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Utilization potentials of the low-enthalpy geothermal aquifer of the Bad Radkersburg – Hodoš pilot area – based on 3D modelling results of the TRANSENERGY project

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ABSTRACT

The Bad Radkersburg – Hodoš area is one of the study areas of the project TRANSENERGY (http://transenergy-eu.geologie.ac.at/). The pilot area extends through the NE part of Slovenia, SE part of Austria and continues to the W part of Hungarian state territory. In order to determine the potential effects of different production scenarios on the low-enthalpy geothermal aquifer in the Pre-Neogene basement of the Mura-Zala basin and to provide support for future utilization in this sensitive transboundary area, a numerical model of flow and heat transfer was established.

The geothermal model is based on the 3D geological model of the pilot area which is founded on the supra-regional geological model of the TRANSENERGY project.

The 3D hydraulic and geothermal model was set up with FEFLOW 6.0 modelling software. Delineation of the computational layers is based on geological horizons of the geological model. Due to sparse borehole data only two geological layers were defined, namely Neogene sediments and sedimentary rocks and Pre-Neogene basement. Values of the model parameters were defined in the calibration process.

In order to estimate the impacts of the planned utilization in Korovci (SI) on the nearby spa resort in Bad Radkersburg (A) several scenarios were tested. First, 8 production scenarios without reinjection were performed and computed drawdowns were observed. In the next step, 5 scenarios using a geothermal doublet in Korovci were performed and potential cool-down effects of the reinjected water front were determined.

The outcome of the modelling as well as the geothermal model itself can be used as a tool for the transboundary management of the thermal aquifer and could support the decision-making process in case of transboundary conflicts.

1. INTRODUCTION

Utilization of the geothermal energy worldwide has been increasing in the past decades. According to Lund et al. (2011) the utilization amount increased from 112,441 TJ/year in 1995 to 423,830 TJ/year in 2010. This is also the case in NE Slovenia where the direct utilization of geothermal energy has increased from 186 TJ/year in 1995 to 411 TJ/year in 2010 (Rman et al. 2012).

If the production rate does not exceed the natural recharge the utilization can be considered as renewable (Stefansson 2000). However, in many cases production rates must be higher in order to achieve economic exploitation. Such production rates exceed the rate of recharge and eventually lead to depletion of the thermal aquifer (Rybach 2003), and in such cases a reinjection borehole or more of them may be needed.

Those adverse effects can be especially sensitive in cases of transboundary aquifers where it could lead to potential conflicts between the involved countries.

In 2008, a deep geothermal borehole was drilled in Korovci (SI) (Kraljić and Lugomer-Pohajda 2008a; Kraljić and Lugomer-Pohajda 2008b), about 5,3 km away from the nearby spa resort in Bad Radkersburg (A) where water is produced from the same aquifer. The maximum projected production rate from the borehole Kor-1gα will not exceed 20 l/s (Lapanje et al. 2012). The projected utilization in Korovci caused concerns on the Austrian side on a potential interference between production wells. As a consequence, a joint bilateral water commission was established to address the ensuing issues.

Thus a new geothermal utilization scheme has been adopted in Korovci by using a geothermal doublet. In that case, all of the abstracted water would be returned back in the same aquifer through the planned reinjection borehole (Lapanje et al. 2012).

2. SETTINGS

The Bad Radkersburg – Hodoš pilot area is situated at the national borders of Austria, Slovenia and Hungary (Fig. 1). The SW border of the pilot area is defined by the water divide between Drava and Pesnica rivers.

Towards the NE the pilot area passes across the Mura River and Goričko hills to the Hungarian national territory. The model covers an area around 2078 km^2.

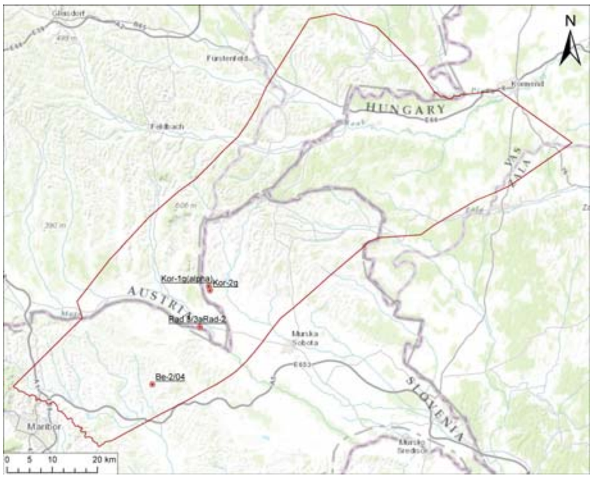

Fig. 1. Delineation of the pilot model area with the production wells (red dots).

