos geoterminė anomalija, geoterminė energija, Klaipėdos parodomoji jėgainė, hidrodinamika, medžiagų ir šilumos pernaša, modeliavimas, poveikio prognozė.

ВОЗДЕЙСТВИЕ КЛАЙПЕДСКОЙ ГЕОТЕРМАЛЬНОЙ СТАНЦИИ НА ГЕОЛОГИЧЕСКУЮ СРЕДУ

А. Зузявичюс, А. Юрявичюс, К. Гальчювене

Р е з ю м е

Оценка возможного воздействия добычи геотермальной энергии на верхнюю часть осадочного чехла при различных схемах закачки использованной воды в продуктивный и другие горизонты проведена моделированием участка Клайпедской показательной станции. Исследование показало, что: 1 – запасы тепловой энергии продуктивного вешвильского комплекса нижнего девона достаточны для эксплуатации станции с предусмотренной производительностью в 20.8 MW на протяжении 50 лет; 2 – использованная и возвращенная в продуктивный комплекс вода к эксплуатационным скважинам поступает через 10–15 лет, однако ее доля в расходе и спустя 50 лет останется менее 10%; 3 – закачка использованной минерализованной (95 г/л) воды в швянтойско-упнинкайский комплекс существенного отрицательного воздействия на его гидро- и термодинамику, а также химический состав не оказывает; аналогичная закачка в верхнепермско-жагарский горизонт привела бы к выходу из строя водозабора пресных вод через 10 лет; 4 – смешение подземных вод различного состава и температуры повышает насыщенность смеси гематитом и магнетитом и их выпадение; 5 – охлаждение продуктивного комплекса за 50 лет закачки охватывает площадь порядка 15 км^2 и в историческом масштабе времени за счет кондукции тепла является необратимым – восстановление температуры с 11^{o}C до исходной 37–39^{o}C возможно спустя 6000 лет.

Ключевые слова: Западно-Литовская геотермальная аномалия, геотермальная энергия, Клайпедская показательная станция, гидродинамика, тепло-массоперенос, моделирование, прогноз воздействия.

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