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SUMMARY REPORT OF THE SCENARIO MODELLING

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5.3.2. Summary report of scenario modelling

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1 INTRODUCTION

The aim of the Transenergy project is to support the harmonized thermal water and geothermal energy utilization in the western part of the Pannonian Basin and its adjacent basins (e.g. Vienna Basin), which are situated in the transboundary zone of Austria, Hungary, Slovak Republic and Slovenia.

During the day to day day management of thermal-water systems, a tool is needed to provide the decision makers with information about the future responses of the system to the effects of various interactions, as well as about available hydrogeothermal resources. This tool can be based on the results of different models. These models assure a sustainable and harmonized utilization and management of the geothermal regime

To provide an overview on the large-scale hydrogeological processes of geothermal systems and the connection among the main groundwater bodies, a supra-regional hydrogeological model was developed (Tóth et al. 2012). It was based on a harmonized 3D geological model (Maros et al. 2012). Applying the results of the geological and hydrogeological model a supra-reginal geothermal model was constructed (Goetzl et al 2013). As a synthesis, based on the results of different types of models the geothermal reservoirs of the entire project area were outlined and characterized (Rotár-Szalkai et al. 2012).

Focusing on local transboundary problems and their detailed geothermal characteristics five pilot area models were constructed. Pilot areas are representative „hot spot" regions along the borders (thermal karst of Komarno-Sturovo area (HU-SK), Pannonian Central Depression of the Danube basin (A-SK-HU), Lutzmannsburg – Zsira area (A-HU), Vienna basin (SK-A) and Bad Radkersburg- Hodoš area (A-SLO-HU). These regions were selected because of their extrem sensitivity for any further intervention by different management policies in the neighboring countries. The pilot models took into consideration the experiences and results of the supra-regional models.

As a fist step of the pilot modelling based on a detailed 3D geological model a coupled groundwater flow and heat transport model were developed. This coupled model emphasizes the importance both of heat conduction and advection in geothermal systems.

From a methodological point of view groundwater modelling can be subdivided into flow and transport modelling. Flow modelling deals with the movement of water, whereas transport modelling is concerned with the distribution and migration of solutes or heat in the subsurface. In the literature the term coupling refers to the situation in which flow and transport are mutually connected. While there is always a link from flow to transport, the link from transport to flow is given if fluid properties, density and viscosity, are affected by the transport variable. In practice salinity or temperature are such variables that affect fluid properties. Therefore coupled models provide more reliable information about geothermal systems.

Steady-state models show the quantitative status of the major thermal water budget. Thermal modeling contents heat base calculation and a quantitative status assessment of the pilot regions. The summary of the steady state modeling (Rotar-Szalkai et al. 2013a) report contains the basic technical information about the modeling methods and the most important results. The results shows the present state of the geothermal reservoirs (geological layout, groundwater heads, velocities and ma-jor path lines, thermal and cold water budgets, exchange at state borders, etc.). It helps in better understanding of the geological, hydrogeological, hydrogeochemical, and thermal characteristic and evolution of the thermal waters of the pilot regions.

Next step of pilot modelling simulations for different heat and thermal water extraction scenarios and different utilization shemes were examined.

This report contains the results of scenario modelling of the pilot areas. It provides information about the possible limitations in thermal water utility and the need of protection, and describes the geothermal exploitation capacity of the region. The results mirror the rate of renewing of geothermics (in terms of water quantity, heat, hydraulic pressures, etc.) and the time period required for it. The report provides the best practice of sustainable heat and thermal water extraction, based on dynamic simulations.

The results of scenario modelling supply the basis of the pilot area thematics of the interactive project web-portal. Final results and considerations support the transboundary management proposals.

2 STRATEGY OF SCENARIO MODELLING

In scenario modelling common approach was applied for each pilot area. Principles of scenario modelling were harmonized, and this same outlook results similar model scenarios, which were applied for the particularity of the pilot areas. During development the same modelling methods and softwares were applied.

Furthermore answering common thermal water and thermal energy management questions, special model solutions were applied to investigate unique transboundary problems of the pilot areas.

2.1 The common principles in harmonization of model scenarios

The aim of the present modelling work was to understand and characterize the natural hydro-geothermal system of the study areas, to investigate the future effects of existing geothermal water extractions, and to make predictions on different extraction scenarios.

To foresee effects of new geothermal installations two different geothermal utilization shemes were applied. Because sustainable use of thermal groundwaters is promoted in all partner countries, primerly scenario tested for additional heat harvesting by means of geothermal doublets. But due to technical limits of water reinjection in porous environment and differenncies between the legislation of the partner countries, traditional direct use of geothermal energy by means of single exploitation wells was investigated too.

Common simultaneous geothermal energy use of the same transboundary reservoir by the neighbouring countries — directly at the state border — by means of two geothermal doublets were examined where it were relevant for the pilot area. The aim of these scenario analyses was to test the proposed well configurations, hydrodinamical interactions and estimate operating life of the system by prediction of thermal breakthrough.

The modelling methods were the same in each pilot area. The steady-state model provided the basis of the scenario model. The model geometry, parameters and boundary conditions of the steady state model were applied.

Furthermore harmonized assessment of possible geothermal resources was carried out each of the pilot area, which allows the comparison between the different geothermal reservoirs. Estimation of geothermal resources in the model areas were undertaken to identify potential geothermal resources included the calculation of the following:

- *Heat In Place* (HIP): The Heat in Place represents the theoretically available heat content by cooling down the entire rock volume of a reservoir to a defined reference temperature. In reality it is not technically feasible to extract the entire HIP from a rock volume.

- *Inferred Geothermal Resource* (IR): An Inferred Geothermal Resource is the theoretical extractable amount of heat assuming a multiple well scheme. It is that part of a Geothermal Resource for which recoverable thermal energy can be estimated only with a low level of confidence.
- *Measured Geothermal Resource* (MR): A Measured Geothermal Resource is the part of a geothermal resource, which has been demonstrated to exist through direct measurements that indicate at least the reservoir temperature, reservoir volume and well deliverability, so that the recoverable thermal energy can be estimated with a high level of confidence.

2.2 Applied software

The three-dimensional (3D) models were developed using FEFLOW 6.1 (Diersch, 2006). **FEFLOW** (Finite Element subsurface FLOW system) is a computer program for simulating groundwater flow, mass transfer and heat transfer in porous media. The program uses finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions, as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems. FEFLOW is a finite-element package for simulating 3D and 2D fluid density-coupled flow, contaminant mass (salinity) and heat transport in the subsurface. It can handle complex geometric and parametric situations.

The package is fully graphics-based and interactive. Pre-, main- and post-processing are integrated. There is a data interface to GIS and a programming interface. The implemented numerical features allow the solution of large problems. Adaptive techniques are incorporated.

2.3 Specialities of the pilot models

Although we applied the same approach in the models, due to specific features of each pilot area special model solutions were applied to investigate unique transboundary problems, which are not relevant for all pilot regions. The specialities of the pilot areas derived from the different geological-hydrogeological conditions. Thermal karst systems, crystalline basement geothermal reservoirs and porous environment both can be found in the different regions. Due to distinct thermal water utilizations other sort of transboundary problems and thermal water management questins occur in the areas. These differences couse several different modelling technics in detailed.
Distinctly from other pilot areas there are no recent geothermal utilization in the Vienna Basin. Therefore scenario model focus on analyses of the hydraulic influence of fault systems and the geometrical shape of the reservoir on the coupled hydraulic and thermal conditions of different doublet-use scenarios, represented by different locations and operational settings.

Due to intense hydrocarbon exploitation in the Vienna Basin the possibility to use the same reservoirs by thermal water users and hydrocarbon industry was studied.

Thermal water utilization is possible only for balneological purpose in the Lutzmannsburg-Zsira transboundary region, hence more scenarios deal with the possible hydraulic connections and interactions resulting due to increase extractions.

3 RESULTS OF THE COUPLED GROUNDWATER FLOW AND HEAT TRANSPORT MODELS

3.1 Lutzmannsburg Zsira model area

The Zsira-Lutzmannsburg pilot area of the TRANSENERGY project is situated at the border between Hungary and Austria. Several thermal spas are operated in the region within a relatively short distance from each other. The effect of thermal water withdrawals on hydraulic heads has been observed in both countries. The effects of groundwater extraction, the relation between the three identified reservoirs (Upper Pannonian, Miocene, and basement reservoirs) and the recharge and thermal conditions of these reservoirs required further clarification.

3.1.1 Model objectives

The aim of the present modelling work was to understand and characterise the natural hydro-geothermal system of the study area, to investigate the effects of existing geothermal water extractions, and to make predictions on different extraction scenarios. To achieve these goals, the modelling study included the following stages:

- Natural state modelling to understand the functioning of the natural geothermal system and to calibrate numerical model (Kovács and Rotár-Szalkai, 2013a);
- Simulation of current groundwater extractions to understand reservoir response and hydraulic interference between extractions bores;
- Scenario modelling to investigate different extraction scenarios and to provide predictions of future reservoir conditions.

The conceptual model, the numerical model setup, and natural state model results are presented in Kovács and Rotár-Szalkai (2013a).

3.1.2 Modelling methodology

The simulation of current conditions and predictive scenarios (Kovács and Rotár-Szalkai 2013b) was based on the calibrated natural state model. Scenario modelling comprised the simulation of hypothetic extraction rates at varios locations to simulate future groundwater and geothermal conditions. The aim of scenario modelling was:

- To separate the influence of different existing groundwater extractions;
- To provide prediction of possible groundwater drawdown rates.

The calibration of model parameters was refined based on extraction data and groundwater monitoring data. In the production model, known groundwater extractions were assigned to the relevant model layers as well boundary conditions. A steady sate assumption was applied in all model scenarios except for the bore doublet scenario simulated as part of the scenario modelling.

To investigate the influence of different extraction groups on regional drawdown, extraction bores in different reservoirs and different geographic locations were “switched off” (***Scenarios 1-6)***.

To investigate the possible effects of increasing groundwater utilisation, a twofold increase of extraction rates at each extraction bore was assigned to the model (***Scenario 7)***.

Simulation of a bore doublet was included in scenario modelling to investigate the applicability of extraction-reinjection systems in the study area (***Scenario 8)***

The scenario modelling involved the following model scenarios:

- No groundwater extractions at Bük (***Scenario 1***);
- No groundwater extractions at Lutzmannsburg (***Scenario 2***);
- No groundwater extractions at Bük or Lutzmannsburg (***Scenario 3***);
- No groundwater extractions in the upper-Pannonian aquifer (***Scenario 4***);
- No groundwater extractions in the Hungarian part of the pilot area (***Scenario 5***);
- No groundwater extractions in the Austrian part of the study area (***Scenario 6***);
- All Groundwater extractions doubled compared to existing discharge rates (***Scenario 7)***;
- Bore doublet (***Scenario 8***).

The geothermal model of the study area was based on the calibrated hydraulic model. Heat transport component was coupled with the hydraulic model to simulate convective and conductive heat transfer.

3.1.3 Results of the Lutzmannsburg-Zsira scenario models

3.1.3.1 Natural state

Results of the natural state modelling are described in the pilot area report (Kovacs et al 2013). The coupled groundwater flow and heat transport model provided three-dimensional information on the following:

- Hydraulic head distribution
- Groundwater fluxes
- Temperature distribution

The simulated groundwater table contours and potentiometric plots are shown in Figure 1 to Figure 5.

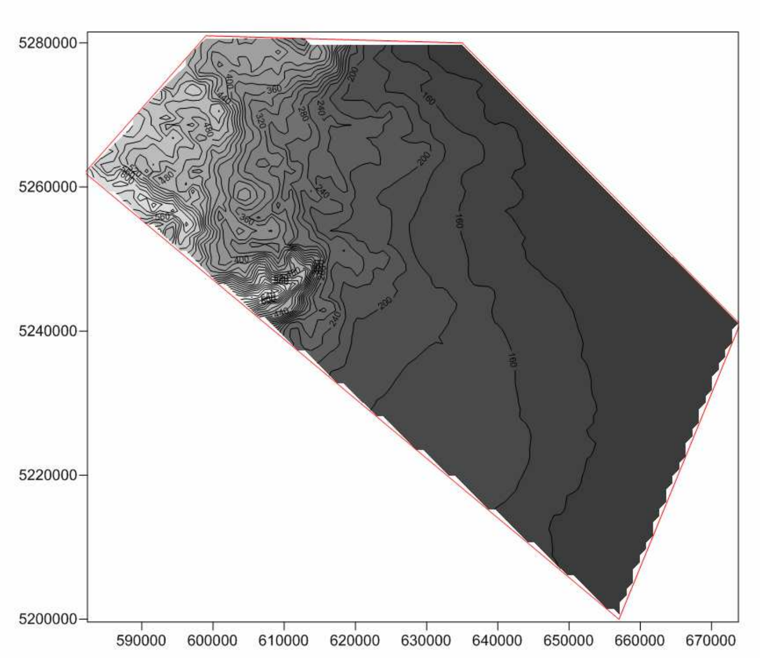


Figure 1. Simulated water table elevation.

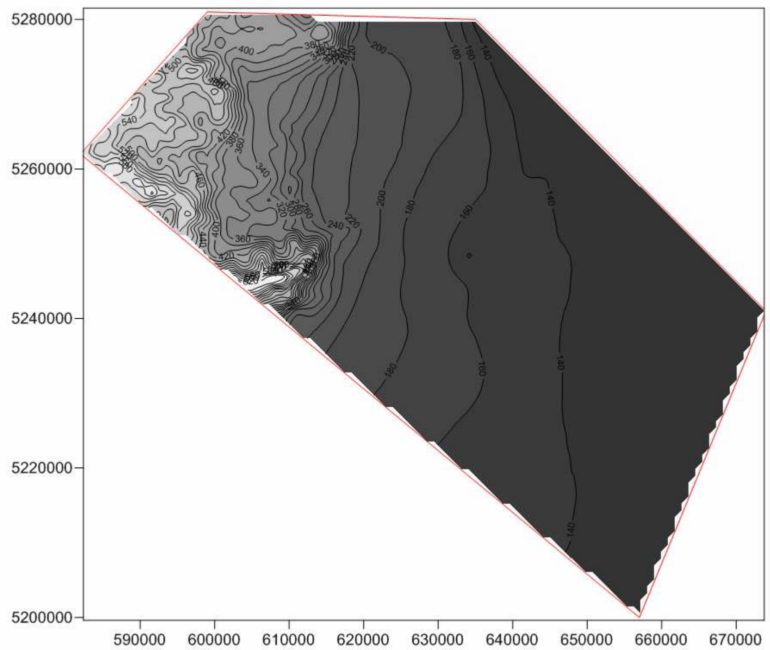


Figure 2. Simulated hydraulic head distribution in the Sarmathian layers (slice 8).

The simulated groundwater head distribution and calculated flux distribution indicate that the dominant flow direction within the model domain is from west towards the north-east, east and south-east. The flow field follows a semi-radial pattern. The main inflow area is along the western model boundary, where the regional flow system feeds the modelled domain. Outflow occurs along the south-eastern (Marcal Valley) and north-eastern model boundaries. The Marcal Valley represents the regional discharge area, while the north-eastern side of the model is a cross-flow area. Surface infiltration represents approximately 97% of groundwater recharge, while the rest arrives as groundwater inflow from the west. The water budget of the area is indicated in Table 1.

Table 1. Simulated water budget.

Boundary	In (m3/d)	Out (m3/d)
Prescribed head	4,180	181,055
Infiltration	176,875	N/A

The simulated temperature distribution at different depths is shown in Figure 3 and Figure 4. A vertical NW-SE profile of simulated temperatures is shown in Figure 5.

The coupling of the hydraulic and heat transport models made it possible to calculate a 3D temperature distribution over the study area. The simulated temperature distribution indicates little vertical variations of temperature within the upper-Pannonian sediments, and gradually increasing temperatures within older sediments and the fractured basement.

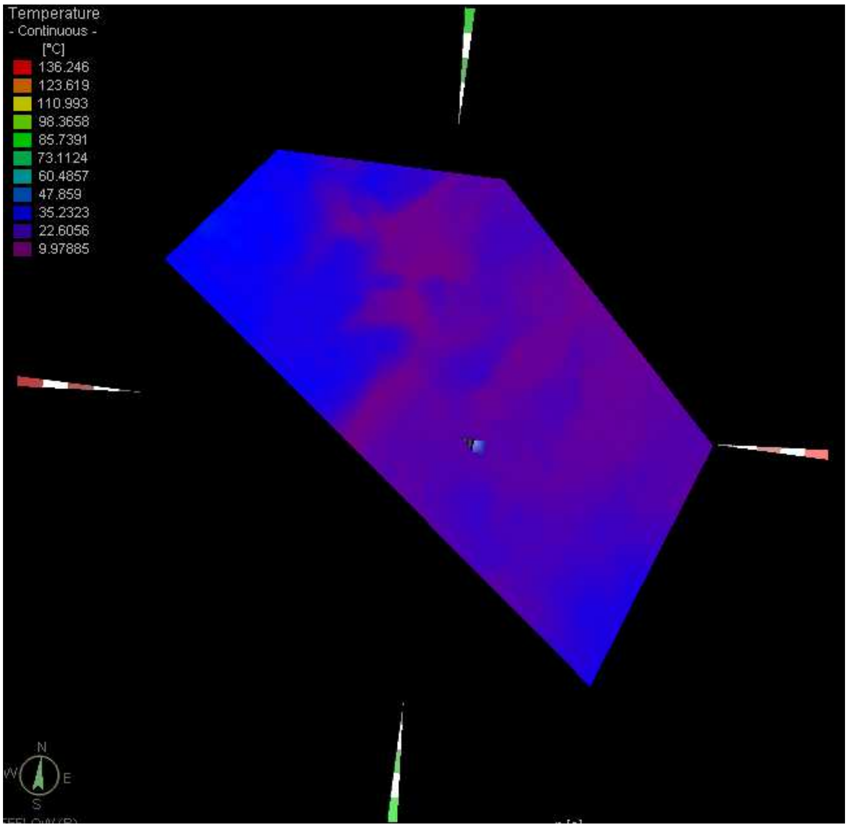


Figure 3. Simulated temperature distribution at -1000 mASL.

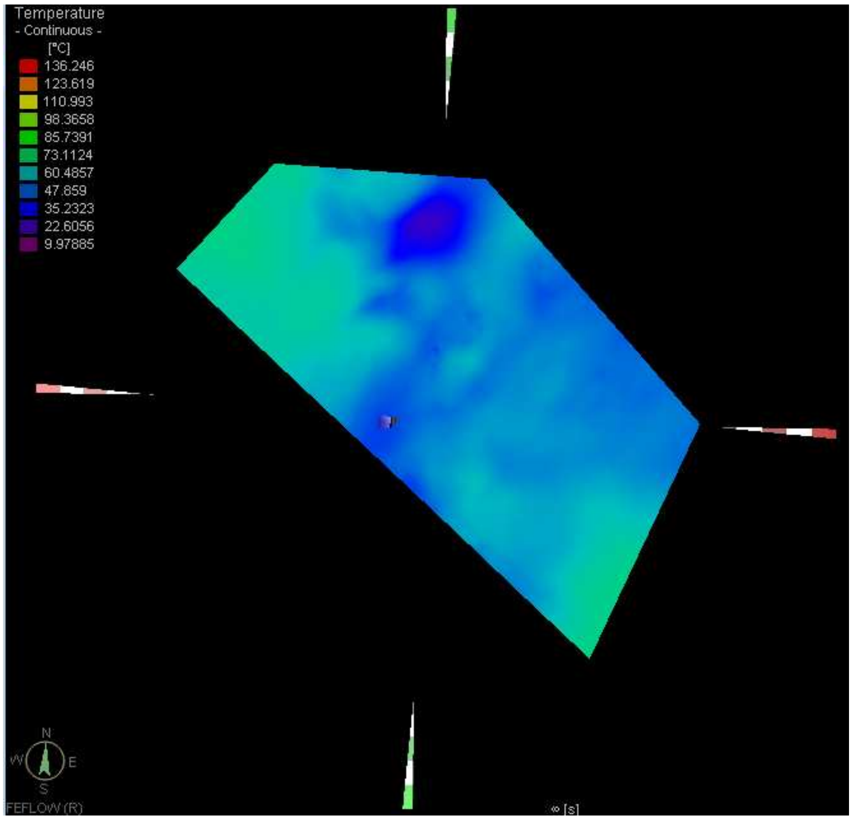


Figure 4. Simulated temperature distribution at -2500 mASL.

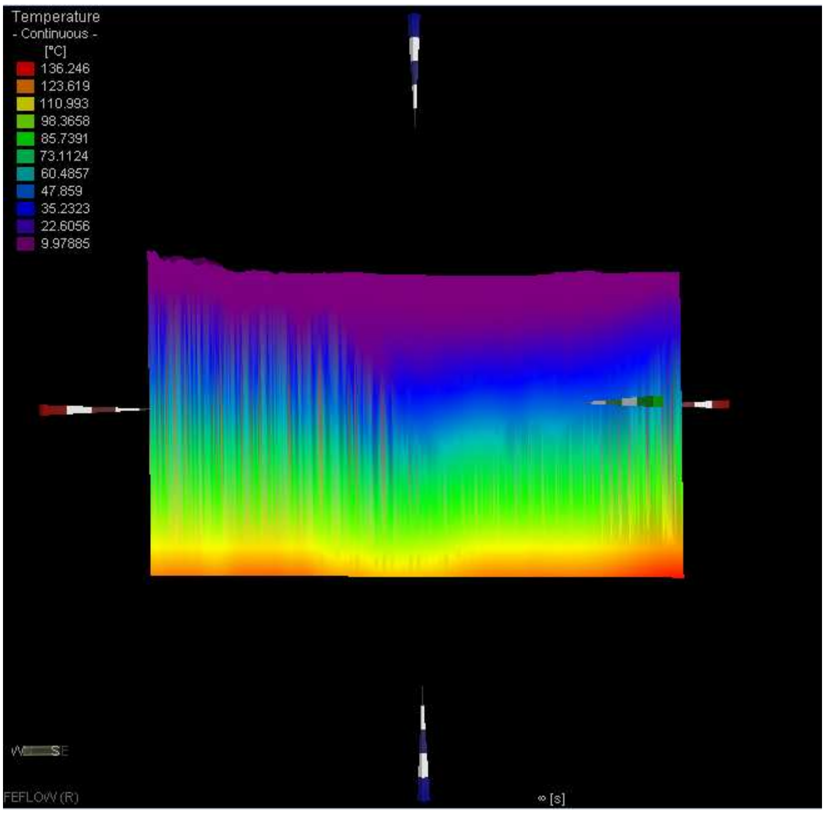


Figure 5. Simulated NW-SE temperature profile.

3.1.3.2 Current production

The simulation of the production scenario included all known groundwater extractions within the model area. The majority (53%) of groundwater extractions takes place within the upper-pannonian aquifer. 9% of total extractions occur from the Quaternay aquifer, while 3.5% is extracted from the Sarmathian reservoir. Devonian bores extract 1.5% of the total rates.

For visualisation purposes, the water table and the potentiometric surface within the Sarmathian reservoir were plotted. While the water table is representative of the head distribution in the upper part of the system, head distribution within the Sarmathian approximates the hydraulic conditions within the lower-Miocene - Devonian reservoir system. The simulated production scenario water table is indicated in Figure 6. Simulated potentiometric surface within the Sarmathian reservoir is indicated in Figure 7.