From geotectonic point of view the bulk of the pilot area occupies the SW part of the Transdanubian Range Unit bordered by the Rába Fault zone to the NW. To the west, the pilot area encompasses a small part of the Styrian Basin. Along the Rába Fault, the Southburgenland Swell divides the Mureck Sub-basin from the Radgona-Vas Subbasin. To the south, the pilot area encompasses the Radgona-Vas Sub-basin and the NW part of the Murska Sobota High. To the NE, the Bad Radkersburg pilot area includes East Mura-Őrszég Sub-basin. The NW and SE borders are represented by uplifted geological structures, Southburgenland Swell and Murska Sobota High respectively (Maros et al. 2012).

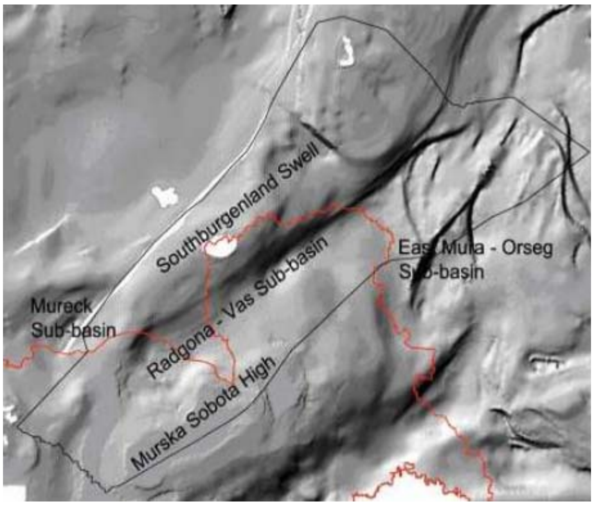

Fig. 2. Sub-basins of the Bad Radkersburg-Hodos pilot area (Maros et al. 2012).

Neogene sediments and sedimentary rocks represent the upper part of the stratigraphical sequence. Their thickness varies through the area and it is generally increasing from SW to NE.

The Pre-Neogene basement rocks below are represented by the Mesozoic carbonate rocks and Paleozoic metamorphic rocks. The top of the Pre-Neogene basement dips in a NE direction from a depth of 760 m in Benedikt (Kralj et al. 2009) to 1700 in Cankova and reaches 4100 m in Dolenci near the state border with Hungary (Fodor et al. 2011). In the SW part of the area, in Slovenia, the metamorphic rocks prevail in the basement. Carbonate rocks can be found only in tectonic patches. Towards the east, in Hungary, the Mesozoic carbonate rocks occur in a wider range as a part of the Transdanubian Range (Fodor et al. 2011).

The Bad Radkerbug-Hodos pilot area comprises of two main subvertical tectonic lines, which represent the continuation of the Raba Fault zone into Radgona-Vas tectonic half graben (Maros et al. 2012). Between those tectonic lines the basement rocks are strongly tectonized. Those fractured and fissured basement rocks along the Raba Line zone represent the main aquifer in the modelled area.

Isotopic analyses carried out in the borehole Be-2/04 in Benedikt indicate that the water in the Pre-Neogene basement is of meteoric origins and of Pleistocene age (Kralj et al. 2009; Szocs et al. 2012). Therefore, we can assume that infiltration is an important recharge mechanism. No other recharge mechanisms are known in this area.

There is no known natural discharge in the modelled area. However, thermal water from the Pre-Neogene basement is being abstracted from three boreholes in Benedikt and Bad Radkersburg at the moment.

In the NE part of Slovenia an elevated heat flow is characteristic due to thinner lithosphere. According to Rajver et al. (2002) the values of heat flux density reach 80-120 mW/m^2 on average.

3. METHODS

In the first step, a conceptual hydrogeological model for the pilot area has been established on the basis of the existent geological model and other geological data (Maros et al. 2012). Due to sparse hydrogeological and other borehole data, we decided to use only two geological layers in the model, namely Neogene sediments and Pre-Neogene basement. Thus all Neogene layers were joined together into one hydrogeological unit.

For the modelling FEFLOW 6.0 software package developed by DHI-WASY GmbH was used. It enables fluid flow modelling coupled with heat transport and/or transport of dissolved constituents, and is based on finite elements (DHI-WASY, 2012).

The model area is outlined in accordance with Transenergy pilot area (Fig. 1). The mesh was generated using the triangle mesh generator. The number of generated elements in the mesh is in total 1000 per each slice. The side length of triangular elements is around 1500 m. In vicinity of the boreholes the mesh was refined.

The topmost boundary of the model is defined by the topography, whereas the bottom boundary is set at the depth of 5 km in the Pre-Neogene basement rocks. The model is comprised of 16 numerical layers in total (Fig. 3).

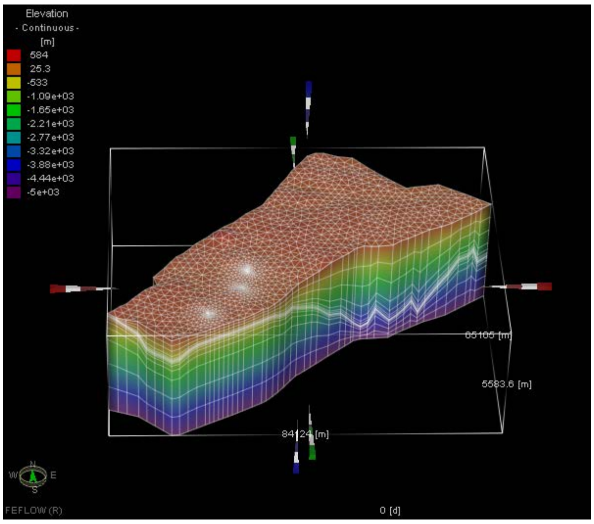

Fig. 3. Geometry of the pilot area model.

The shape of the model area follows the major fault systems on both (northern and southern) sides. According to our working hypothesis, the Southburgenland Swell on the north represents a hydraulic barrier. The metamorphic rocks of the Murska Sobota High act similarly. Therefore, both boundaries were defined as no flow boundaries. The western border was set as a fixed hydraulic head boundary at 200 m. At the eastern border of the model fixed hydraulic head boundary was set to 100 m. Those values were derived and interpolated from available hydraulic head data from Slovenian (Be-2/04, Kor-1gα) and Hungarian boreholes (NK-1 Nádasd, Va-1 Vasvár, K-30 Hévíz).

Due to lack of information, recharge in the model is dependent on the boundary conditions which were adjusted in the calibration phase. The model is recharged at the SW boundary, due to hydraulic gradient, caused by hydraulic head differences at SW and NE boundaries. Another source of recharge is infiltration which was set at 1.5 mm/year.

There is no known natural discharge from the basement rocks in the pilot area. Subsurface discharges in the model are simulated by the outflow at the NE boundary. However, thermal water is abstracted from three deep production wells (Table 1).

Table 1. Production rates from the existing production wells in the pilot area.

Well name	Abstraction depth interval (m)	Production rate (m^3/day)
Be-2/04	823.27 - 1857.34	864
Rad-2	1792 - 1857	1200
Rad 3/3a	1769 - 1858	720

First, a steady state hydraulic model was developed. Due to lack of measured data, the model parameters were defined in the calibration process (Table 2). Available data from three existing deep boreholes was used for this purpose. According to the available piezometric heads measurements in the Bad Radkersburg and Benedikt, no long term declining trends in piezometric heads are observed which indicates a balanced aquifer system. This hydraulic equilibrium was a target in the calibration of the model's hydraulic parameters.

Next, a steady state thermal model was developed. The lowermost thermal boundary is defined by surface heat flow density and is set as a uniform value at 0.1 W/m^2. The uppermost boundary is set as a uniform temperature of 10 °C which corresponds to annual mean air temperature in the model area (Fridl et al. 1998).

Calibration of geothermal parameters was based on temperature measurements in boreholes Peč-1, Kor-1gα and Be-2. The thermal conductivity values used in the model are based on internal database data of the Geological Survey of Slovenia (Rajver 2012). They were derived from core analysis and temperature measurements. Porosity in the basement has been set higher in the Raba fault (RF) zone than outside.