The difference between water table elevation and hydraulic head distributions at depth indicates the dominant flow regime obtained from model simulations. Figure 8 indicates the zones of dominantly downward flow areas (recharge zones) and dominantly upward flow areas (discharge areas). As expected, topographic highs represent the main recharge zones within the study area, while lowlands function as discharge areas including the Marcal and Répce valleys.

Drawdown distributions compared to natural state conditions were also plotted for the above hydrostratigraphic units. The simulated drawdown distributions are provided in Figure 9-Figure 10.

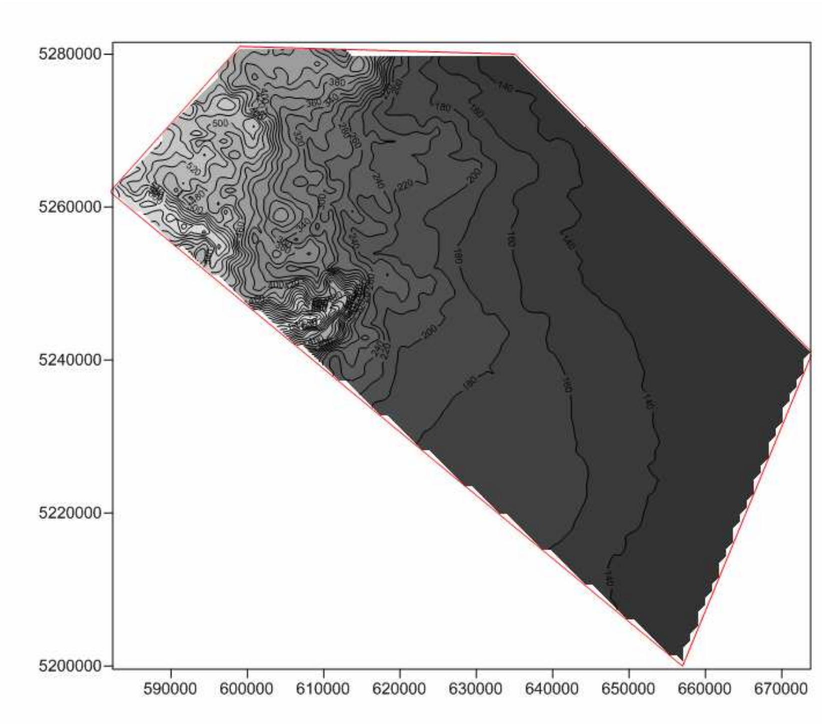


Figure 6. Simulated water table - Production state.

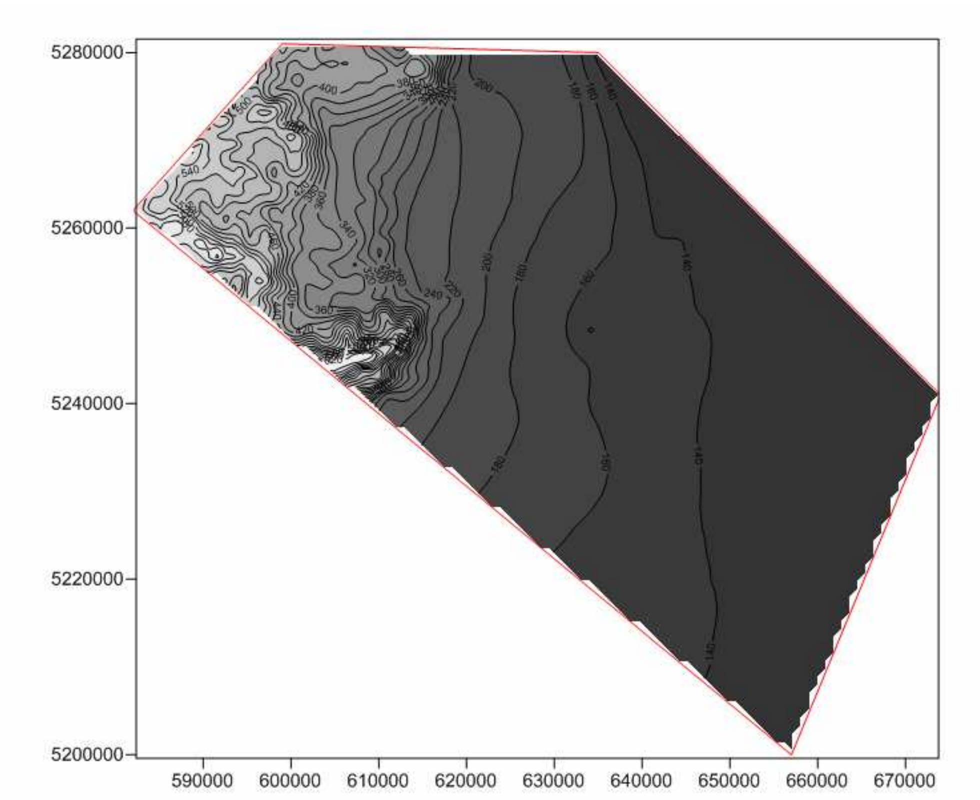


Figure 7. Simulated head distribution in the Sarmathian reservoir - Production state.

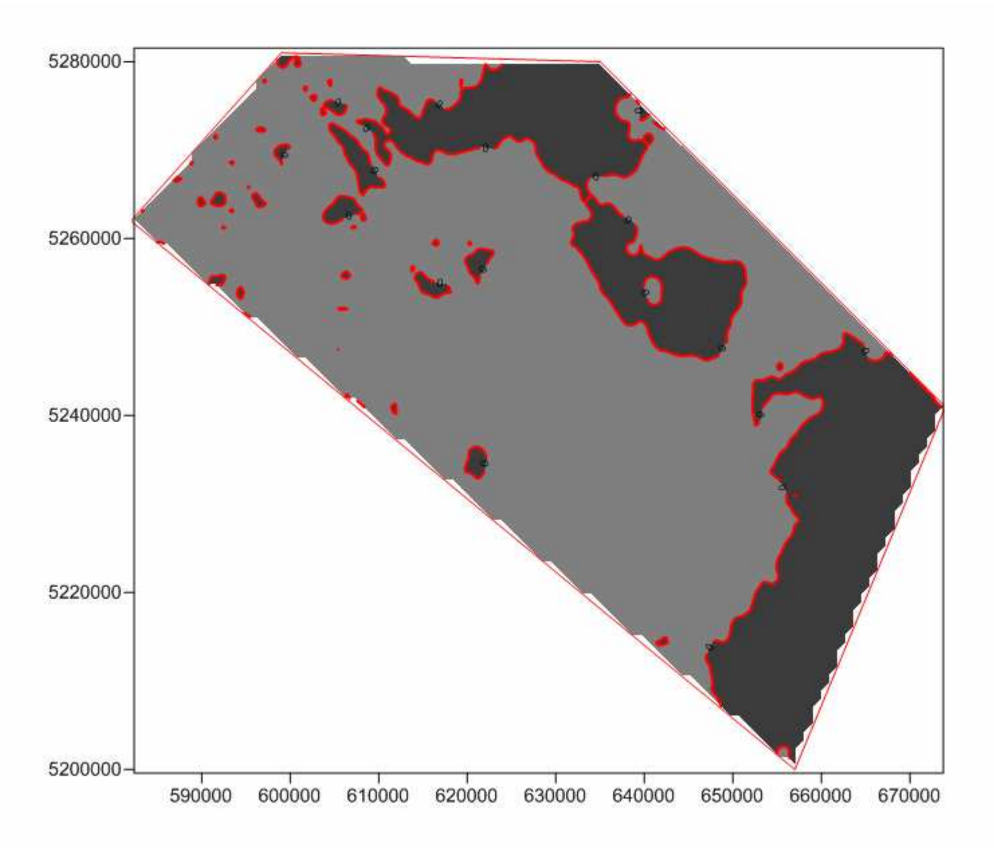


Figure 8. Simulated flow regimes. Gray areas indicate downward flow (recharge areas), while black areas represent upward flow (discharge areas).

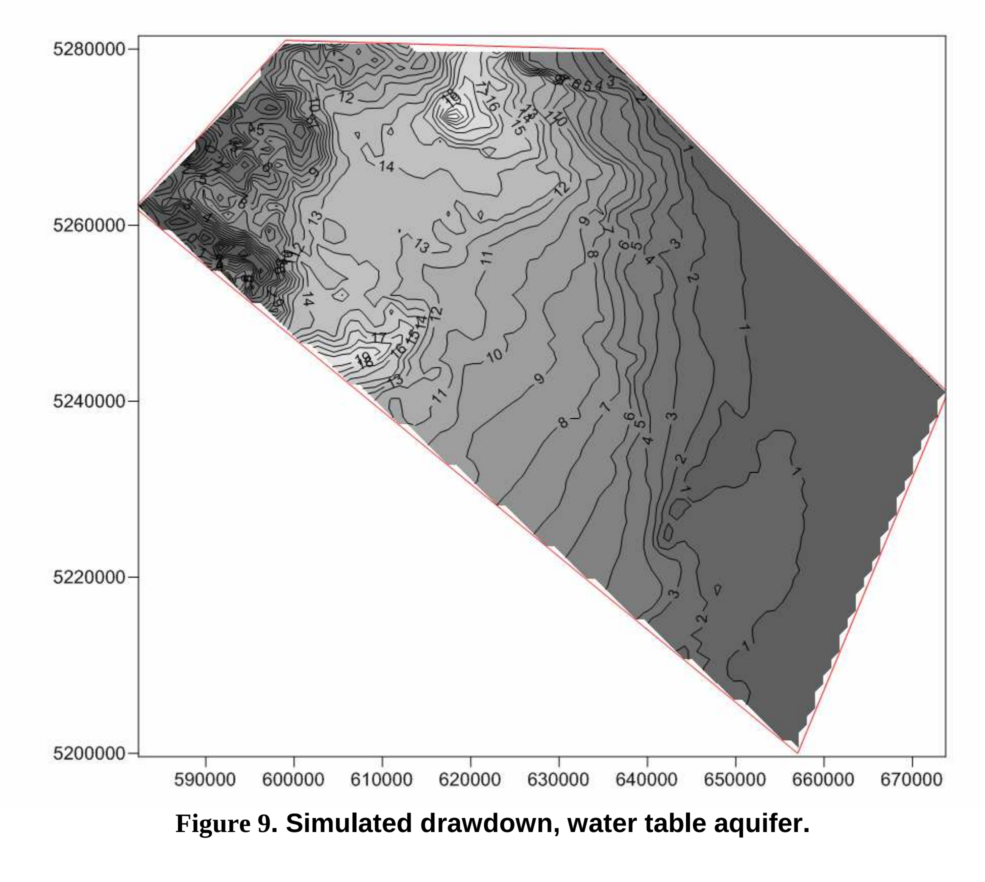


Figure 9. Simulated drawdown, water table aquifer.

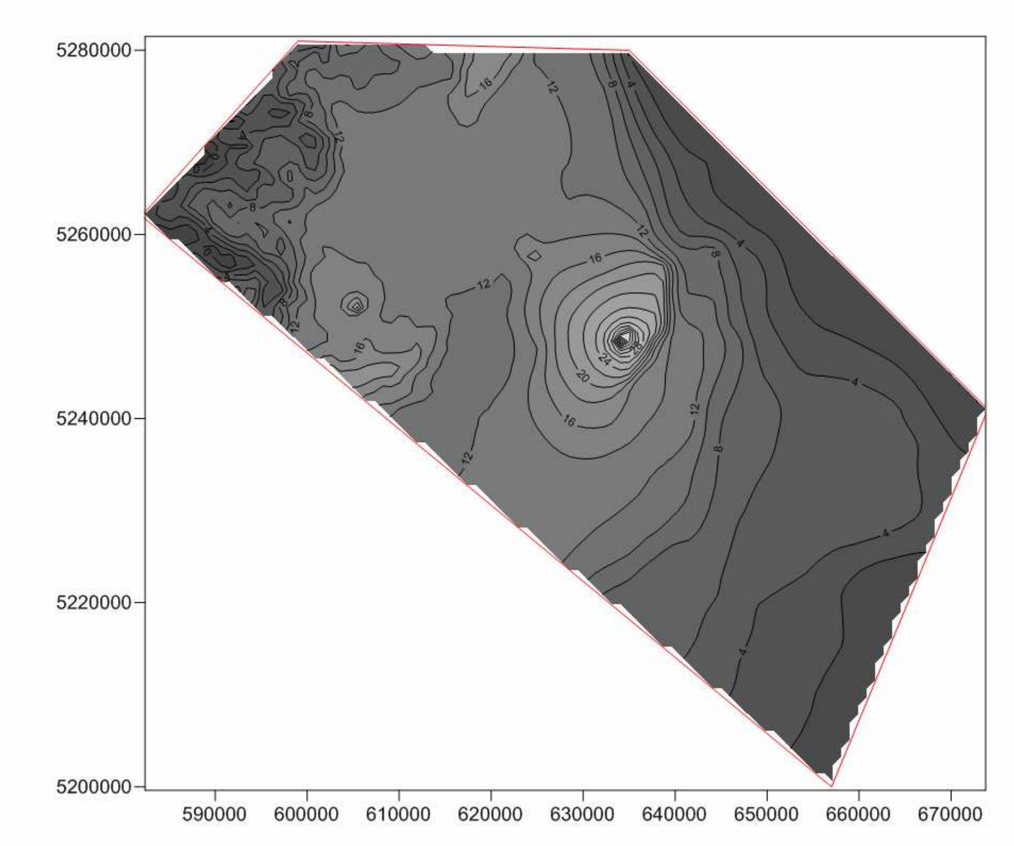


Figure 10. Simulated drawdown, Sarmathian reservoir.

Model simulations indicate that regional groundwater table drawdown varys between 1-15 metres in response to groundwater extraction. The largest drawdowns exists in the western side of the model domain resulting from the depression of resource bores located in Austria.

The depressurisation of pre-neogene aquifers generally varies between 2-12 metres. The largest pressure drop is simulated to exist around the Bük extraction bores. A significant depressurisation is observed around the Lockenaus extraction bore.

The simulated production state water budget is indicated in Figure 2.

Table 2. Simulated water budget.

Boundary	In (m3/d)	Out (m3/d)
Prescribed head	4,725	140,805
Infiltration	176,875	N/A
Extraction bores	N/A	40,795

3.1.3.2.1.1 The Zsira-Lutzmannsburg system (Scenarios 1-6)

The Zsira-Lutzmannsburg system comprises the following components:

- Two extraction bores at Bük: Bük K-4 and Bük K-10 extract groundwater from the Devonian Bük dolomite at a total rate of 1500 m^3/day. Extraction of thermal groundwater started in 1962 at a rate of 200 m^3/day and was gradually increased over the following years to the current extraction rate. The temperature of the outflowing water is 58 C.

- Two extraction bores at Lutzmannsburg: Thermal- 1 and Thermal -2 started operation in 1994 at an extraction rate of 430 m3/day. These bores are screened within the Karpatian sediments, and are operated alternately.
- An observation bore at Zsira: Zst-1 is screened within the Karpatian sediments, and is located in between the Zsira and the Lutzmannsburg extraction bores, thus providing information ion the combined effects of these extractions.

The stratigraphic setup of he local system is shown in a cross section in Figure 11. The figure indicates, that the Devonian dolomite block is partially overlain by Karpatian sediments in the west, and Badenian sediments in the East. This is the consequence of the pinching out of Karpatian sediments in the central area of the Dolomite body.

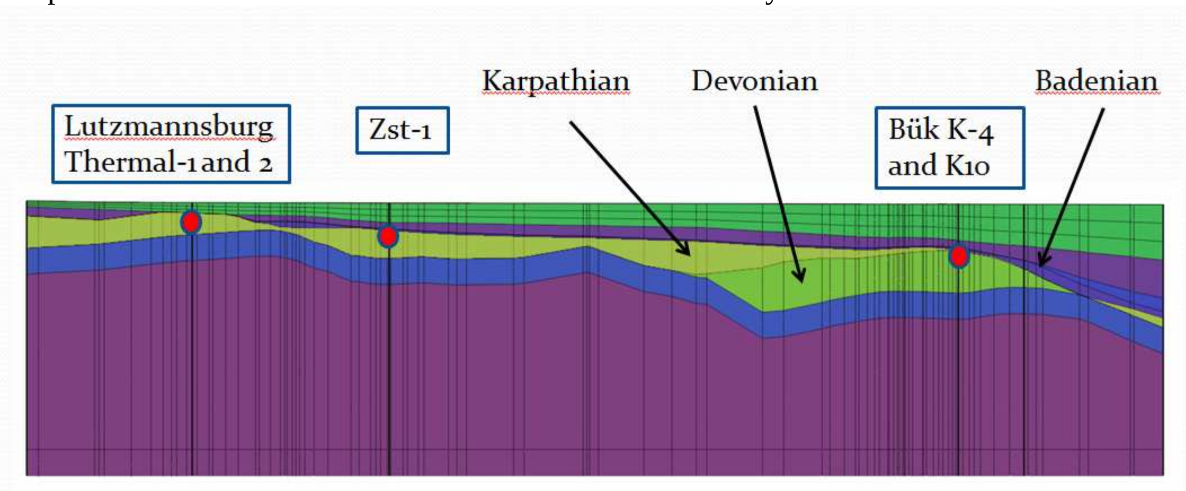


Figure 11. Local hydrostratigraphy of the Zsira-Lutzmannsburg system (NW-SE cross section).

Since the beginning of groundwater extraction at the above locations, the following changes in groundwater conditions were observed:

- A gradual increase in the concentration of main water components including Na, K, HCO3, Cl and SO4 was observed in Bük K-4 and K-10 (Figure 12);
- A gradual pressure drop up to 15 metres was observed in Zsira Zst-1.

It was suspected, that the pressure drop observed in Zst-1 was caused by the depressurisation of the Bük thermal bores. It was also assumed, that increasing salinity was the result of saline water leakage from underlying or overlying reservoirs. The exact source of saline groundwater has not been identified. The goal of the modelling study with respect to the Zsira-Lutzmannsburg system was to answer the following questions:

- What is the source of saline groundwater observed in the Bük observation bores?
- Which extractions cause the depressurisation observed in the Zsira Zst-1 monitoring bore?

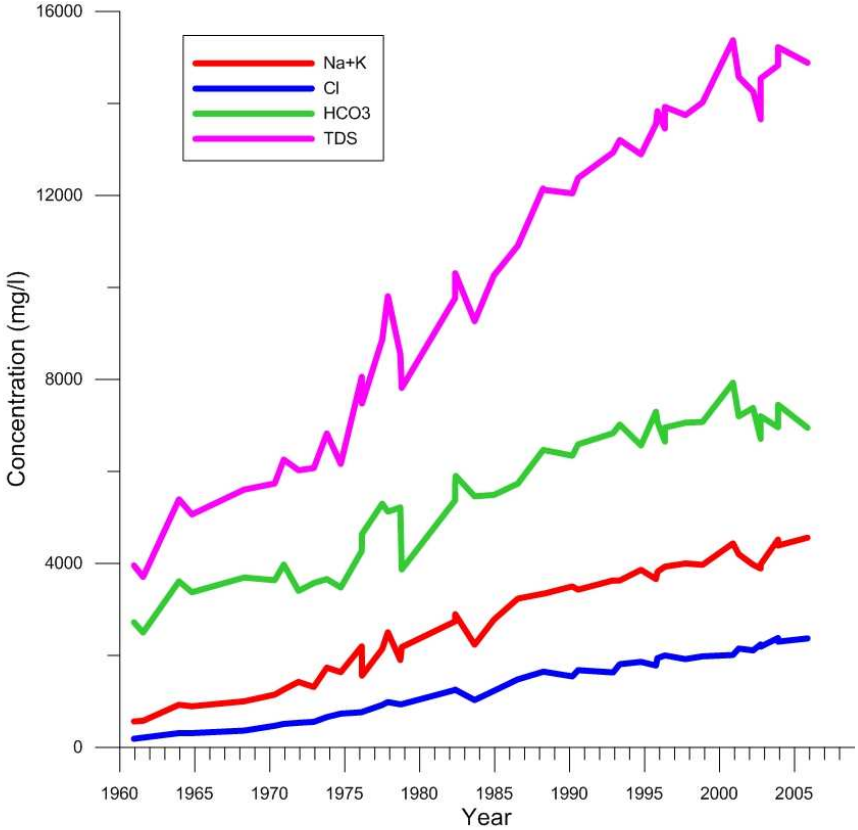


Figure 12. Concentration of main components in the Zsira extraction bores.

To answer the main questions concerning the Zsira-Lutzmannsburg local system, the production state model was utilised. In order to investigate the source of saline water, flow directions were analysed in the vicinity of the Bük extraction bores. Piezometric plots along a cross section including the Lutzmannsburg, Zsira and Bük bores are provided in Figure 13. The flow vectors in natural state and under current production conditions are indicated in Figure 14.

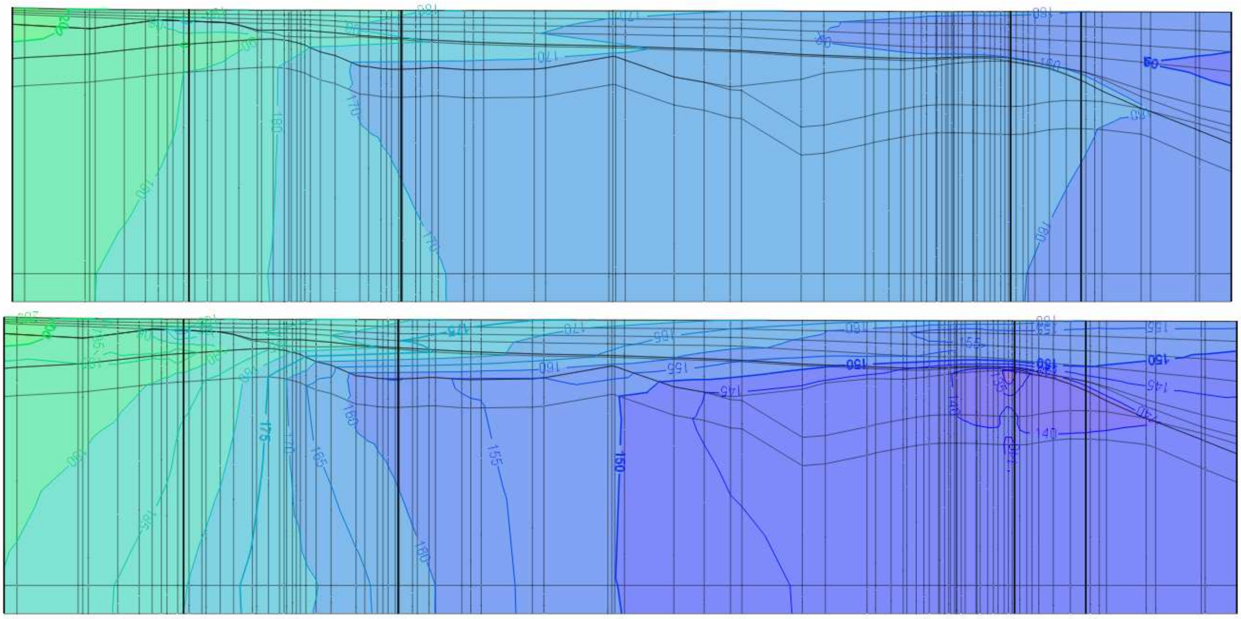


Figure 13. Piezometric cross-sections (NW-SE) across the Lutzmannsburg, Zsira and Bük bores (a. natural state, b. production state).