Table 2. Parameters used in the pilot area model.

Parameter	Neogene	Basement	
		RF zone	Outside RF zone
Horizontal hydraulic conductivity [m/s]	1×10^{-7}	$1 \times 10^{-5} - 1 \times 10^{-7}$	5.8×10^{-8}
Vertical hydraulic conductivity [m/s]	1×10^{-9}	$1 \times 10^{-5} - 1 \times 10^{-7}$	5.8×10^{-8}
Porosity	0.2	0.1-0.2	0.05
Specific storage [1/m]	1×10^{-4}	$1 \times 10^{-4} - 1 \times 10^{-4}$	1×10^{-4}
Heat conductivity of solid [W/mK]	2	5	5
Heat conductivity of fluid [W/mK]*	0.65	0.65	0.65

Expansion coefficient [1/K]*	0	0	0
Volumetric heat capacity of solid [JK/m^3]*	2.52 × 10^6	2.52 × 10^6	2.52 × 10^6
Volumetric heat capacity of fluid [JK/m^3]*	4.2 × 10^6	4.2 × 10^6	4.2 × 10^6
Longitudinal dispersivity [m]	5	5 - 150	5
Transverse dispersivity [m]	0.5	0.5 - 15	0.5
Anisotropy of solid heat conductivity [W/mK]*	1.16 × 10^{-5}	1.16 × 10^{-5}	1.16 × 10^{-5}

* Default values in FEFLOW

Furthermore, several production scenarios were developed in order to determine the potential impact of production in Korovci on other wells, especially in Bad Radkersbug. In all scenarios computed hydraulic heads after 30 years of thermal water production in Bad Radkersburg were used for the initial conditions. In this way, present state of the aquifer and head distribution was approximated. First, 8 different scenarios of production without reinjection were developed and computed hydraulic heads in all of the boreholes were observed (Table 3). In order to incorporate uncertainty, related to defined parameter values, ranges of parameters values were implemented. All production scenarios were simulated for 50 years period.

Table 3. Production scenarios in Korovci (without reinjection).

Scenario	Hydraulic conductivity in RF [m/s]	Aquifer thickness (m)	Specific storage	Rate [l/s]
1	1×10^{-6}	70	1×10^{-4}	20
2	1×10^{-6}	150	1×10^{-4}	20
3	1×10^{-6}	300	1×10^{-4}	20
4	1×10^{-6}	150	5×10^{-5}	20
5	1×10^{-6}	150	1×10^{-5}	20
6	1×10^{-7}	150	1×10^{-5}	20
7	1×10^{-5}	150	1×10^{-5}	20
8	1×10^{-6}	150	1×10^{-5}	40

Next, 5 different scenarios were developed using a geothermal doublet in Korovci (Table 4). The aim of these scenarios was to determine the potential cool-down effects of cold water reinjection in well Kor-2g. The temperature of reinjected water was set to 35 °C. The production (Kor-1gα) and reinjection (Kor-2g) wells in the model are 700 m apart.

Table 4. Reinjection scenarios in Korovci.

Scenario	Longitudinal / Tranverse dispersivity	Hydraulic conductivity [m/s]	Reinjection rate [l/s]
1	5 / 0.5	1×10^{-6}	20
2	50 / 5	1×10^{-6}	20
3	150 / 15	1×10^{-6}	20
4	150 / 15	1×10^{-5}	20
5	150 / 15	1×10^{-5}	40

In the first 3 scenarios the simulation time was 1000 years, whereas in scenarios 4 and 5 was 100 years.

4. RESULTS

4.1 Temperature comparison

Comparison between computed and measured temperatures was carried out in three deep geothermal boreholes (Fig. 4, Fig. 5 and Fig. 6). In the case of borehole Kor-1gα match is good. In the case of the borehole Peč-1 the match is good in the upper Neogene layers, whereas in the basement rocks the computed temperatures are slightly higher than measured. However, according to Gosar (1995) the Pečarovci antiform is a tectonically isolated structure. Therefore, the temperature measurements in borehole Peč-1 are not representative for the pilot area model.

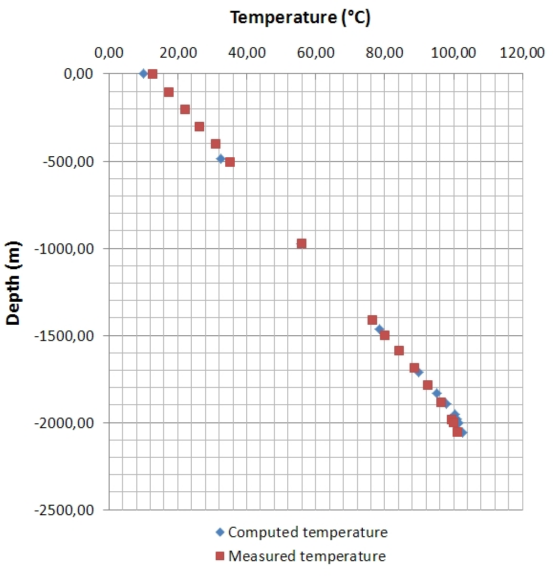

Fig. 4. Comparison of computed and measured temperatures in Kor-1gα borehole.

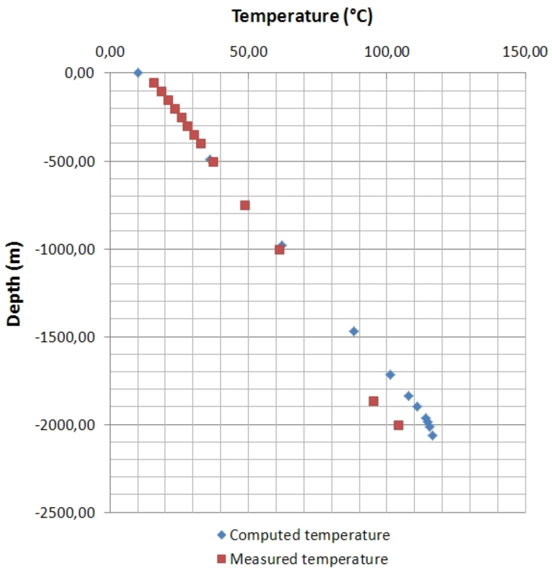

Fig. 5. Comparison of computed and measured temperatures in Peč-1 borehole.

The largest discrepancy between computed and measured temperatures is observed in the borehole Be-2/04. It indicates geothermal anomaly in the Benedikt area which cannot be simulated with the model on a pilot area scale. In order to simulate local geothermal conditions different modelling approach was used which enables simulation of hydrothermal system with dominated vertical groundwater movement and convective heat transfer (Fuks et al. 2013).

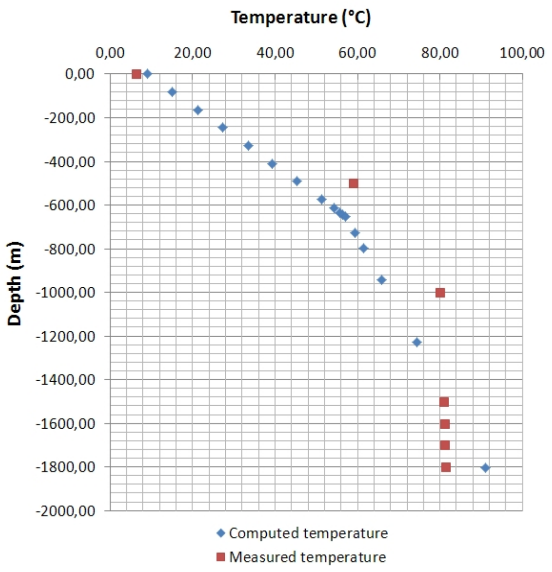

Fig. 6. Comparison of computed and measured temperatures in Be-2 borehole.

4.2 Utilization without reinjection scenarios

Table 5 shows the computed hydraulic heads after 50 years of production (without reinjection) in Korovci. The constant production rate is set to 20 l/s in all scenarios except scenario 8, where it is set to 40 l/s. The last one is an extreme abstraction rate which is used to show sensitivity of the model to abstraction rate. In scenario 7, hydraulic conductivity in Raba fault zone was set to higher value.

Table 5. Computed drawdown after 50 years in production in Korovci for all scenarios.

Scenario	Computed drawdown Kor-1ga [m]	Computed drawdown Kor-2g [m]
1	14.5	5.0
2	14.5	5.0
3	13.5	4.7
4	14.5	5.0
5	14.5	5.0
6	15	5.2
7	11	4.5
8	30	9.3

Scenarios 1 (Fig. 7) to 6 produce similar results. The computed drawdown in scenario 7 is lower than in other scenarios, but the effects extend further away from the production borehole Kor-1gα.