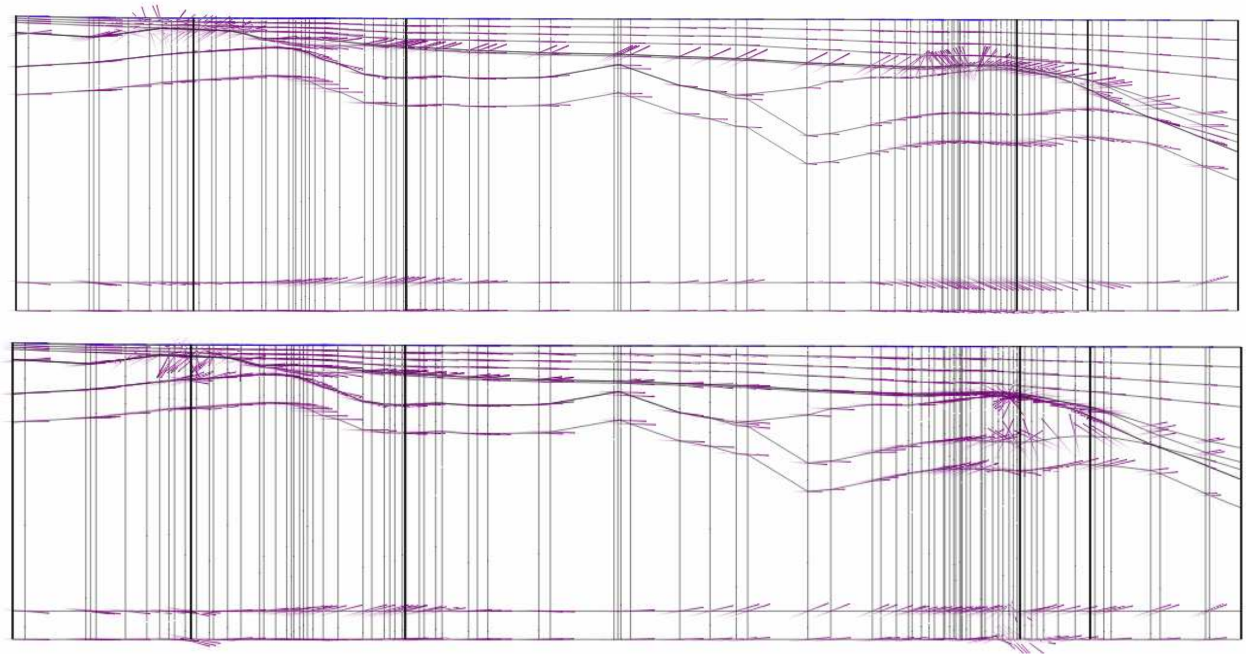


Figure 14. Flow vectors along NW-SE cross-sections across the Lutzmannsburg, Zsira and Bük bores (a. natural state, b. production state).

The piezometric plots indicate significant depressurisation both at the location of the Bük and the Lutzmannsburg bores. The flow vectors indicate the reversal of natural flow directions at these locations. While the natural recharge of the Bük dolomite is through overlying Karpatian sediments from the west, the depressurisation casuses the reversal of natural flow. As a consequence, groundwater leaks into the devonian reservoir from the overlying Badenian sediment located in the west and from the low-permeability basement rocks underlying the Bük dolomite. The production-induced leakage directions are indicated in Figure 15 below.

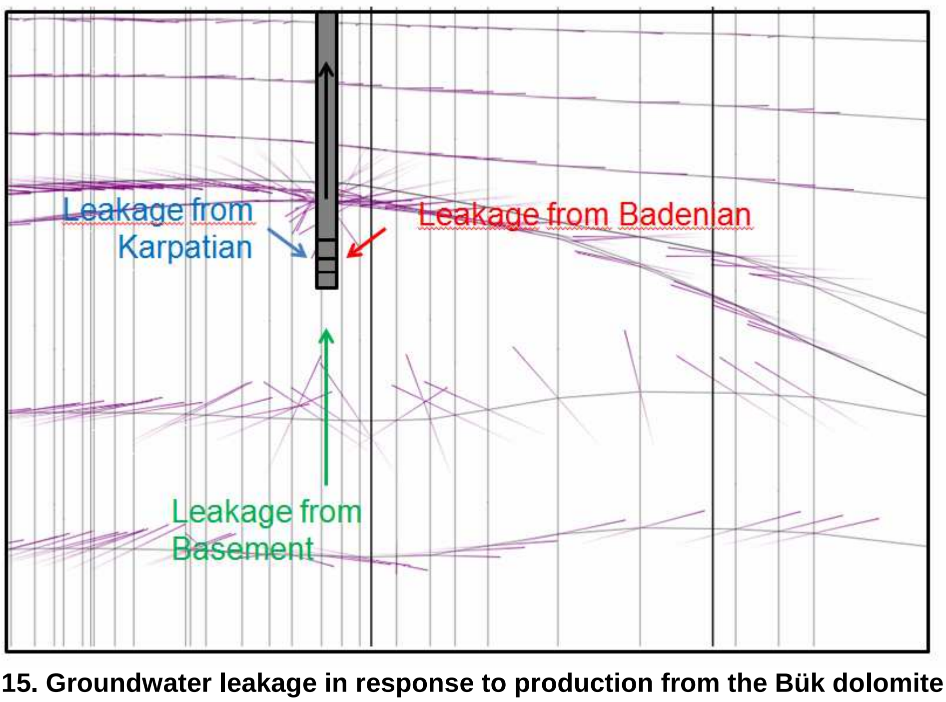


Figure 15. Groundwater leakage in response to production from the Bük dolomite block.

The analysis of water chemistry of the main reservoirs around the Bük dolomite block indicates that Badenian reservoirs contain high-salinity waters which might alter groundwater composition of the Bük dolomite through mixing processes.

The piper plot of main reservoir water types indicate the gradual change in water chemistry of the Bük dolomite between 1960 and 2005 (Figure 16). The plot clearly shows that the increasing salinity originates from mixing with Badenian reservoir waters.

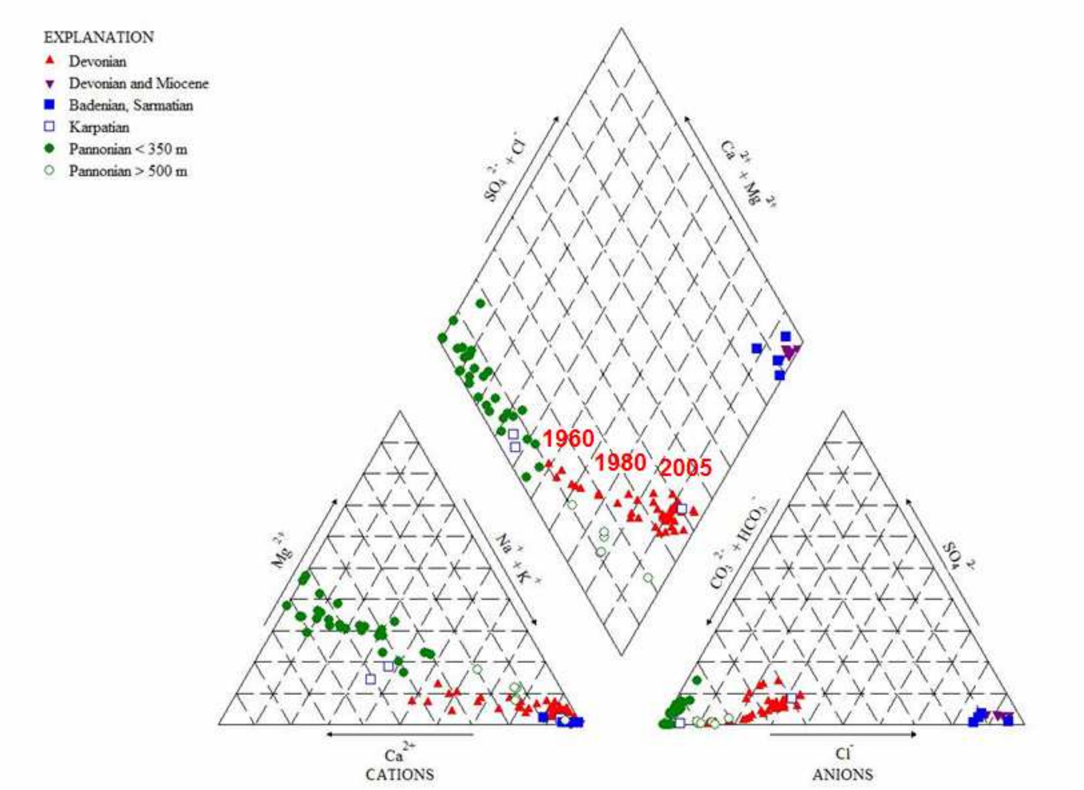


Figure 16. Piper plot of main reservoir waters in the pilot area.

In order to separate the hydraulic influence of different water extractions and to determine the sources of depressurisation observed in the Zsira Zst-1 bore, the production state model was applied. By »switching off« user groups, different scenarios could be investigated and the hydraulic impact of extraction bores could be evaluated. The simulated scenarios included the following:

1. No groundwater extractions at Bük;
2. No groundwater extractions at Lutzmannsburg;
3. No groundwater extractions at Bük or Lutzmannsburg;
4. No groundwater extractions in the upper-Pannonian aquifer;
5. No groundwater extractions in the Hungarian part of the pilot area;
6. No groundwater extractions in the Austrian part of the study area;

The simulated drawdown rates are indicated in Table 3. Simulated depressurisations. below.
The calculated steady state drawdown contours are indicated in Figure 17-Figure 22. These figures indicate the active extraction bores corresponding to each reservoir type. It was assumed, that the lower Pannonian aquitard behaves as a hydraulic barrier (The model results disprove this assumption). For this reason, the outcrop line of the lower Pannonian strata is also indicated in the drawdown plots.

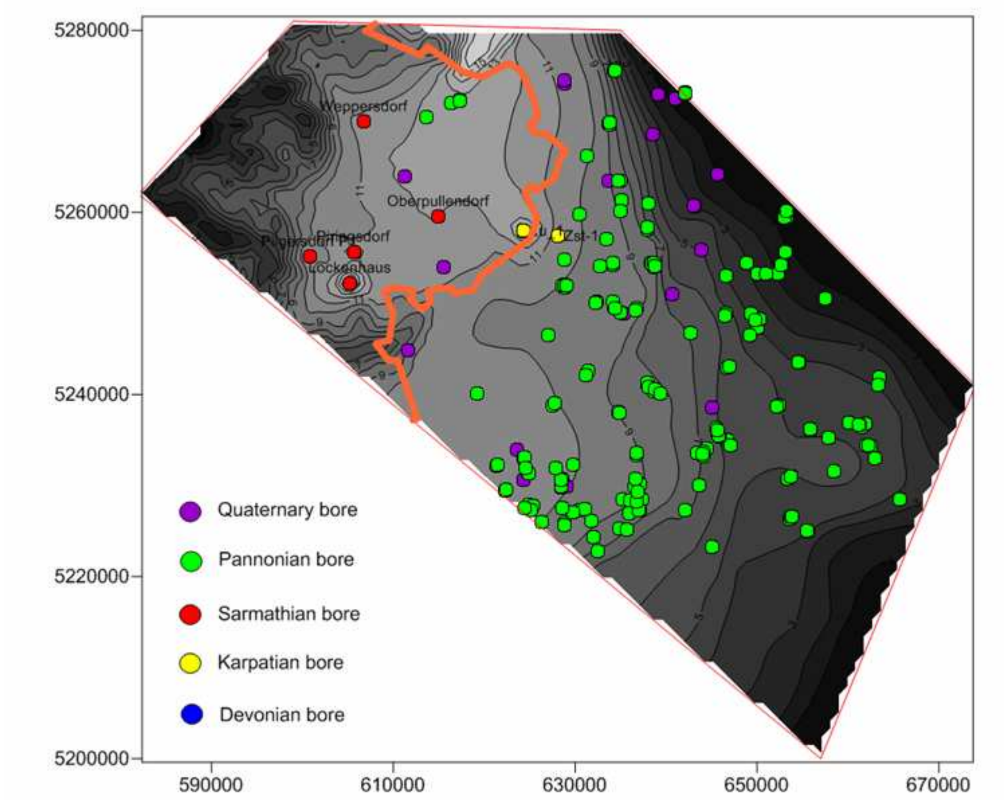


Figure 17. Simulated drawdown in the Sarmathian reservoir - Scenario 1.

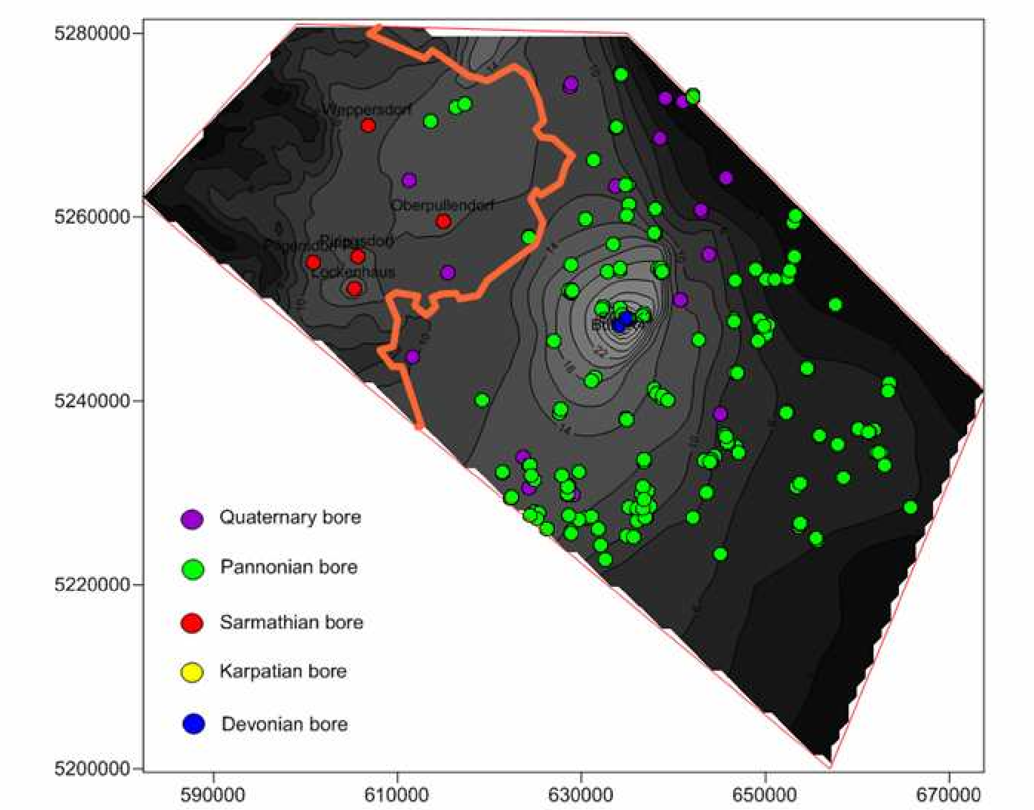


Figure 18. Simulated drawdown in the Sarmathian reservoir - Scenario 2.

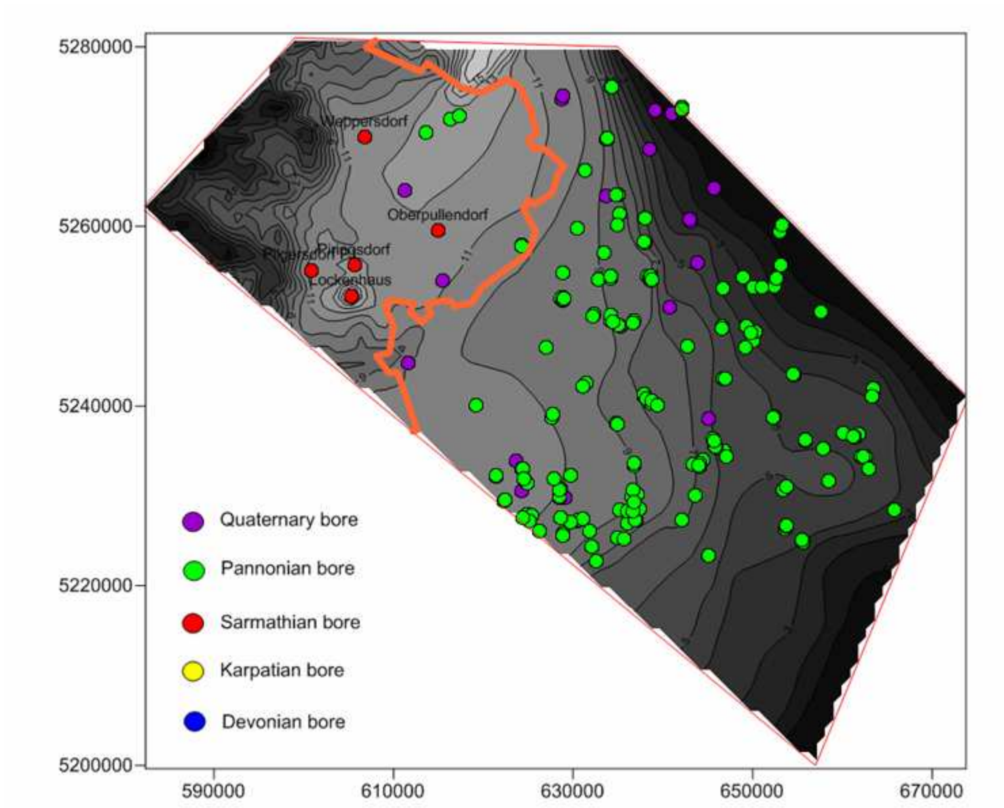


Figure 19. Simulated drawdown in the Sarmathian reservoir - Scenario 3.

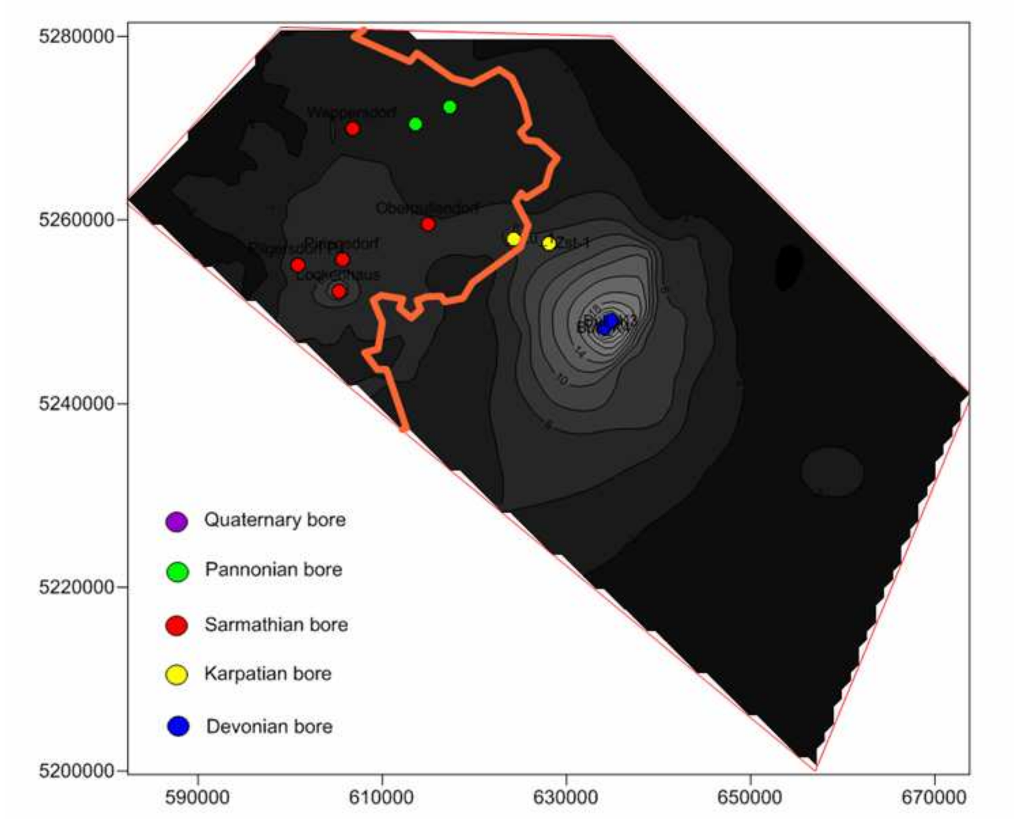


Figure 20. Simulated drawdown in the Sarmathian reservoir - Scenario 4.

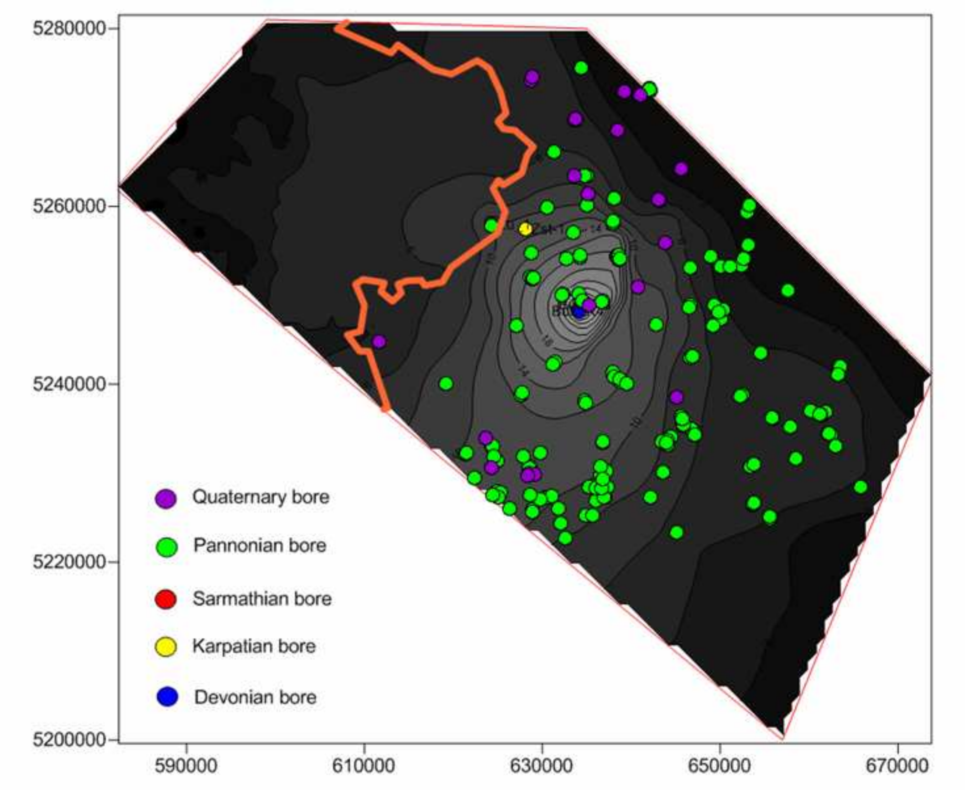


Figure 21. Simulated drawdown in the Sarmathian reservoir - Scenario 5.

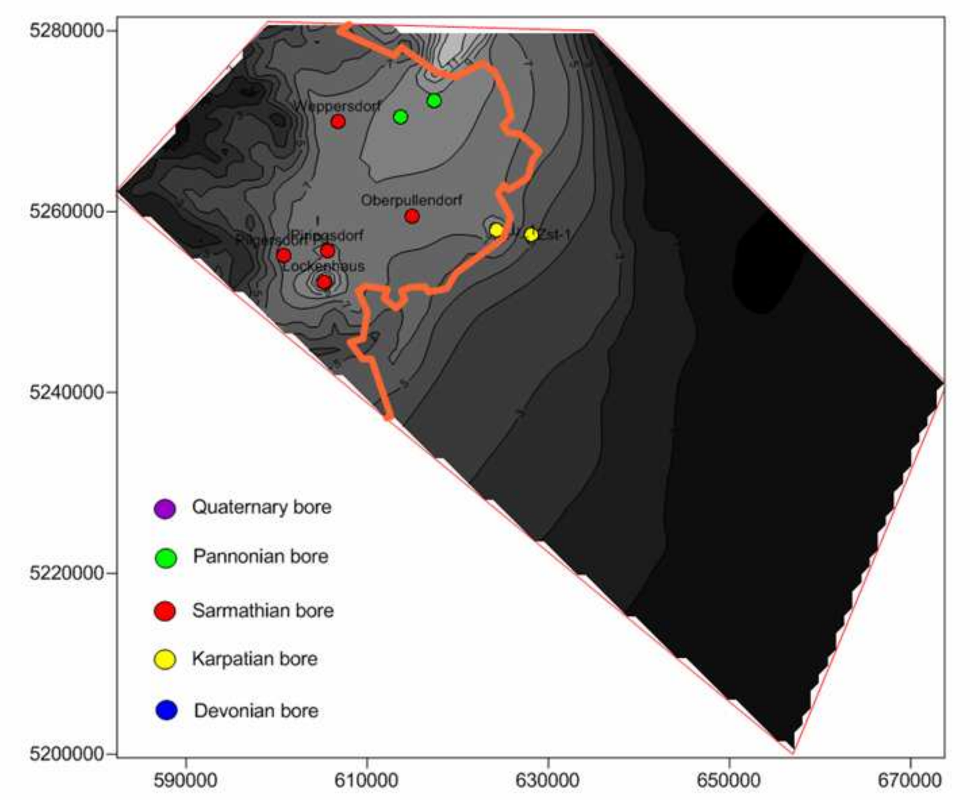


Figure 22. Simulated drawdown in the Sarmathian reservoir - Scenario 6.

The drawdown scenarios indicate the following:

- Both the Bük and Lutzmannsburg extractions contribute to the drawdown observed in Zst-1;

- The upper Pannonian extractions also contribute to the depressurisation observed in Zst-1. When the Bük and Lutzmannsburg bores are switched off, an approximate 10 m depressurisation remains in the borderzone area. This suggests, that the lower Pannonian aquitard is not an effective hydraulic barrier in the long term;
- The contribution of the Upper Pannonian and Quaternary extractions located in Hungary is comparable to that of the Bük and Lutzmannsburg extractions. Both extraction groups contribute to the depressurisation along the borderzone equally;
- The Sarmathian extraction bores located in Austria contribute to the depressurisation in the border zone (especially the groundwater extractions at Lockenhaus);
- Both Austrian and Hungarian extractions contribute to the depressurisation in Zst-1; the contribution of the Hungarian bores is slightly larger.

Table 3. Simulated depressurisations.

Bore	Simulated depressurisation (m)						
	current production	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Zsira-1	15,3	10,6	14,1	9,6	9,7	5,1	11,2
Lutzmsb Th-1	32,3	30,7	11,4	10,1	21,5	25,7	27,3
Bük K-4	59,9	9,4	59,0	9,1	51,5	3,1	56,8
Bük K-10	49,8	9,3	49,3	8,9	41,8	3,0	47,1

The above observations indicate that a harmonised cross-boundary groundwater management is essential for the successful optimisation of groundwater and thermal water utilisation.

3.1.3.3 Predictive scenarios

3.1.3.3.1 Increased production (Scenario 7)

In order to investigate the potential consequences of the future stress on the geothermal and groundwater systems of the pilot area, a twofold increase in production rates has been simulated. This included the increase of existing productions (no additional production bores were introduced) and the simulation of equilibrium potentials. The simulated groundwater table drawdown contours (compared to natural state) are indicated in Figure 23. The depressurisation of the Sarmathian reservoir (compared to natural state) is indicated in Figure 24.

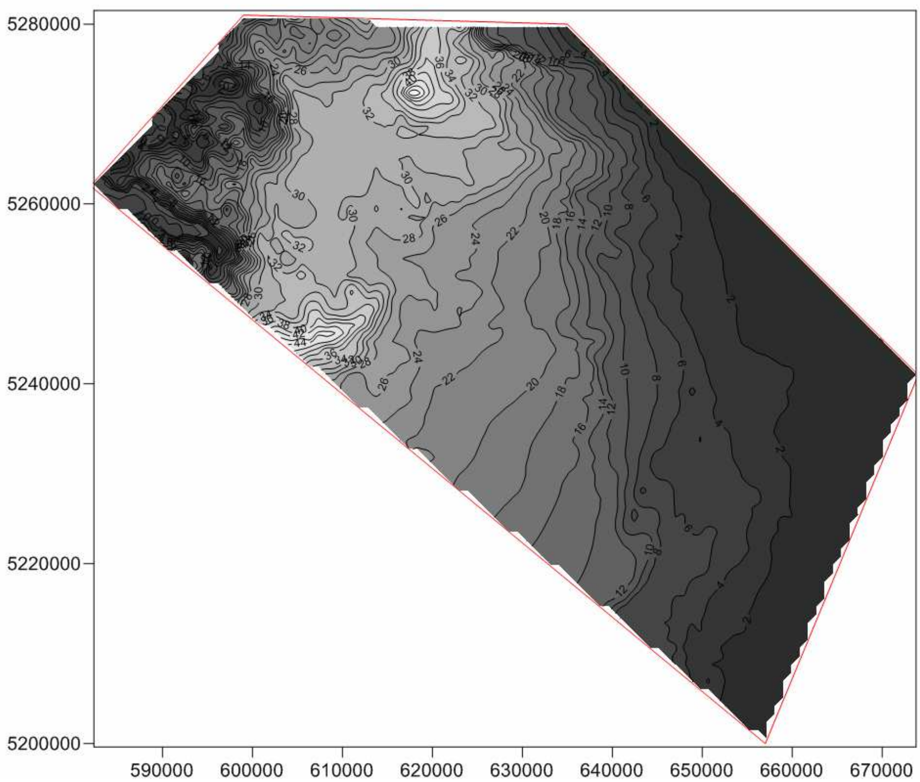


Figure 23. Simulated water table drawdown. Scenario 7 – increased extraction rates .

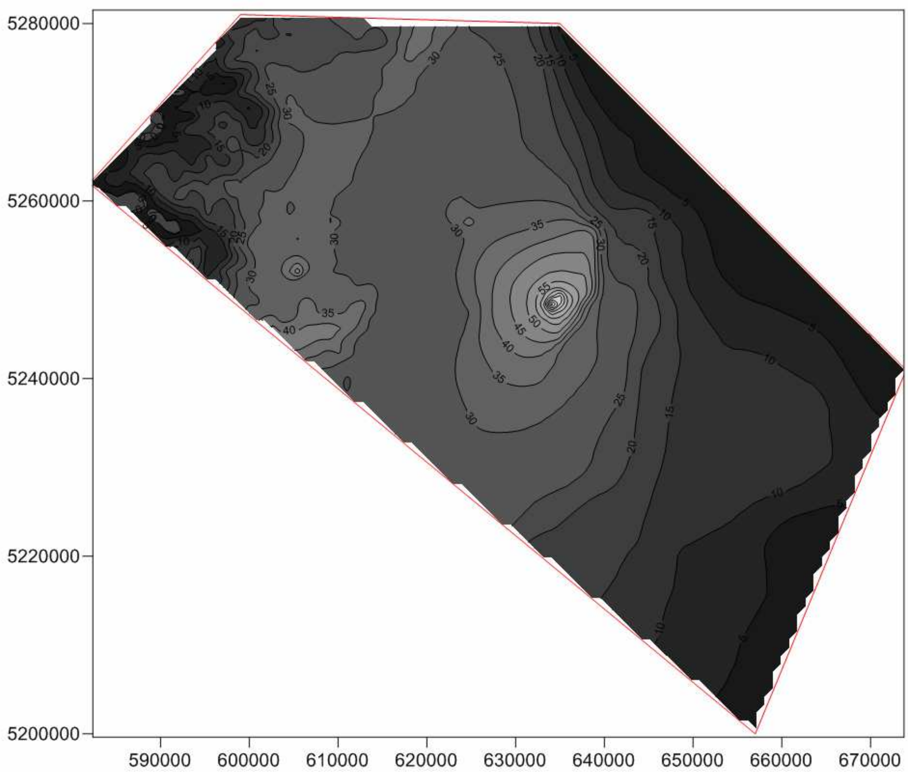


Figure 24. Simulated depressurisation in the Sarmathian reservoir. Scenario 7 – increased extraction rates.

Simulation results predict a significant increase in water table drawdown of up to 16 metres in the border zone of the pilot area. While current simulated drawdown was around 10-12 metres, the predicted drawdown in this area is around 26-28 metres.

Similarly, the current depressurisation of the Sarmathian reservoir of 12 metres simulated in the border zone is predicted to increase to 30 metres in response of a twofold increase in production rates.
Predictive model results suggest that the increase of extraction rates would put a significant stress on the groundwater system.

3.1.3.3.2 Bore doublet (Scenario 8)

In order to investigate the thermal effects of reinjection of geothermal heating water, a geothermal bore doublet has been simulated. Scenario 8 included the simulation of an extraction and a reinjection bore in the Eastern Devonian dolomite block. This reservoir is similar to the dolomite reservoir exploited by the Bük extraction bores, but is hydraulically independent and thus not affected by artificial activities. Similarly to the Bük extraction bores, 1500 m3/day extraction rate has been applied. The same amount is reinjected in a bore located approximately 500 metres apart. Using a conservative approach, the temperature drop is plotted in Figure 25, assuming infinite operation time. Figure 26 shows the Steady-state drawdown rates around a virtual bore doublet and Figure 27 shows the drowdawn around a virtual extraction bore, when no reinjection is assumed.

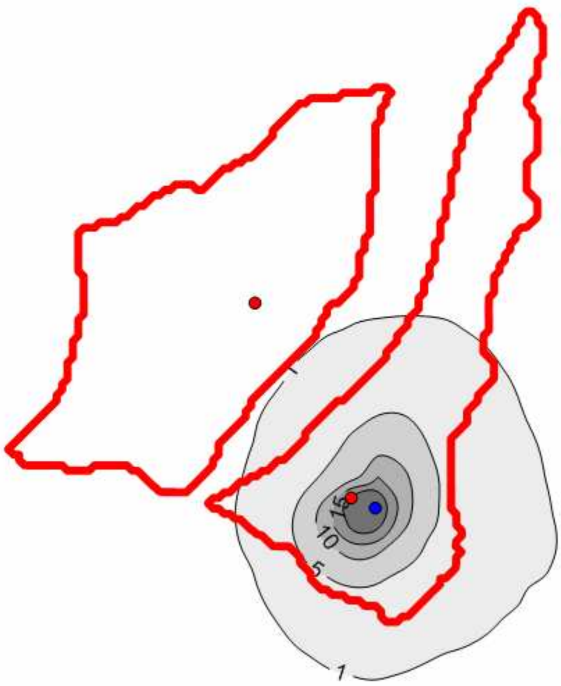


Figure 25. Steady-state temperature drop around the reinjection bore of a virtual bore doublet installed in the Eastern Bük dolomite block. Simulated extraction rate is 1500 m3/day, reinjection temperature is 20 C.

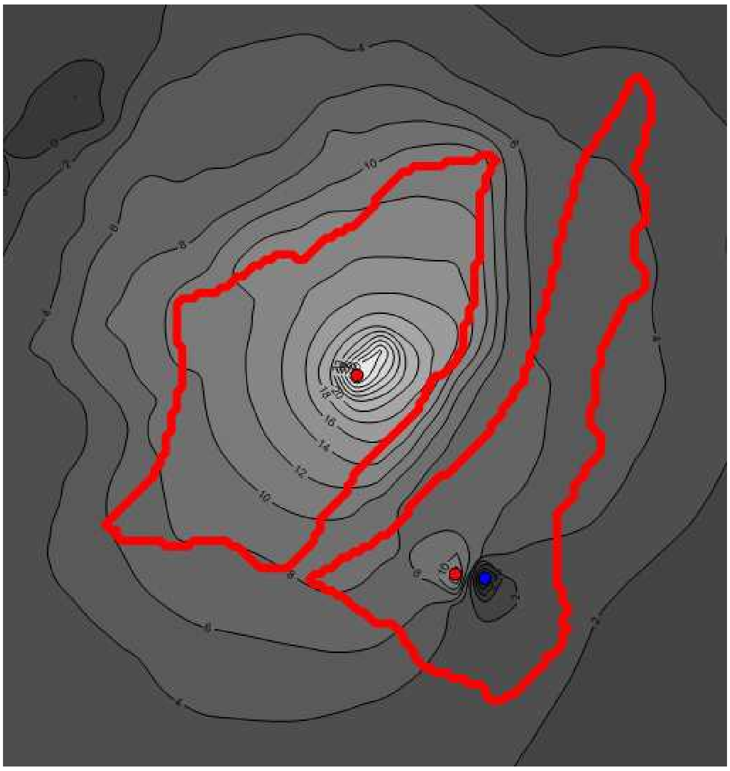


Figure 26. Steady-state drawdown rates around a virtual bore doublet installed in the Eastern Bük dolomite block. Simulated extraction rate is 1500 m^3/day, reinjection temperature is 20 C.

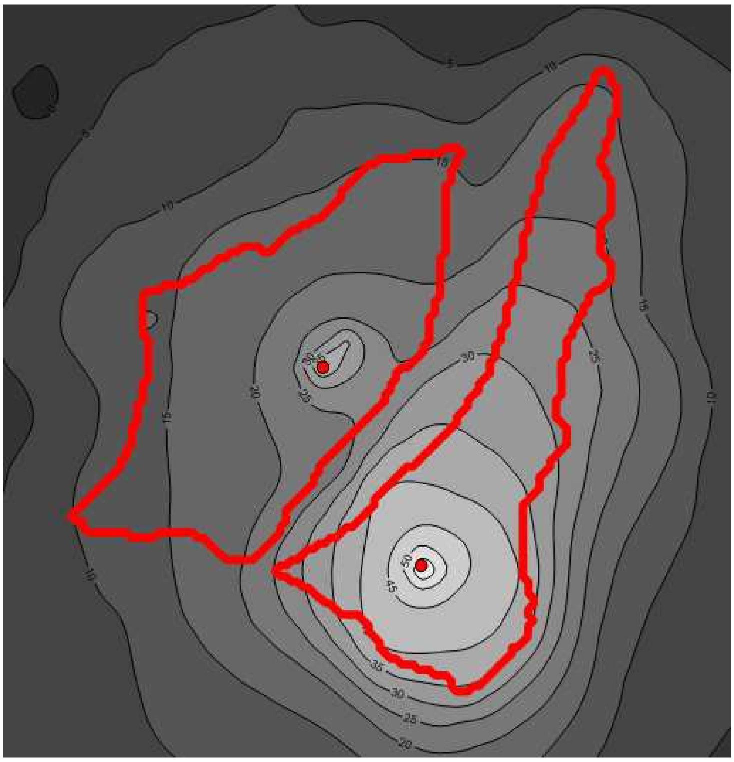


Figure 27. Steady-state drawdown rates around a virtual extraction bore installed in the Eastern Bük dolomite block. No reinjection assumed. Simulated extraction rate is 1500 m^3/day.

According to the simulation results, the reinjection bore had a thermal influence in a circle of 4 km radius around the bore. The cooling effect did not extend far beyond the boundaries of the dolomite block. Using a transient simulation, the thermal influence did not extend more than 500 metres around the reinjection bore within 20 years of simulation time.

The simulated drawdown plots indicate, that the extraction bore had a steady state depressurisation of up to 60 metres without reinjection. If reinjection is applied, the maximum depressurisation rate around the extraction bore dropped to 13 metres. At the same time, a pressure increase of 7 m developed around the reinjection bore.

Based on the Scenario 8 simulation, it can be stated that reinjection of the extracted fluids significantly decreases the hydraulic impacts of groundwater extraction. The cooling effect of cold water reinjection had little influence of the temperature distribution within 20 years of simulation time, and has only a local impact on reservoir temperatures in the case of long-term utilisation.

3.2 Bad Radkersburg-Hodos model area

The Bad Radkersburg – Hodoš pilot area is situated along the national borders of Austria, Slovenia and Hungary. There is a competition between an existing thermal water user of the Pre-Neogene basement aquifer in Bad Radkersburg (AT) and a developer in Korovci (SI). The latter plans to reinject part of the water which will be used for heating, but the one used for balneology will have to be treated on a purifying plant to prevent pollution of the transboundary stream Kučnica. The monitoring data on Austrian wells is not available, and therefore the assessment of impact of Korovci to this site is uncertain. No quality or quantity changes have been reported for thermal water abstracted from the Pre-Neogene basement aquifer.

3.2.1 Model objectives

In 2008, a deep geothermal borehole was drilled in Korovci (SI) (Kraljić 2008a and 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 impact of production in Korovci on wells in Bad Radkesburg.

The aim of the numerical modelling was to determine the potential impacts of different utilization strategies in Korovci on the nearby geothermal wells in Bad Radkersburg. The modelling was performed for the optimization of utilization of these geothermal resources.

Major questions that were addressed are:

- What impact of abstraction in Korovci on thermal water production in Bad Radkersburg can be expected?
- What would be the impact in case of implementation of reinjection in a geothermal doublet scheme in Korovci?

Different model set-ups and scenarios were implemented to answer the questions.

3.2.2 Modelling methodology

The main issue addressed in this study was 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.

Scenario modelling is based on the steady state model. A detailed model setup description can be found in the report on the steady state model (Fuks et al 2013a).

In the scenario model two different utilization sheme were applied, single well without reinjection and well doublet. The aim of the reinjection scenarios was to determine the potential cool-down effects of reinjection in well Kor-2g. The temperature of reinjected water was set to 35 °C. The production (Kor-1gα) and reinjection (Kor-2g) zones are 700 m apart. All production scenarios were simulated for 50 years period.

Sensitivity analysis indicated that hydraulic conductivity is the model parameter that has the largest impact on the model output. Therefore, different values of hydraulic conductivity in the main aquifer in the Raba fault zone were tested, ranging from 10-5 to 10-7 m/s, depending on the scenario. In addition, aquifer thickness and specific storage values were adjusted in each scenario. In the reinjection scenarios also different values of porosity, longitudinal and transverse dispersivity were tested.

3.2.3 Results of the Bad Radkersburg-Hodos scenario models

3.2.3.1 Abstraction in Korovci without reinjection scenarios

For the purpose of determining the effects of planned production in Korovci on other wells, 8 different scenarios without reinjection have been developed (Table 4). In order to incorporate uncertainty, related to defined parameter values, ranges of parameters values were implemented. Table 5 shows the computed drawdawn after 50 years in production in Korovci for all scenarios.

Table 4. Scenarios for abstraction in Korovci (without reinjection).

Scenario	Hydraulic conductivity of RF [m/s]	Aquifer thickness [m]	Specific storage	Production 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

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

For the initial conditions computed hydraulic heads after 30 years of thermal water production in Bad Radkersburg were used. This way, present state of the aquifer and head distribution was approximated. All production scenarios were simulated for 50 years period.

Figure 28 and Figure 29 show the computed 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. It 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.

Scenarios 1 to 6 produce similar results (Figure 30-Figure **35**). The computed drawdown in scenario 7 is lower than in other scenarios, but the effects extend further away from the production borehole Kor-1gα (Figure 36).

Effects of the production in Korovci are detected in Bad Radkersburg only in scenarios 7 and 8, whereas the effects in Benedikt are not seen in any of the scenarios (Figure 37).

Based on sensitivity analysis hydraulic conductivity and specific storage were found the most sensitive parameters of the model.

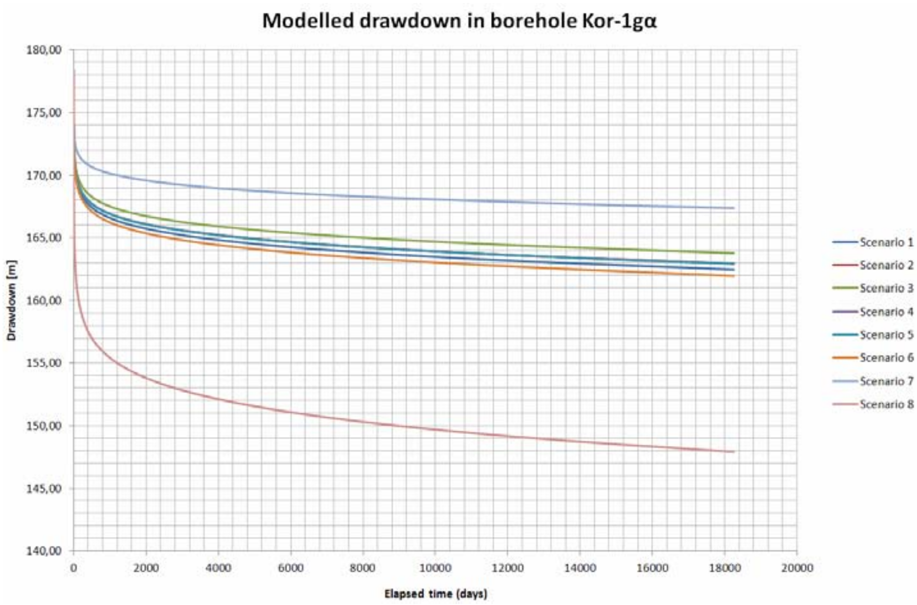


Figure 28**.** Modelled hydraulic heads in borehole Kor-1gα. Simulation time 50 years.

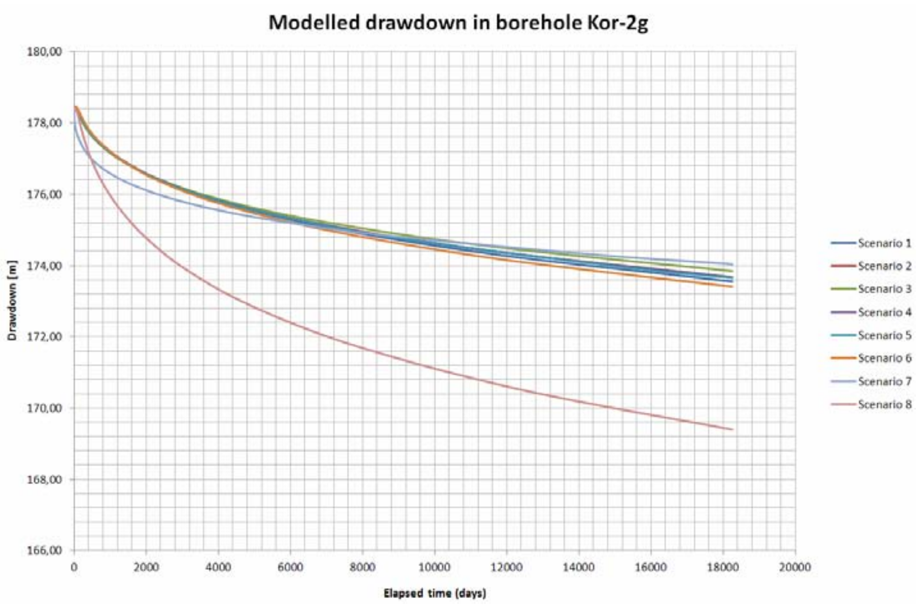


Figure 29. Modelled hydraulic heads in borehole Kor-2g. Simulation time 50 years.