Effects of the production in Korovci are detected in Bad Radkersburg only in scenarios 7 (Fig. 8) and 8 whereas the effects in Benedikt are not seen in any of the scenarios.

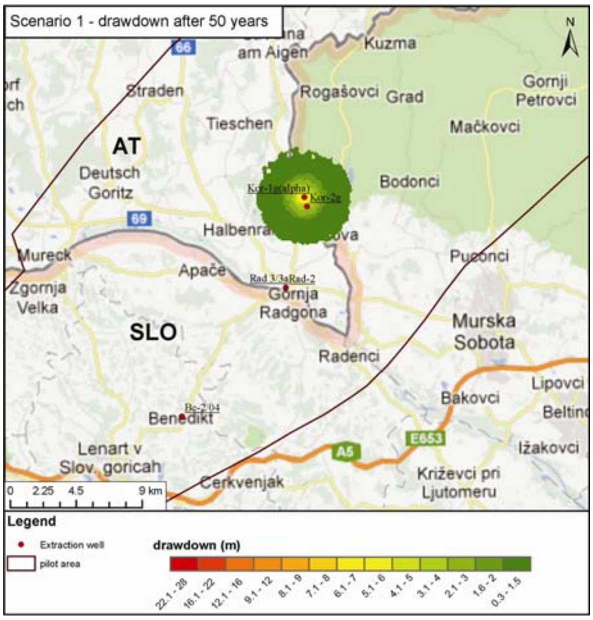

Fig. 7. Scenario 1 – computed drawdown after 50 years of production in Korovci (without reinjection).

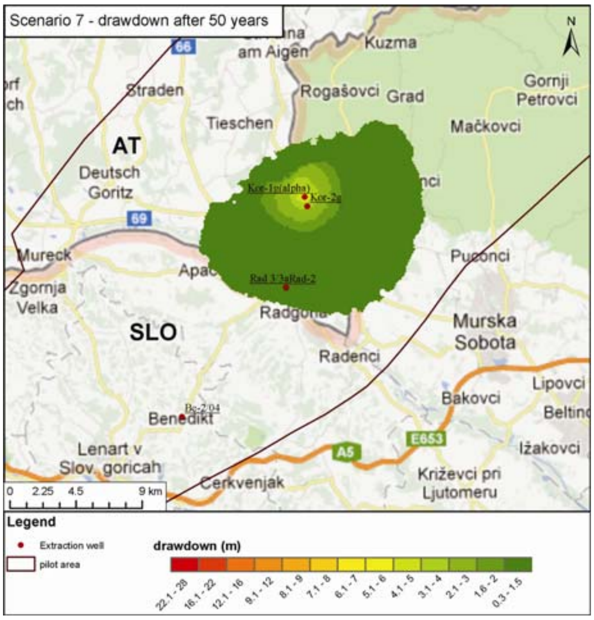

Fig. 8. Scenario 7 – computed drawdown after 50 years of production in Korovci (without reinjection).

4.3 Geothermal doublet scenarios

The aim of the reinjection scenarios was to determine the potential cooling effects caused by reinjection of colder water into the well Kor-2g. The temperature of reinjected water was set to 35 °C. The production (Kor-1gα) and reinjection (Kor-2g) points are 700 m apart.

Table 6. Temperature decrease in production borehole Kor-1gα for all scenarios.

Scenario	Temperature decrease [°C]	Simulation time [years]
1	0.3	1000
2	0.3	1000
3	0.6	1000
4	0.6	100
5	3.9	100

Scenarios 1 to 3 show that if the hydraulic conductivities values are in the range of 10^{-6} or lower, the thermal breakthrough does not take place even in 1000 years of simulation (Fig. 9, Table 6).