Figure 30 shows the computed drawdown for scenario 1 after 50 years of simulation. It shows no impact after 50 years of production on the Bad Radkersburg wells. The drawdown in the production borehole Kor-1gα after 50 years of production is 14.5 m.

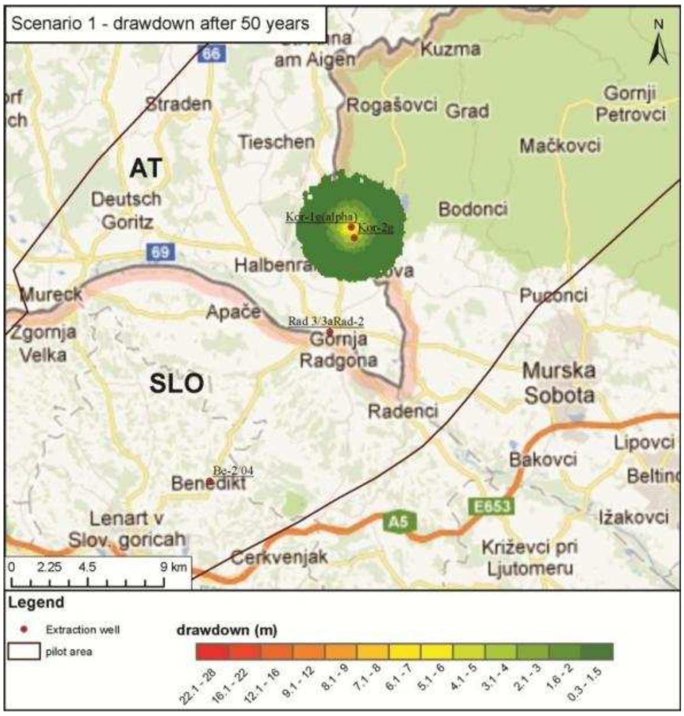


Figure 30. Scenario 1 – computed drawdown after 50 years of production in Korovci (without reinjection).

Figure 31 shows the computed drawdown for scenario 2 after 50 years of simulation. The drawdown does not reach the Bad Radkersburg wells in this case after 50 years of production. The drawdown in the production borehole Kor-1gα after 50 years of production is 14.5 m.

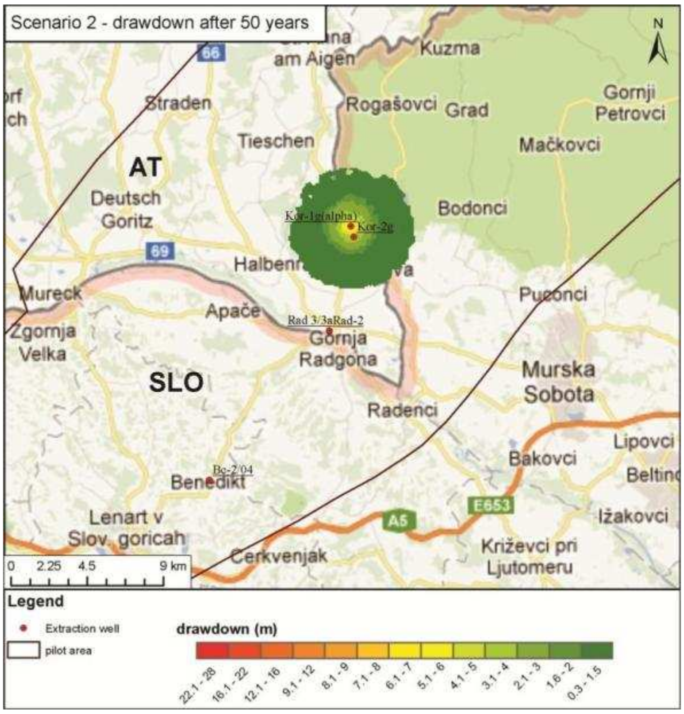


Figure 31. Scenario 2 – computed drawdown after 50 years of production in Korovci (without reinjection).

Figure 32 shows the computed drawdown for scenario 3 after 50 years of simulation. The drawdown does not reach the Bad Radkersburg wells in this case after 50 years of production. The drawdown in the production borehole Kor-1gα after 50 years of production is 13.5 m.

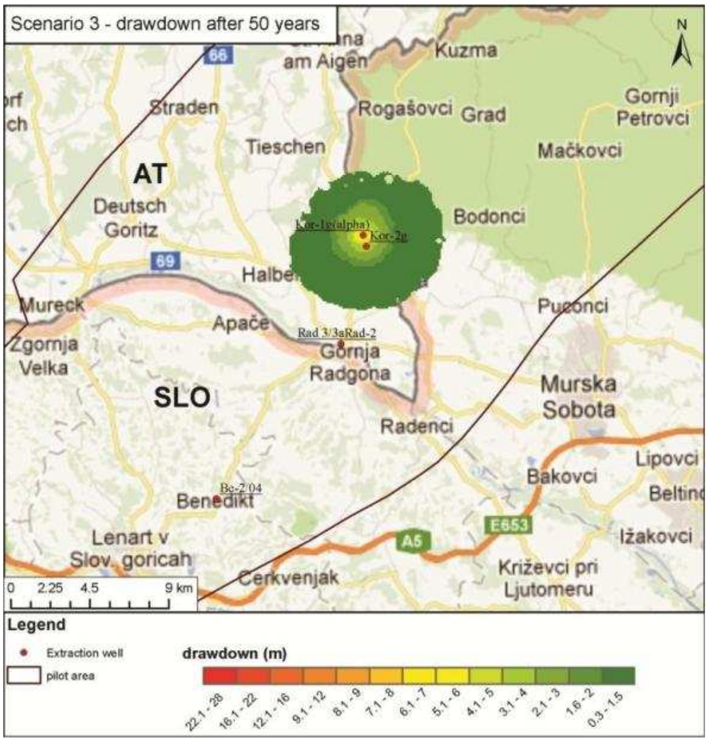


Figure 32. Scenario 3 – computed drawdown after 50 years of production in Korovci (without reinjection).

Figure 33 shows the computed drawdown for scenario 4 after 50 years of simulation. The drawdown does not reach the Bad Radkersburg wells in this case after 50 years of production. The drawdown in the production borehole Kor-1gα after 50 years of production is 14.5 m.

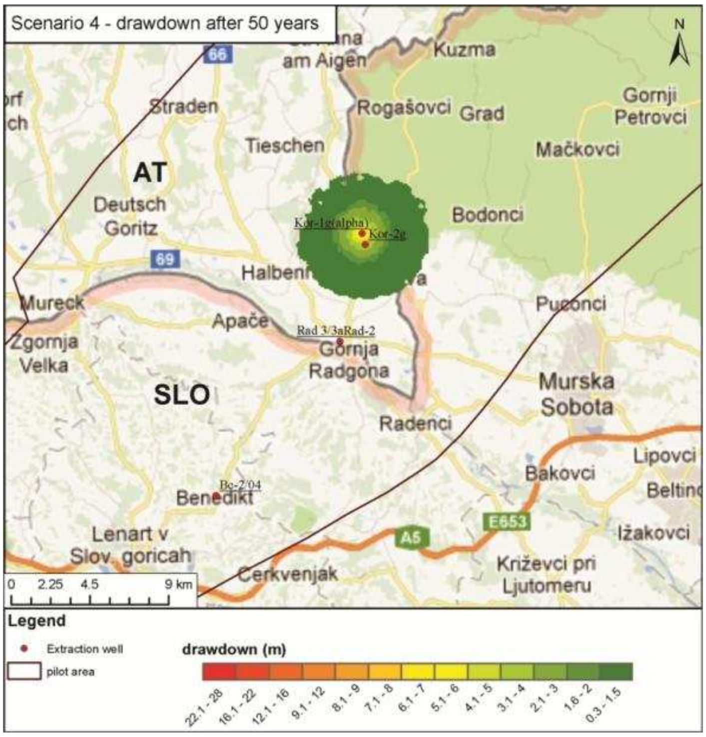


Figure 33. Scenario 4 – computed drawdown after 50 years of production in Korovci (without reinjection).

Figure 34 shows the computed drawdown for scenario 5 after 50 years of simulation. The drawdown does not reach the Bad Radkersburg wells in this case after 50 years of production. The drawdown in the production borehole Kor-1gα 50 years of production is 14.5 m after.

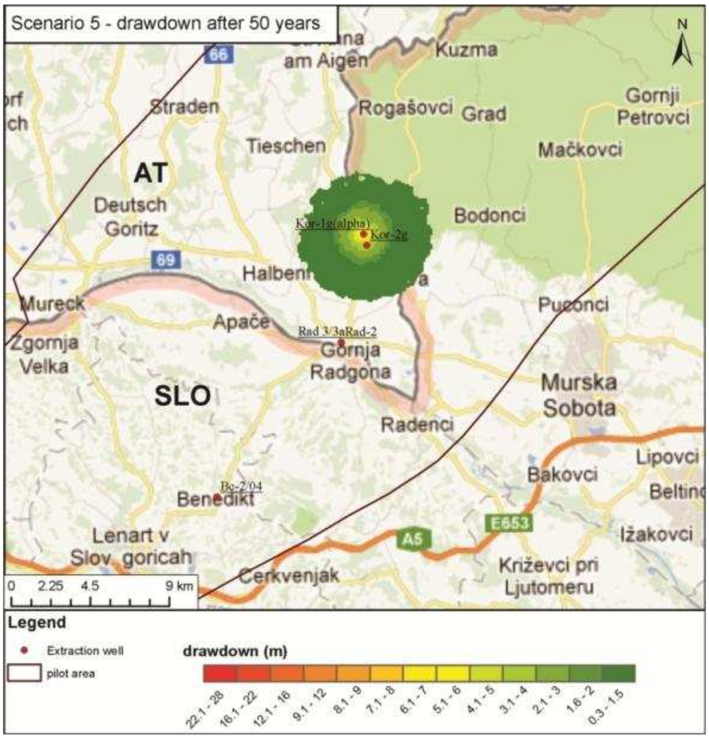


Figure 34. Scenario 5 – computed drawdown after 50 years of production in Korovci (without reinjection).

Figure 35 shows the computed drawdown for scenario 6 after 50 years of simulation. The drawdown does not reach the Bad Radkersburg wells in this case after 50 years of production. The drawdown in the production borehole Kor-1gα years of production is 15 m after 50 years.

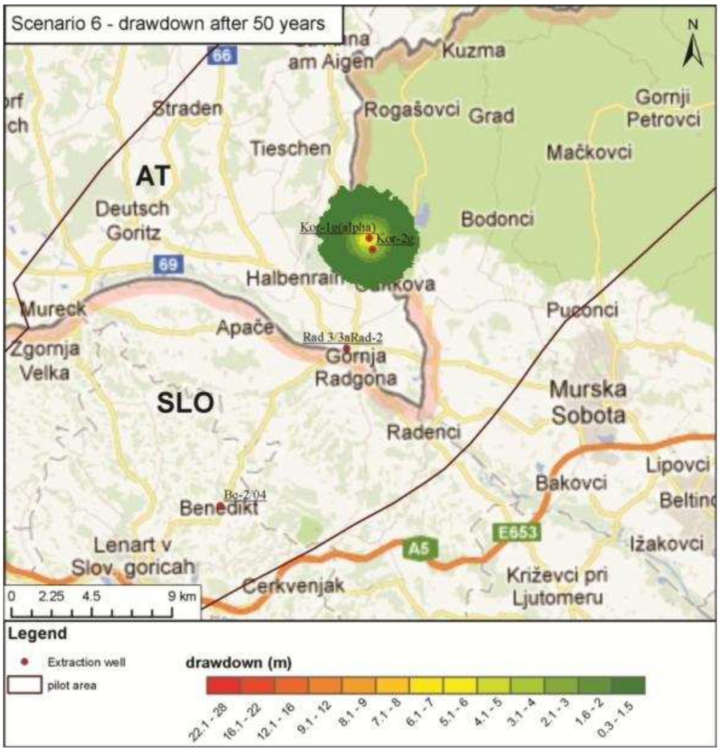


Figure 35. Scenario 6 – computed drawdown after 50 years of production in Korovci (without reinjection).

Figure 36 shows the computed drawdown for scenario 7 after 50 years of simulation. The drawdown in the production borehole Kor-1gα is 11 m and reaches Bad Radkersburg.

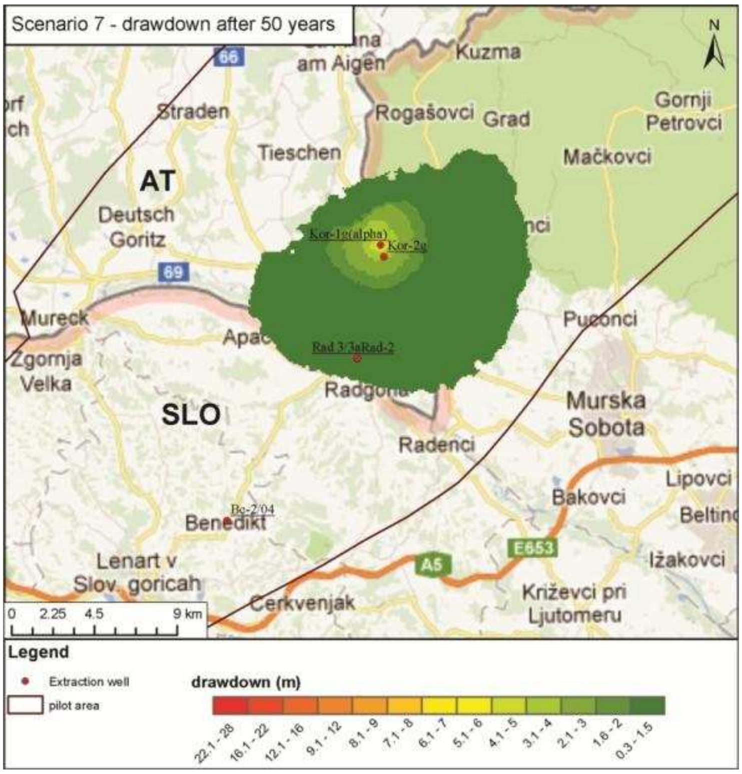


Figure 36. Scenario 7 – computed drawdown after 50 years of production in Korovci (without reinjection).

Figure 37 shows the computed drawdown for scenario 8 after 50 years of simulation. The drawdown in the production borehole Kor-1gα is 30 m. The effects of production in Korovci reach the Bad Radkersburg boreholes in this case.

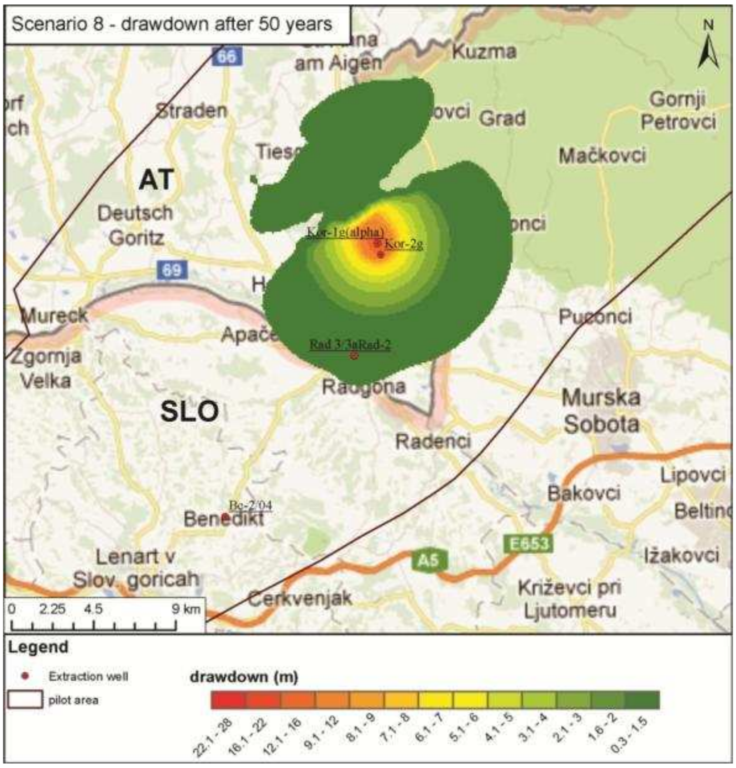


Figure 37. Scenario 8 – computed drawdown after 50 years of production in Korovci (without reinjection).

3.2.3.2 Reinjection scenarios

The aim of the reinjection scenarios was to determine the potential cool-down effects of reinjection in well Kor-2g. The temperature of reinjected water was set to 35 °C. The production (Kor-1gα) and reinjection (Kor-2g) zones are 700 m apart. Scenarios developed for this purpose are listed in Table 6**. Modelled temperature decrease in production borehole Kor-1gα are shown in**

Table 7.

Table 6. Reinjection scenarios in Korovci.

Scenario	Longitudinal dispersivity	Transverse dispersivity	Hydraulic conductivity [m/s]	Reinjection rate [l/s]	Simulation time [days]
1	5	0.5	1×10^{-6}	20	365000
2	50	5	1×10^{-6}	20	365000
3	150	15	1×10^{-6}	20	365000
4	150	15	1×10^{-5}	20	36500
5	150	15	1×10^{-5}	40	36500

Table 7. Modelled temperature decrease in production borehole Kor-1gα for all scenarios.

Scenario	Temperature decrease [°C]
1	0.3
2	0.3
3	0.6
4	0.6
5	3.9

Three additional numerical observation points were added. Those are shown in Figure 38.

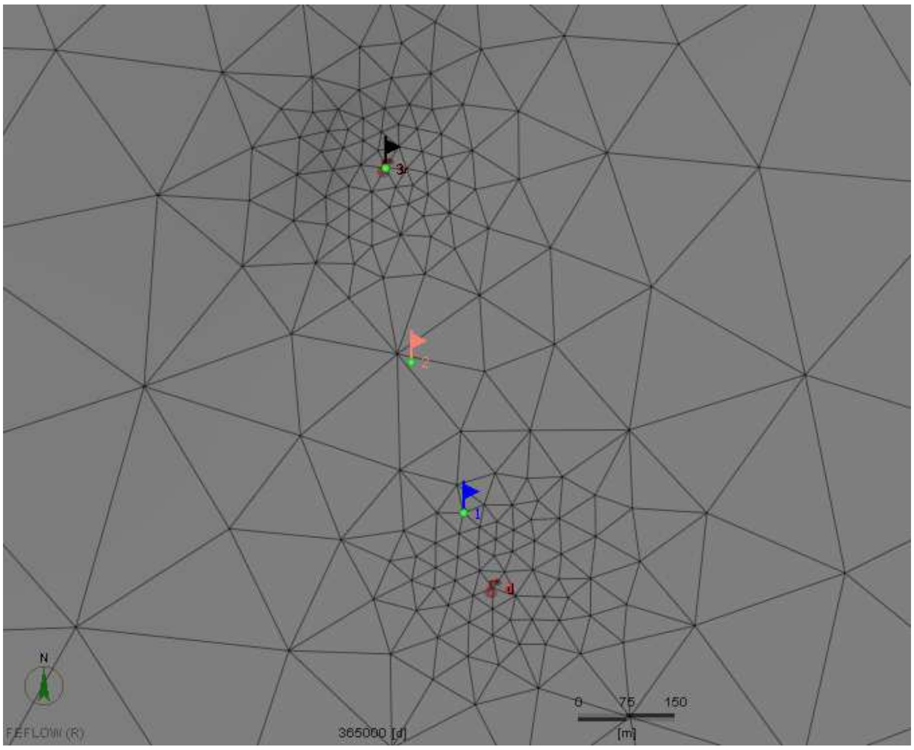


Figure 38. Observation points in reinjection scenarios; d – reinjection borehole Kor-2g, 1 and 2 – numerical observation points, 3 – observation point set in the production borehole Kor-1gα

Figure 39 to Figure 44 show the effects of the reinjected water in the observation points for the first 3 scenarios. The effects reach the production borehole in roughly 500 years (180000 days). However, the temperature decrease after 1000 years of simulation is very low and does not exceed 1 °C in any of those scenarios.

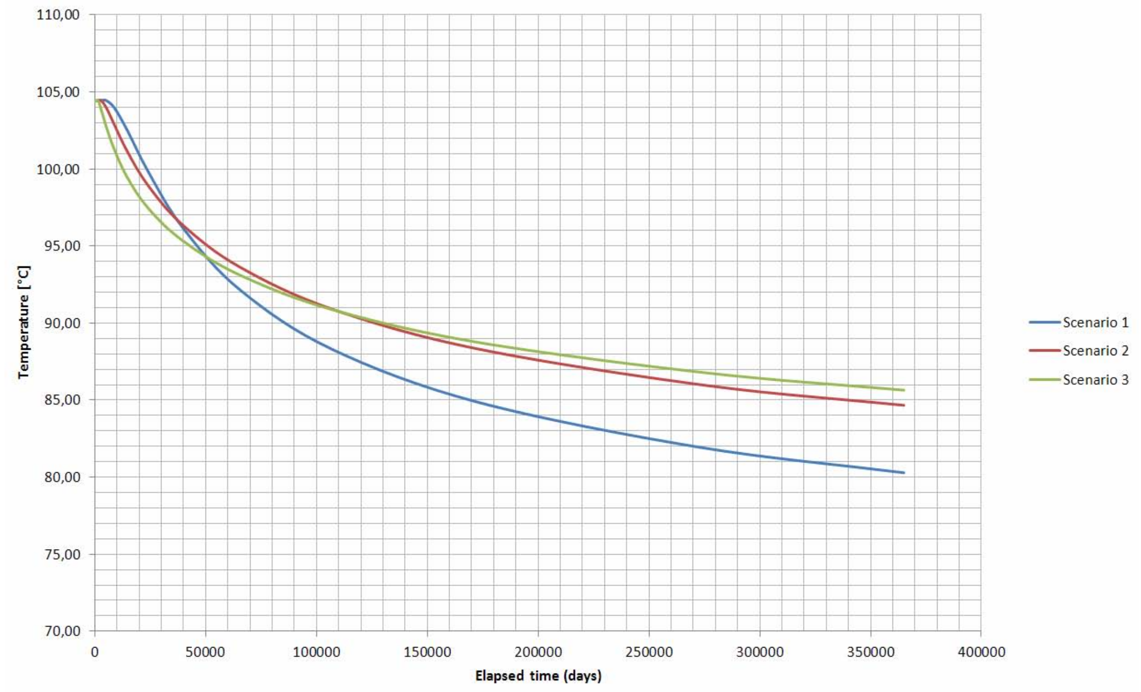


Figure 39. Modelled temperature decrease in observation point 1 – scenarios 1, 2 and 3.