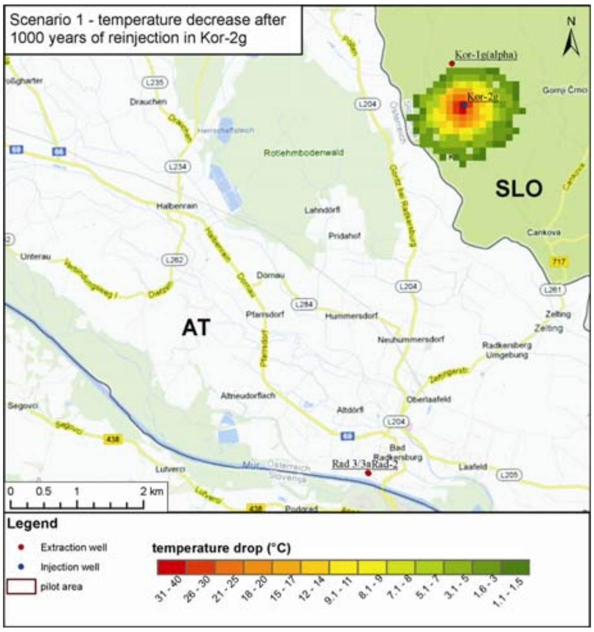

Fig. 9. Scenario 1 – temperature decrease and extend of the thermal front after 1000 years of reinjection in Korovci.

However, hydraulic conductivity values in the range of 10^{-5} combined with higher reinjection rates (40 l/s) the thermal breakthrough takes place in less than 50 years (Fig. 10, Table 6).

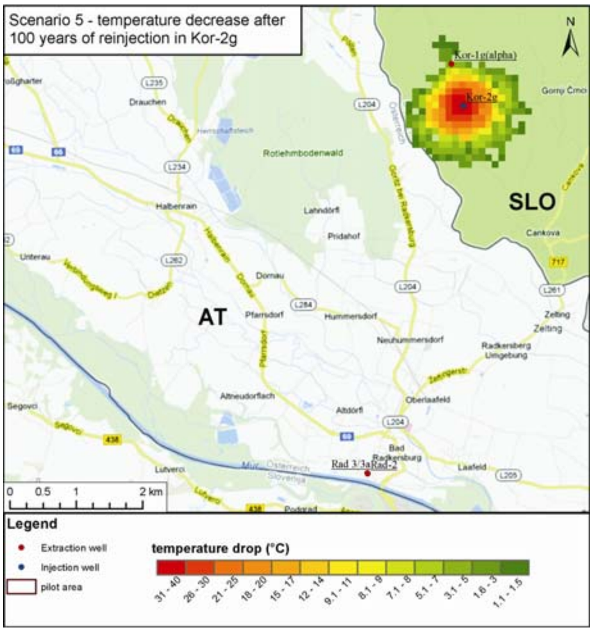

Fig. 10. Scenario 5 – temperature decrease and extend of the thermal front after 100 years of reinjection in Korovci.

5. CONCLUSIONS

The modelling of the Bad Radkersburg – Hodoš pilot area was focused on deep geothermal aquifers in the Pre-Neogene basement. The constructed models enabled simulation of hydrogeological and geothermal conditions in the pilot area. Good agreement between computed and measured temperatures confirmed the assumption that conductive heat transfer is characteristic in most of the pilot area. However, positive geothermal anomaly in Benedikt had to be modelled separately and indicated that could be related to hydrothermal system with convection flow.

Another issue addressed in the study was the assessment of the impact of planned utilisation of geothermal energy in Korovci. For this purpose scenarios taking into account different utilisation strategies and range of model parameter values were performed. Simulations showed no impact of abstraction in Korovci on Benedikt. The impact on Bad Radkersburg was simulated with and without reinjection well. When no reinjection was applied the simulated hydraulic depression reaches Bad Radkersburg only if higher than expected hydraulic conductivity or abstraction rate are applied in the model. The predicted drawdown in the Korovci production well after 50 years of 20 l/s abstraction is between 11 and 15 m. Five reinjection scenarios imply that thermal breakthrough is noticeable after 50 years only if very high hydraulic conductivity is used in the model. Higher (double than planned) abstraction and injection rates in the model cause the breakthrough after 30 years already.

It has to be emphasised that presented study is based on available data and current knowledge, which all have certain limitations. To ensure higher reliability of the numerical model detailed geological structure and its hydrogeological characteristics have to be known much better that currently. The uncertainty of the model can be diminished with additional measurements which would enable better quantification of relevant geological, hydraulic, geochemical and geothermal processes. Transboundary exchange of all relevant hydrogeological and abstraction data is a prerequisite to perform a reliable estimation of this transboundary geothermal aquifer.

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