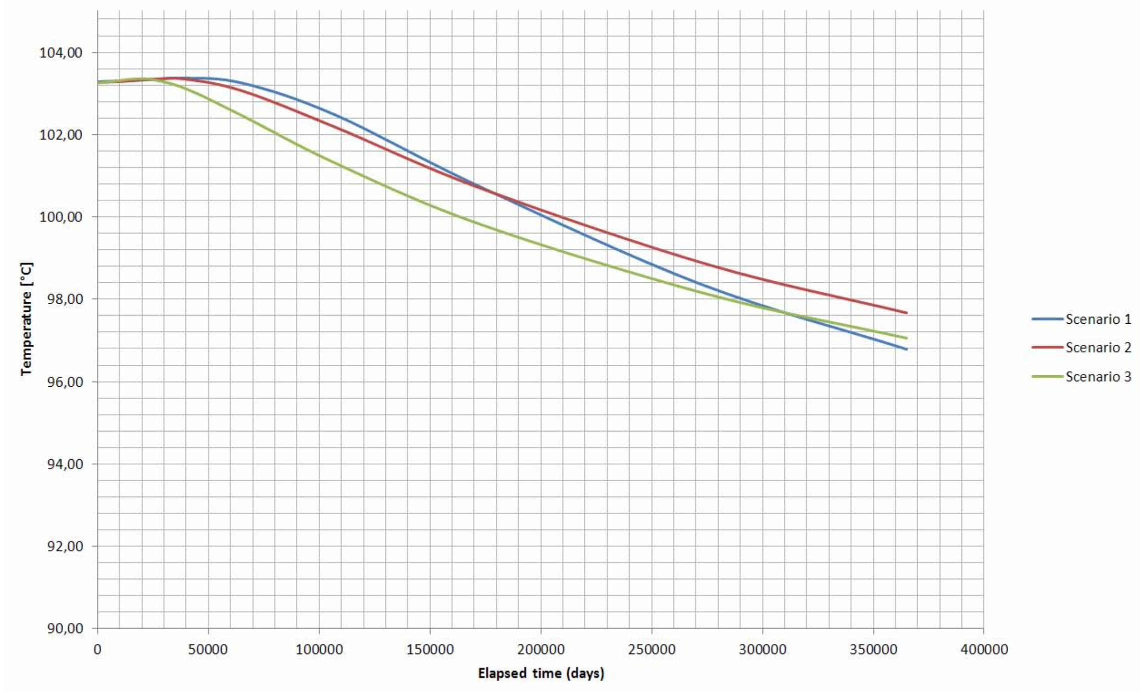


Figure 40. Modelled temperature decrease in observation point 2 – scenarios 1, 2 and 3.

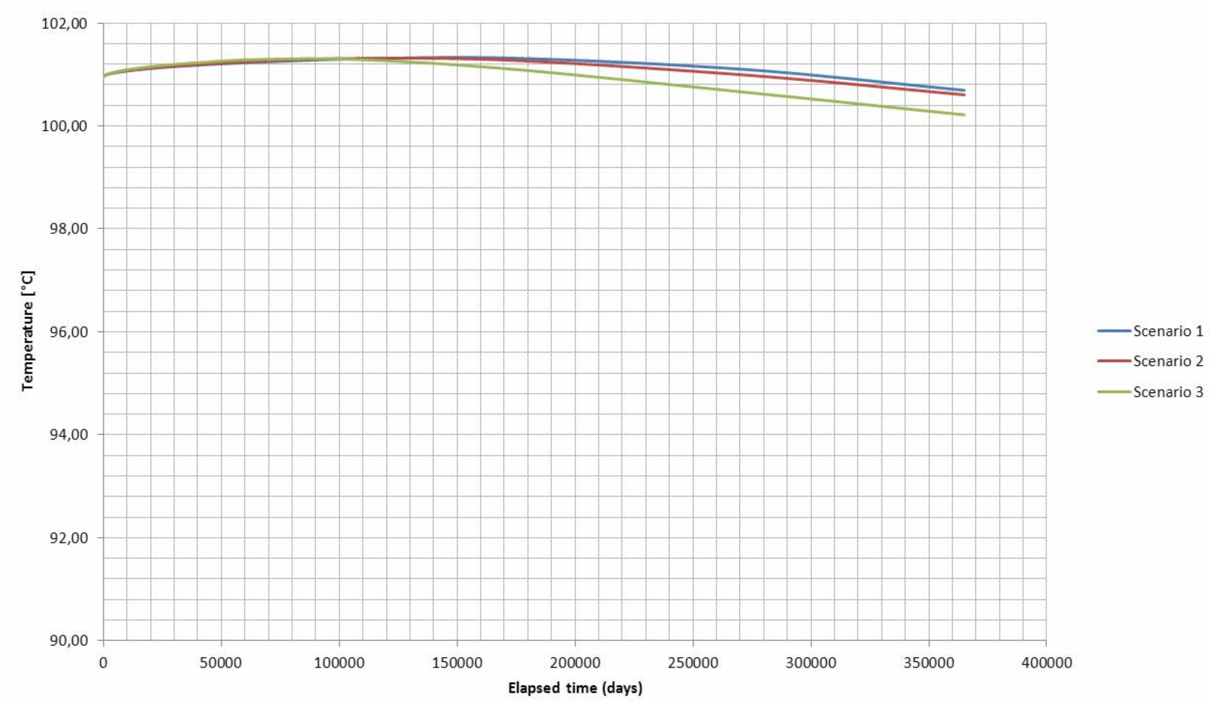


Figure 41. Modelled temperature decrease in observation point 3 (production borehole) – scenarios 1, 2 and 3.

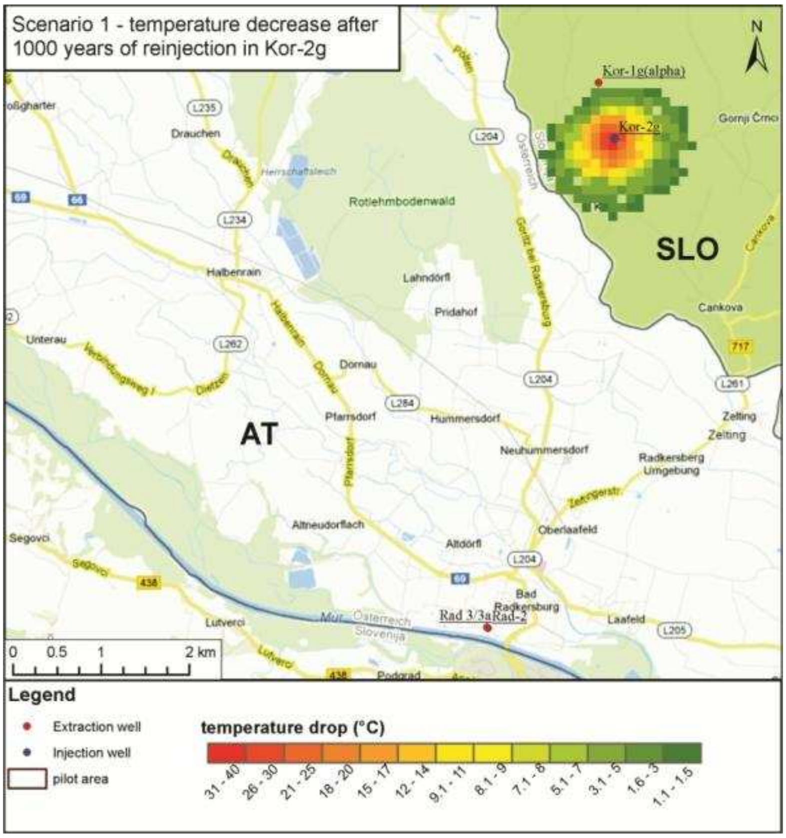


Figure 42. Scenario 1 – modelled temperature decrease and extend of the thermal plume after 1000 years of reinjection in Korovci.

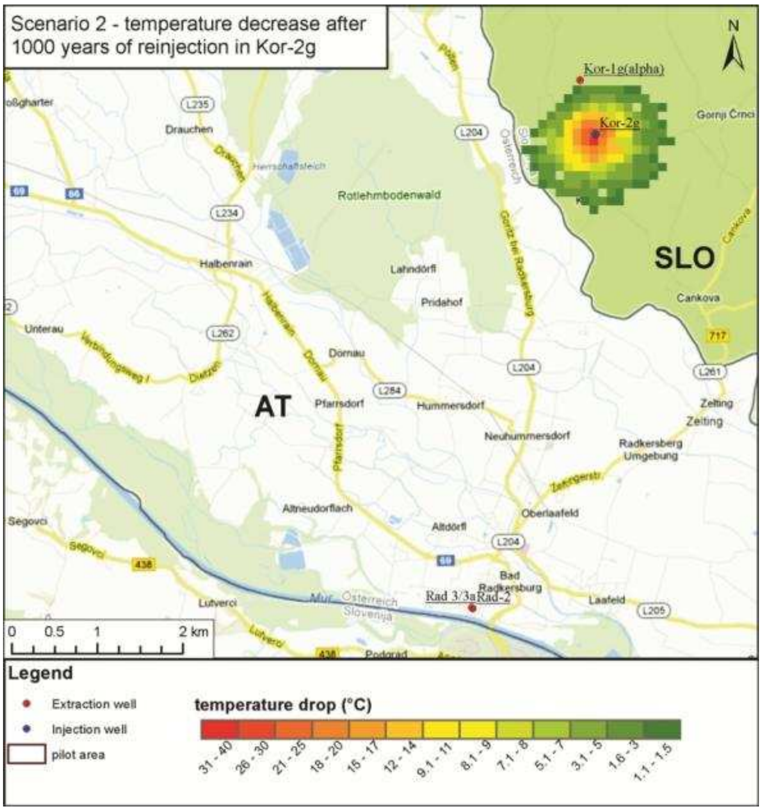


Figure 43. Scenario 2 – modelled temperature decrease and extend of the thermal plume after 1000 years of reinjection in Korovci.

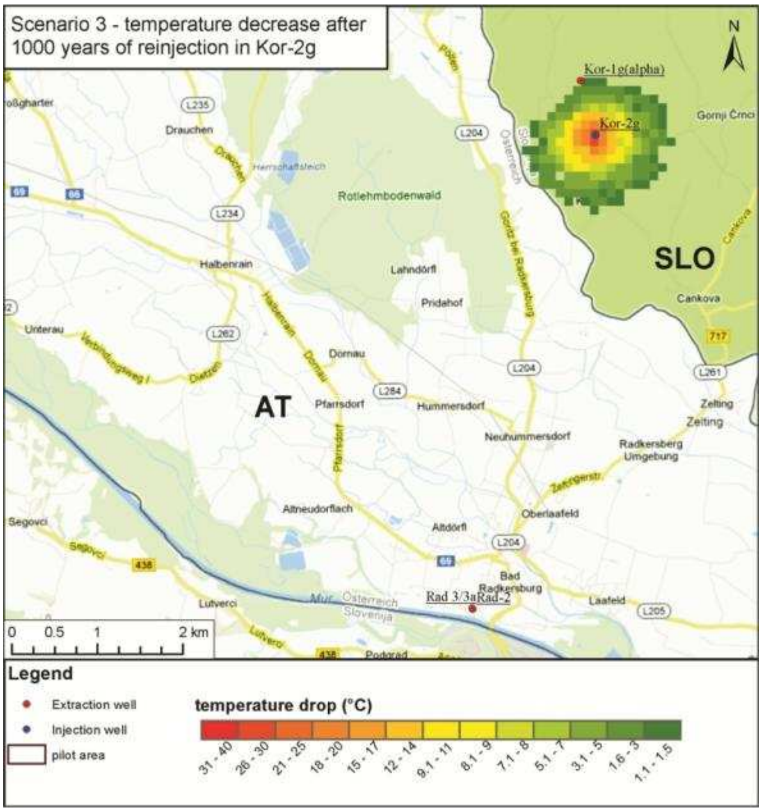


Figure 44. Scenario 3 – modelled temperature decrease and the extend of the thermal plume after 1000 years of reinjection in Korovci.

Figure 45-Figure 47 show the temperature decrease in scenarios 4 and 5. In those scenarios conductivity values have been set to higher values at 1×10^{-5} m/s. After the simulation time of 100 years effects of reinjected water are detected in the production borehole in both cases. In scenario 4, the decrease is very small (less than 1 °C) and occurs after 50 years of simulation. In the case of scenario 5, the reinjection rate was doubled to 40 l/s. The temperature decrease in the production borehole is detected in less than 30 years of reinjection. The temperature decrease after 100 years of simulation is around 4 °C.

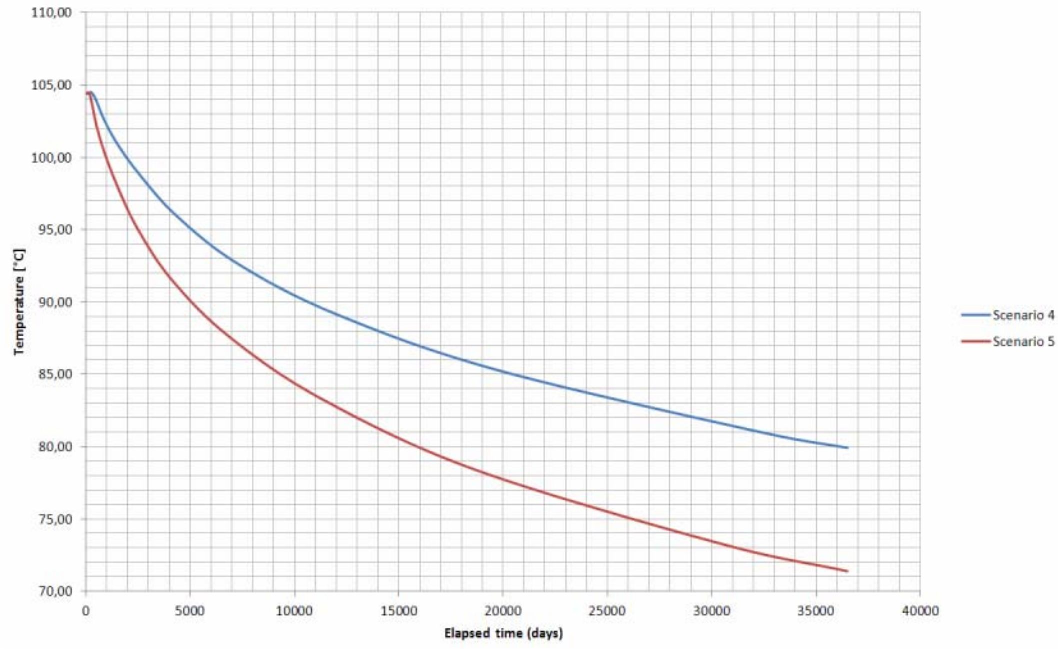


Figure 45. Modelled temperature decrease in observation point 1 – scenarios 4 and 5.

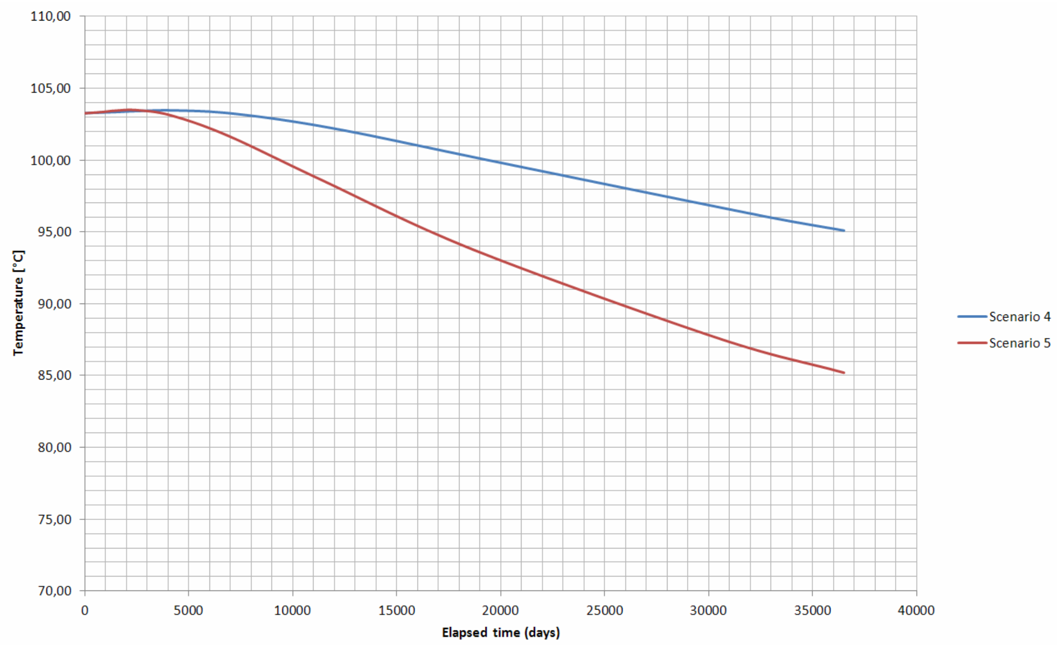


Figure 46. Modelled temperature decrease in observation point 2 – scenarios 4 and 5.

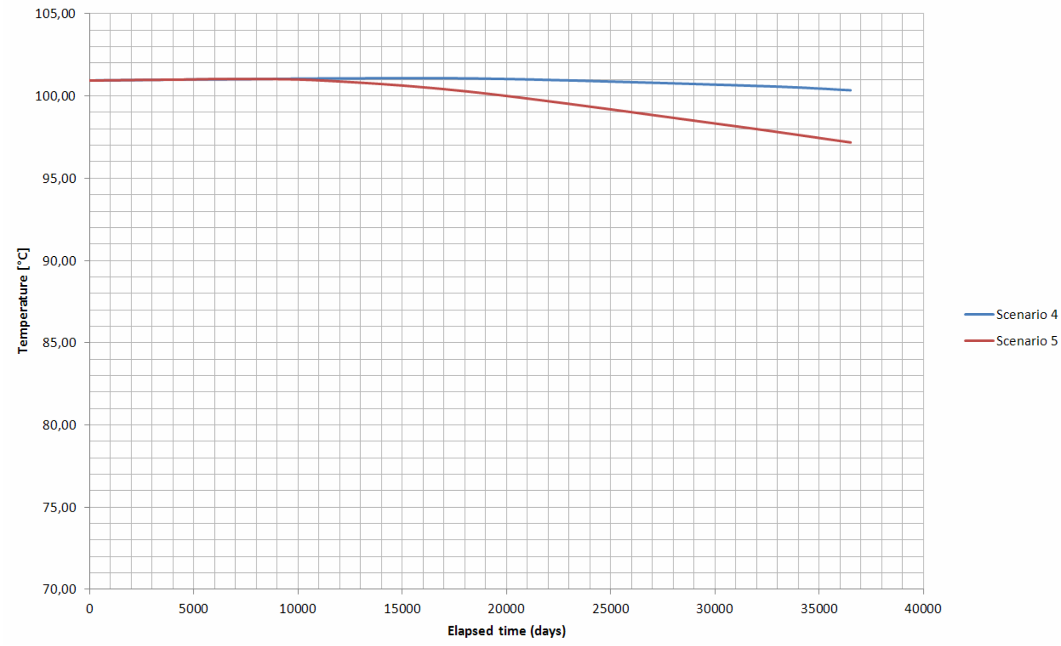


Figure 47. Modelled temperature decrease in observation point 3 (production borehole) – scenarios 4 and 5.

Figure 48 shows extend of the thermal plume after 100 years of simulation for the scenario 4. Temperature decrease in the production borehole does not exceed 1 °C. **Figure 49** shows the Modelled hydraulic head changes for geothermal doublet in Korovci after 100 years of simulation.

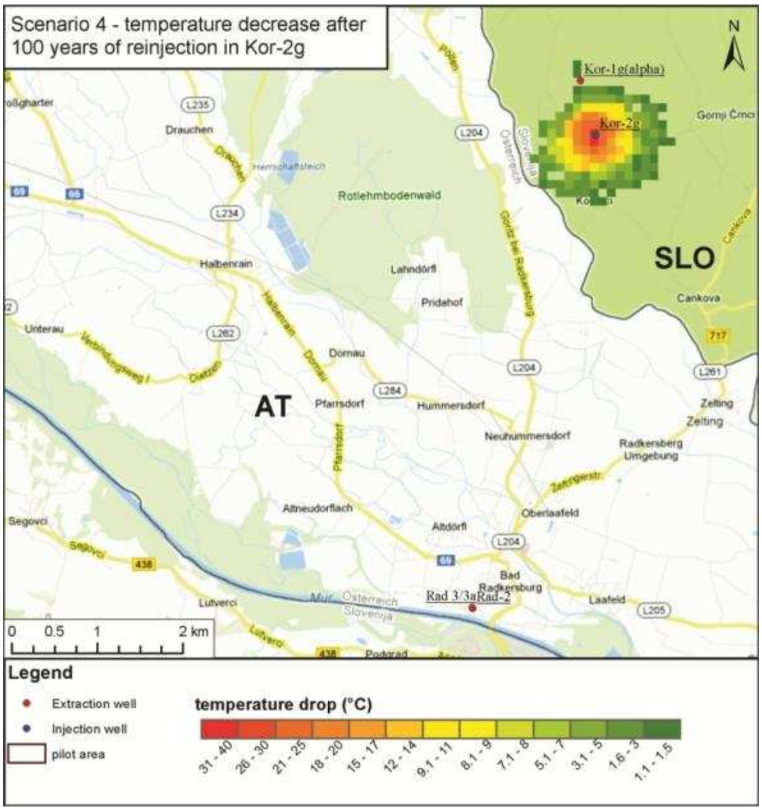


Figure 48. Scenario 4 – modelled temperature decrease and extend of the thermal plume after 100 years of reinjection in Korovci.

Figure 49. Modelled hydraulic head changes for geothermal doublet in Korovci after 100 years of simulation.

Figure 50 shows extend of the thermal plume after 100 years of simulation for the scenario 5. The thermal plume reaches the production borehole in this case and the temperature decrease exceeds 1 °C after 100 years of reinjection.

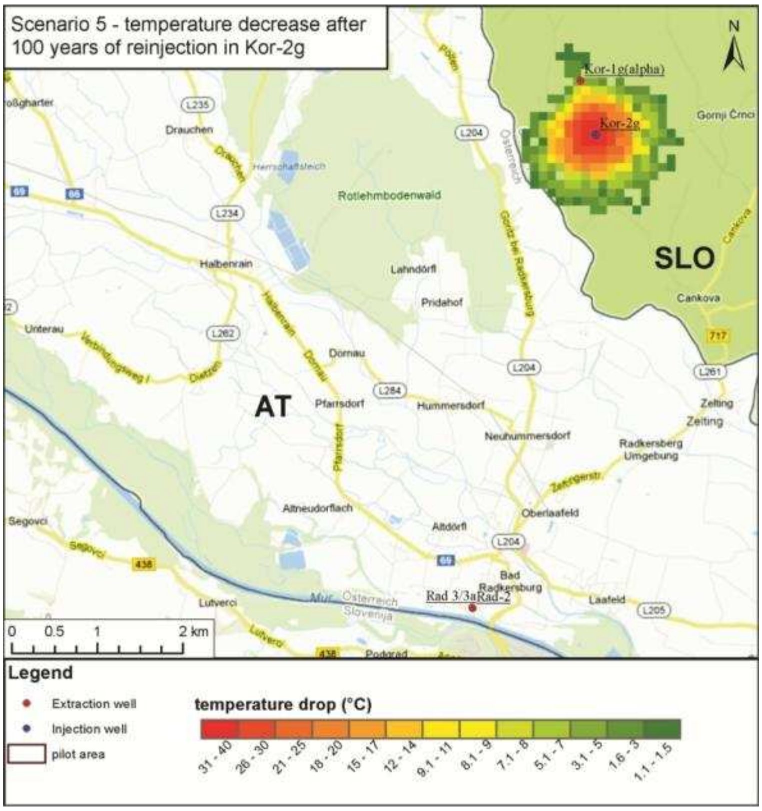


Figure 50. Scenario 5 – modelled temperature decrease and extend of the thermal plume after 100 years of reinjection in Korovci.

3.3 Danube Basin model area

The pilot area of Danube basin is situated in Slovakia, Hungary and partly at Austria. Nowadays there is no existing utilization conflict in Danube basin geothermal area. Though future problems in excessive utilization can happen. Modeled groundwater temperatures and pressure may significantly drop after long-term exploitation.

3.3.1 Model objectives

Possible future influence was predicted based on the current utilization magnitude. The steady state models (Svasta et al 2013a) allowed to identify sensitive areas were future monitoring of geothermal aquifer should be established. Scenarios of additional direct use of thermal ground water proved the necessity of geothermal water reinjection.

The aim of the numerical modelling was to investigate impacts of additional geothermal installations on thermal and pressure conditions of the porous aquifer in the upper Pannonian geothermal aquifer of the Danube basin, together with evaluation of geothermal resources that can be potentially harvested by the respective means. The modelling comprises steady state 3D groundwater flow and heat transport simulations. Two scenarios are compared – extraction of geothermal energy by means of geothermal doublets and direct use of thermal groundwater by pumping. The results of the two scenarios are compared.

A detailed study on interstate cooperation on geothermal energy exploitation was performed as well. The scenario of common geothermal energy use directly at the state border, by means of two geothermal doublets, organized in a tight 2 by 2 diagonal cluster. The main goal of this study, performed by transient coupled flow and heat simulations, was to test the proposed wells configuration and estimate operating life of the system by prediction of thermal breakthrough.

3.3.2 Modelling methodology

The basis of the scenario model was built on the basis of the steady-state model. Parameters and boundary conditions are detailed in the steady state model report (Svasta et al 2013a). The area where new hypothetical well installations were emplaced is the area of the upper Pannonian geothermal play, which extend was defined by recoverable heat in place (identified resources), with temperature of water over 30°C. New 21 geothermal doublets were placed randomly in areas with higher identified resources away from existing geothermal installations. Pumping and re-injection wells are separated by a distance of 2 km. Due to limited permeability of upper Pannonian sediments, pumping and re-injection rates were set to 20 l/s only, with temperature of re-injected water 25°C. For simplicity, the whole thickness of the upper Pannonian hydrostratigraphic unit was screened.

3.3.3 Results of the Danube Basin scenario models

3.3.3.1 Potencial installasions scenarios

Steady state simulation with additional 21 geothermal doublets revealed a significant effectiveness of the thermal energy harvesting (Figure 51). It also showed that in some areas a potential for additional installations still remains.

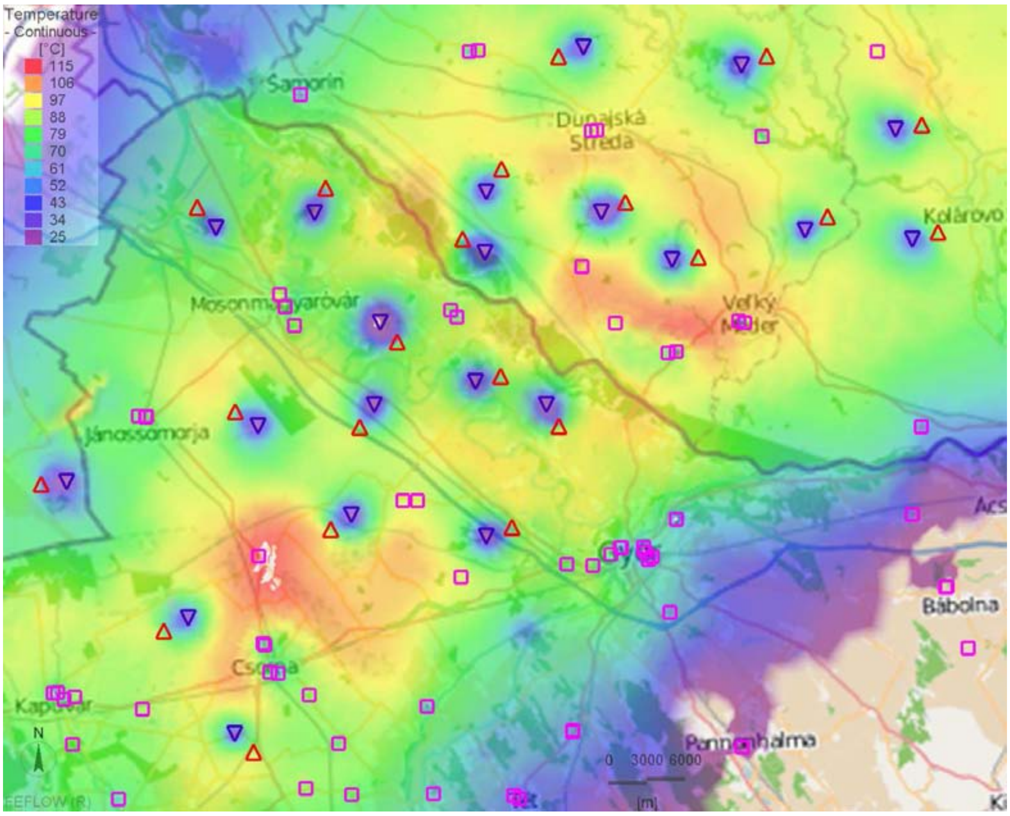


Figure 51**.**: Deformation of thermal field in upper Pannonian geothermal play caused by geothermal doublets.

Utilization of pumping wells without re-injection also shows significant cooling of the area in broader vicinity of the wells (Figure 52). Comparing to the doublet scenario, the temperature decrease is spread much more in lateral extend.

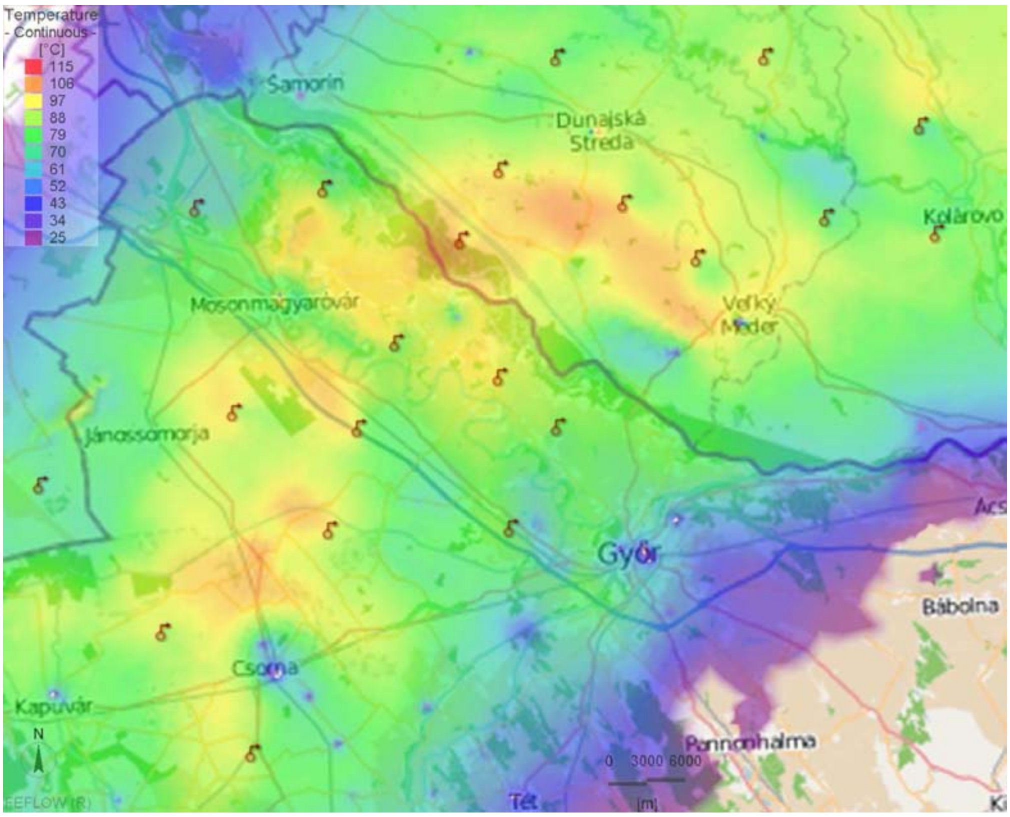


Figure 52: Deformation of thermal field in upper Pannonian geothermal play caused by pumping wells.

While temperature effects show generally similar pattern in both models, the two scenarios differ in much greater sense when it comes to hydraulics and especially groundwater pressure. Because in doublets scenario the extracted water is returned into the same aquifer, the negative pressure changes are compensated by increase of groundwater head near infiltration wells, and these changes are limited only to relatively close vicinity of the wells, what can be seen on distribution of hydraulic heads on Figure 53.

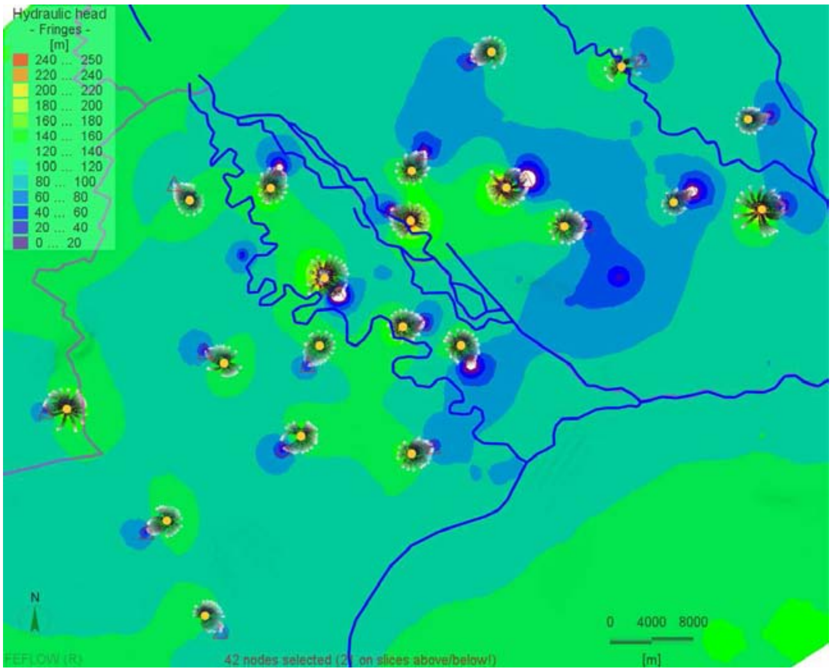


Figure 53: Hydraulic heads field in upper Pannonian geothermal aquifer, doublets scenario.

This picture is radically different from the scenario without re-injection (**Figure 54**), where pressure drop affects whole aquifer, with magnitude increasing towards its centre of the basin. In large areas the groundwater head drops over more than 100 meters, which would significantly affect technical limits of pumping of not only new wells, but also existing ones.

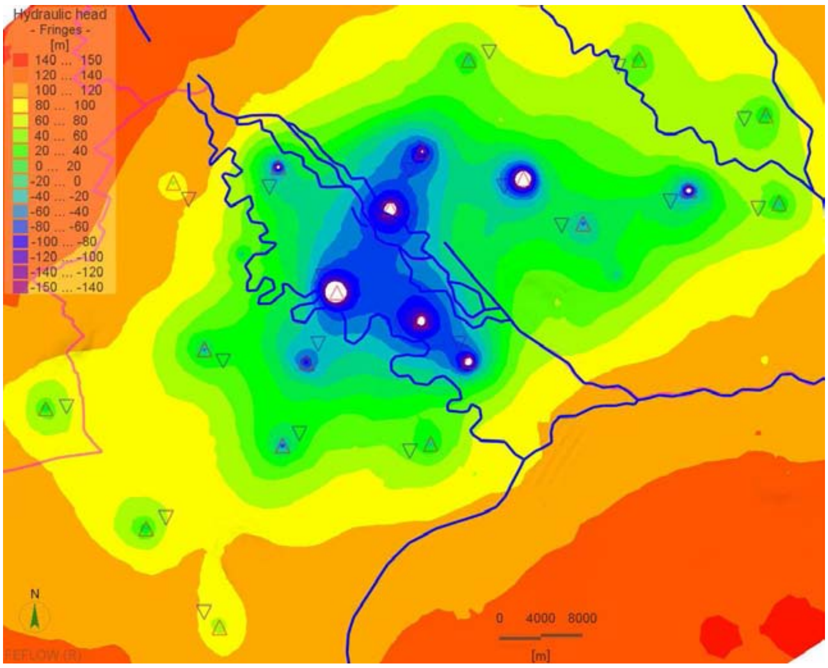


Figure 54: Hydraulic heads field in upper Pannonian geothermal aquifer, pumpig wells scenario.

By analysing the energetic balance of the models we studied energetic impact of the two scenarios. In the scenario with re-injection, we identified 55.46 MW of potential sustainable geothermal energy to be used.

For the scenario without reinjection, the calculated thermal power is higher, 82.32 MW. But the real energetic use will be much lower, since this number assumes extraction of all energy stored in the water by cooling it to the ambient temperature of 10°C, which is only theoretical. In the same time we observed a decrease of thermal power of existing geothermal wells of 3.64 MW, which attributes to cooling of significant portions of the resource aquifer.

3.3.3.2 Boundary doublet cluster scenarios

The aim of the numerical modelling was to investigate thermal and hydraulic response under the 2 doublets utilization configuration in Slovak – Hungary transboundary area (Figure 55). As a demonstration site for fissure – karst type of the aquifer in the pilot area of the Danube basin Mesozoic carbonates of the underlying Komarno marginal block (sensu Slovak interpretation of the geothermal water bodies and geothermal structures) was chosen. The fissure – karst type of permeability is suitable for reinjection of the energetically used water and is proven by practical experience as a favourable environment of the used thermal water disposal. The configuration of two doublets cluster can be seen on Figure 56.

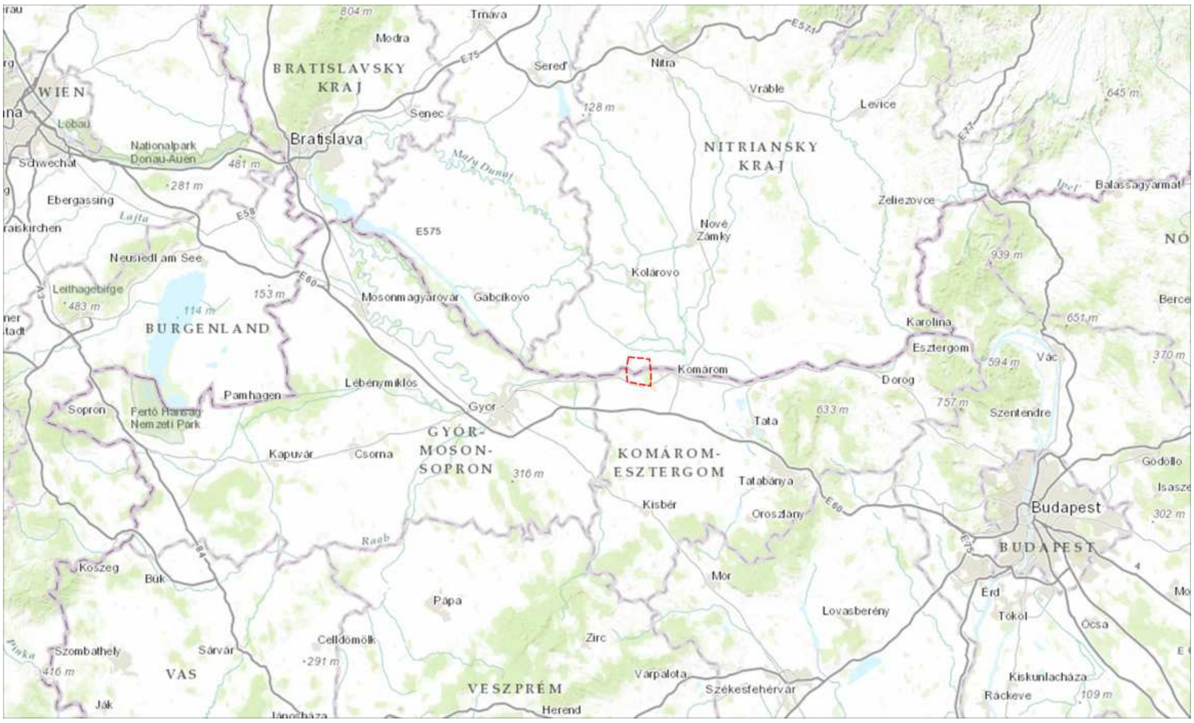


Figure 55.: Localization of the investigated area.

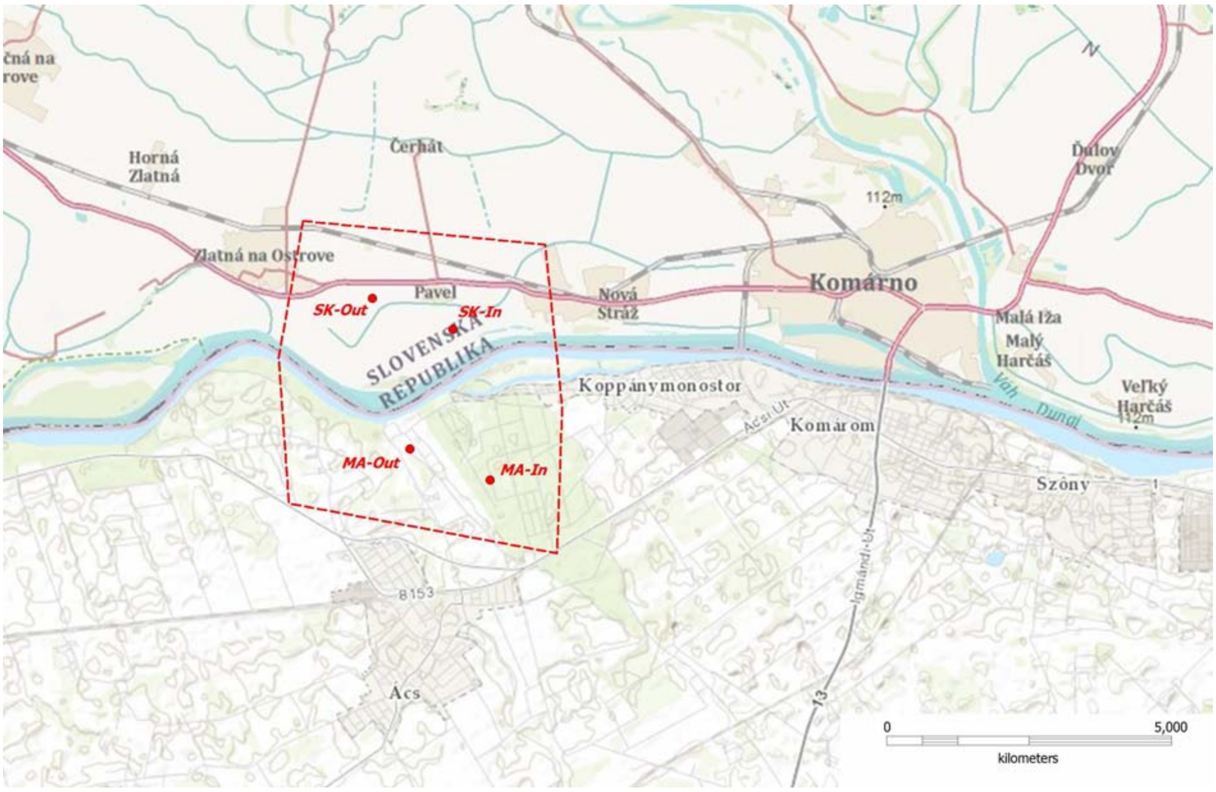


Figure 56: Model area and design of the doublet cluster.

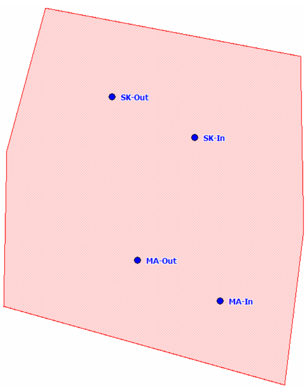
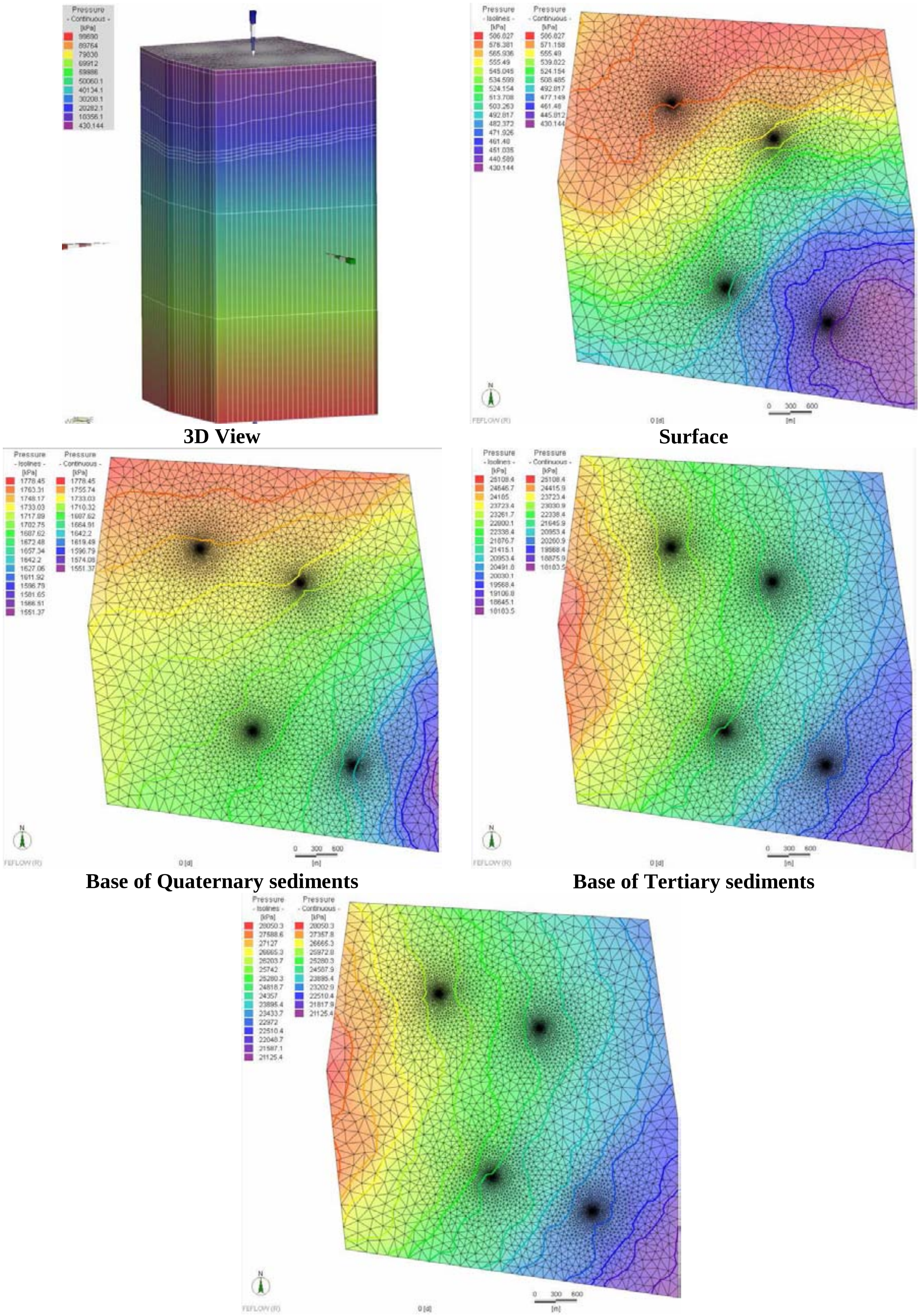


Figure 57: Scheme of the doublet cluster.

As was discussed previously, evaluated hydrogeological structure of geothermal waters is closed and also there is no water transfer on tributaries with surrounding structures. For modelling purposes has been chosen relatively small area of approximately 5x5 km (Figure 57). This areal extent was determined by the impact range options of geothermal water use by re-injection. For re-injection two wells were designed to pump the geothermal water and two for its subsequent re-injection. These two doublets are designed in the transboundary area of Slovakia and Hungary and in each country is one separate system. In the geothermal model, water is pumped from defined two wells and upon its use and cooling to 15°C is injected back into the geothermal structure.

From the geological point of view in vertical direction the model is divided into four geological layers. The detailed model geometry, the applied parameters and boundary conditions described in the “Report on the numerical modelling of the Danube basin pilot area – scenario modelling” (Svasta et al. 2013b).

For modelling the unsteady state of flow and heat transport is important in our model to have initially defined pressure and water temperature conditions in the modelled area. For purposes of determining these spatial properties was created steady flow / steady heat transport model. The simulation results of groundwater temperature and pressure are shown in Figure 58 and Figure 59.



Base of Mesosoic rocks

Figure 58. Water pressure values from steady state model of flow and heat transport modelling.

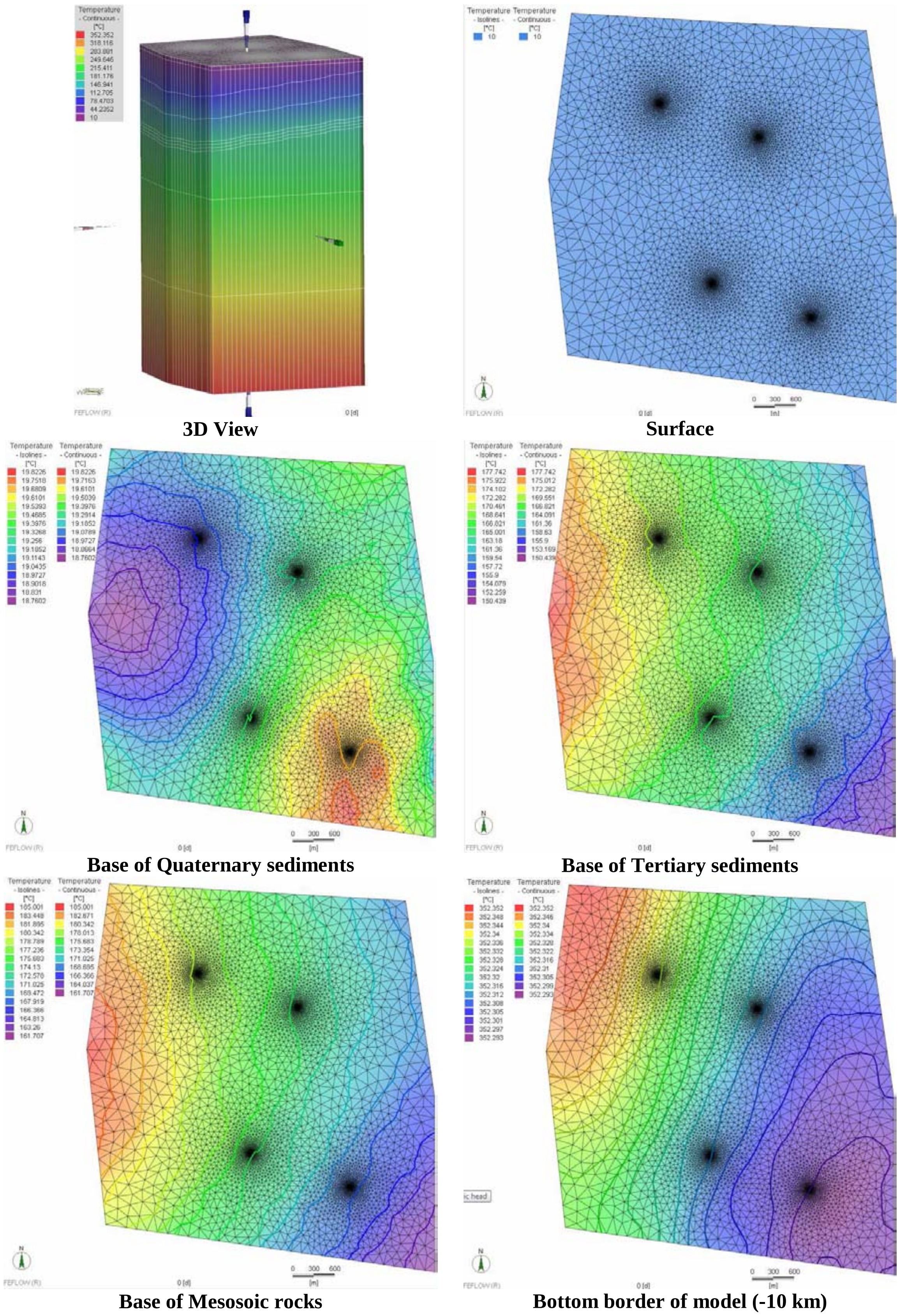


Figure 59: Water temperature values from steady state model of flow and heat transport modelling.

Adding the two well doublets a transient simulation were done to investigate the effect of the supposed utilizations both side the national border. Figure 60 shows the streamlines in the Slovak part of the geothermal water use system. As a result of this scenario it can be established, that during the system lifetime the cooled water does not reach the pumping system.

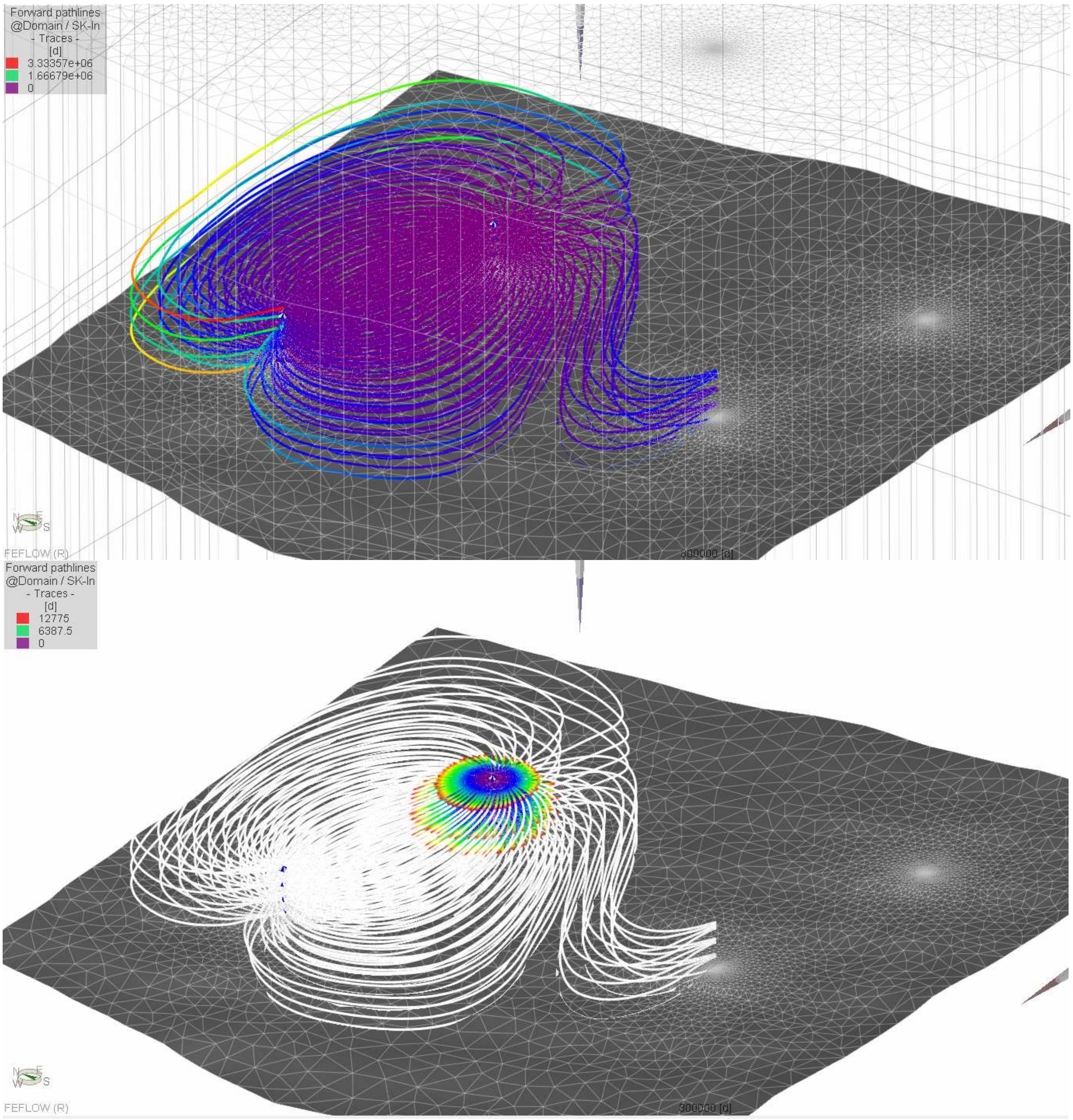
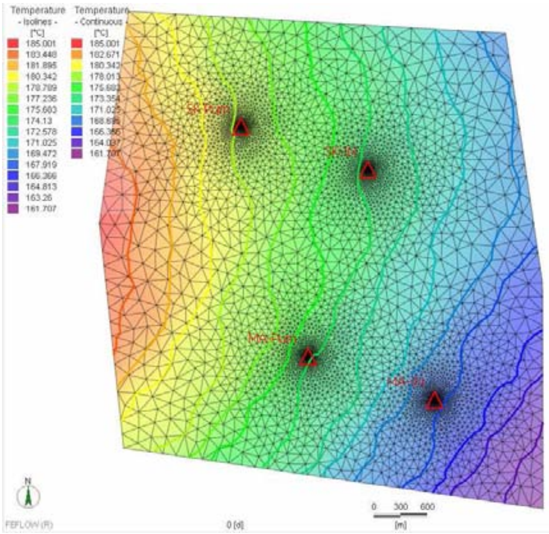
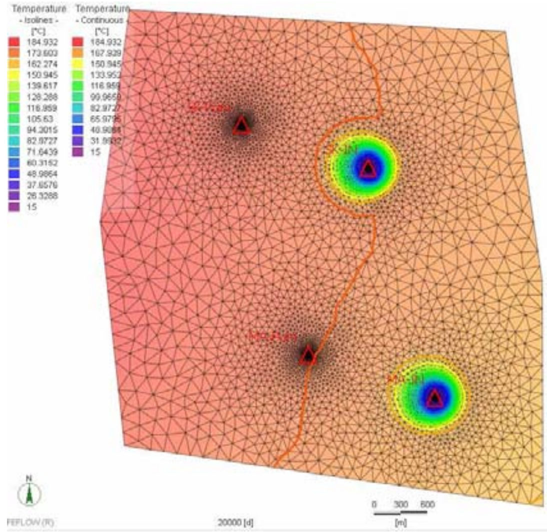


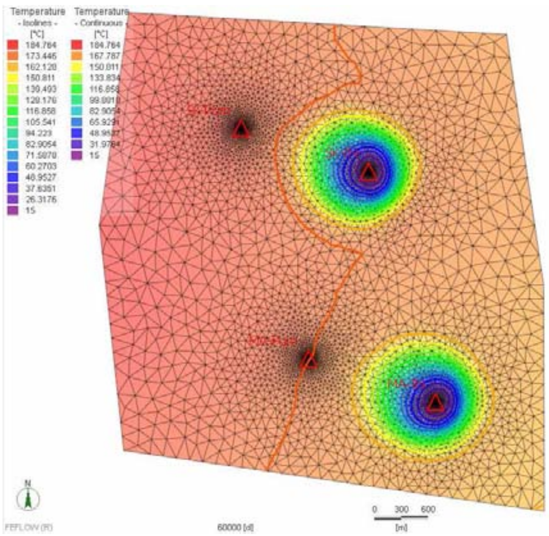
Figure 60. Visualization of flow pathlines of water (Top – long-term pathlines of water from Slovak-side injection well to pumping well; Bottom –flow pathlines radius – colored – after 35 years).

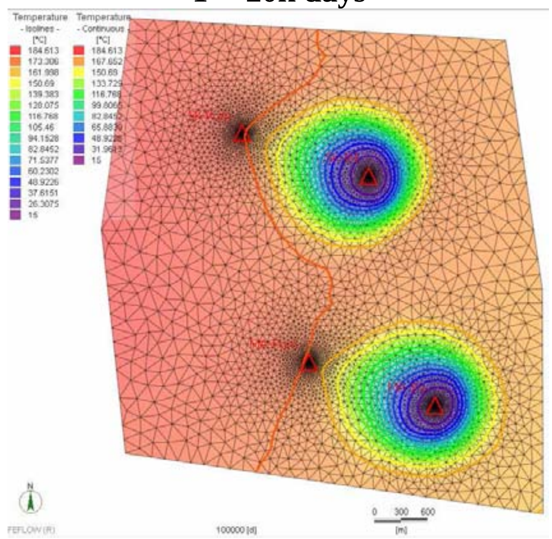
Figure 61 displays the water temperature changes at the base of carbonate collector. From this visualization is evident that the same character of heat transport is also within the Hungarian part of the geothermal system.



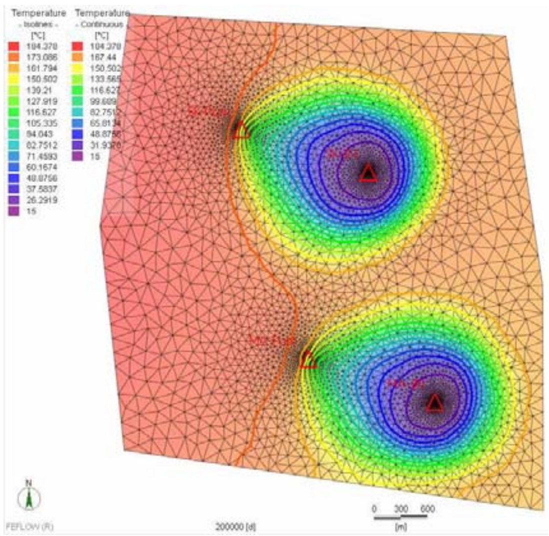


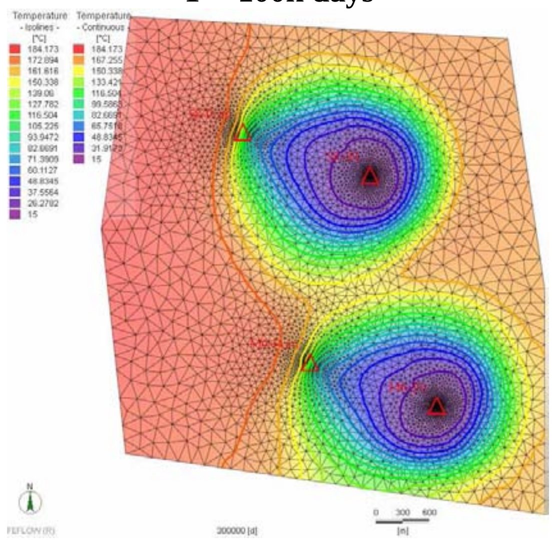
T = 0 days T = 20k days





T = 60k days T = 100k days





T = 200k days T = 300k days

Figure 61. Visualization of the water heat transport on the base of carbonate colector at pumping and injecting 50 l/s of water.

Figure 62 shows tempereature changes in time at different amounts of pumped and injected water.

The results of this modelling, we found that while using the projected system the cooled water does not receive form the injection area into area of pumping wells. This result is identical for all simulated amount of pumped and injected water. The injected water will begin impact the temperature in pumping wells after more than 100 years of use. This means that the evaluated structure is suitable for sustainable transboundary utilization of the geothermal water applying reinjection method by well doublet sheme.

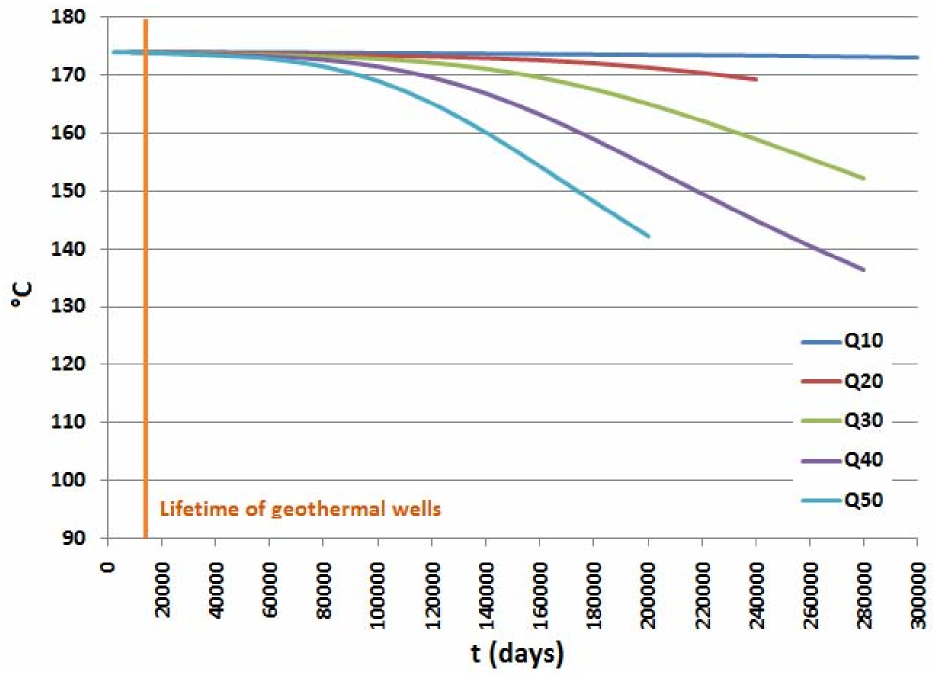


Figure 62. The course of changes in water temperature in the pumping well from the long-term point of view at different amounts of pumped/injected water.

In a new scenario it was studied, that how long doesl it take until the water temperature in the geothermal structure returns to its original natural values. Supposing a closed system the thermal values of the carbonate aquifer would be renewed for up to more than 2,500 years.

After closing this system, although it will take a very long time until the groundwater temperature returns back to the initial conditions, this effect has in hydrogeological structure relatively small spatial extent.

3.4 Komárno – Štúrovo model area

The karst system of the area is strongly affected by the bauxite and coal mining from the beginning of the 1950’s: the intense karst water abstractions seriously impaired the natural karst flow system and caused regional, transboundary depressions in the Transdanubian Range. Several lukewarm (15-30°C) springs had dried up due to this activity. It effected the balneological utilizations of these spring waters. After the mine closures the karst flow system started to regenerate and the beginning of the 2000’s the hydraulic heads continuously rising (e.g. Tata, Tatabánya, Patince, etc.) and some of the springs reactivated (e.g. Dunaalmás, Tata, etc.).

Besides this balneological utilization of the lukewarm waters in the northwestern part of the area (near Komárom and Komárno) in higher temperature conditions (~50-70 °C) the resources can be utilized for energetic purposes (eg. greenhouse heating, district heating). By the help of the scenario modelling we investigated the (transboundary) effects of theoretical dublet(s) in this NW area.

3.4.1 Model objectives

The goal of modelling that comprises 3D groundwater flow and coupled heat transport simulations was to provide information for better understanding of the hydrogeological and geothermal conditions in the Komárom – Štúrovo Pilot Area. The first step in modelling process and gives the basis for scenario analysis for sustainable utilisation of the regional groundwater and geothermal resources. In the second step we simulated the effects of the bauxite and coal mining on the karst system and the third step investigated the (transboundary) effects of theoretical dublet(s) in the most perspective area of Komárom and Komárno (geothermal facility and heat market are also took place here).

During the modelling we focused on the following:

- simulate and examine the effect of the mine water-abstraction on the karst flow system,
- investigate the recovering of the karst system after the mine closure,
- the possibility of further geothermal utilizations on the area via different extraction and injection scenarios in the perspective area.

The main questions are:

- What impact of energetic purposed abstraction(s) in Komárno and/or Komárom on thermal water production in Komárom and/or Komárno can be expected?
- What would be the impact(s) of the reinjection in a geothermal doublet in this area?

3.4.2 Modelling methodology

The simulation of the different scenarios is based on the existing steady state flow and coupled heat model (Gáspár et al 2013a). In this part we present only the results and the conclusions of the scenario modelling (the previous chapter is summarized the steady state model).

In this step (the first was the steady state modelling) we investigate two main kind of scenario. The first "scenario-group" was the effects of the water abstractions during the bauxite and coal mining in the past. The second is the modelling of the effects of a hypothetical geothermal doublet in the transboundary region of Komárom-Komárno. The aims were the following:

- simulate and examine the effect of the mine water-abstraction on the karst flow system,
- investigate a possible increasing of the drinking water needs,
- the possibility of future geothermal utilizations on the area.

To simulate and examine the effects of the mine water-abstraction on the karst flow system we made three different versions/scenarios due to the quasi-equilibrium condition during the period of the mine water abstraction:

- Scenario 1: Mine water abstraction with the yield in the late 1980's.
- Scenario 2: Reduced water abstraction with the yield in the early 2000's.
- Scenario 3: Drinking water abstractions in the area after the mine closures.

To simulate the effects of a hypothetical geothermal utilization on the area we investigate different extraction and reinjection scenarios in the perspective area of Komárom-Komárno. The distance between the (abstraction and reinjection) wells is constant, 1000 m. The yield is 1500 m^3/day, the temperature of the injected water is 15 °C. The investigated scenarios are the following:

- Scenario 4: Geothermal utilization without reinjection in Slovakia,
- Scenario 5: Geothermal utilization with reinjection in Slovakia,
- Scenario 6: Geothermal utilization without reinjection in Hungary,
- Scenario 7: Geothermal utilization without reinjection in Hungary,
- Scenario 8: Geothermal utilizations without reinjection in both countries,
- Scenario 9: Geothermal utilizations with reinjection in both countries.

All the applied parameters, boundary conditions and the detailed description of the scenario model is described in the "Report on Komárom - Štúrovo Pilot Area scenario modeling" (Gáspár et al 2013b).

3.4.3 Results of the Komarno- Štúrovo scenario models

3.4.3.1 The effects of the mine water abstractions

The natural state of the system is described in the steady state Pilot Area report (Gáspár et al 2013).

During this section of the scenario modelling we focused on the connection between the cold karst water abstractions and the behaviour of the lukewarm part of the karst flow system. We simulated the following scenarios due to the quasi-equilibrium condition during the period of the mine water abstraction:

- Scenario 1: Mine water abstraction with the yield in the late 1980's.
- Scenario 2: Reduced water abstraction with the yield in the early 2000's.
- Scenario 3: Drinking water abstractions in the area after the mine closures.

In the middle of the 1950's two main mining regions worked and abstracted water from the aquifer in Tatabánya and Dorog (HU). The abstractions continuously increased in the following 10-15 years. From the end of the 1960's started to decrease in the Dorog region, but it increased/stagnated in the Tatabánya region. For the late 1980's the abstractions greatly decreased in the Tatabánya region and started to increase in the Dorog region, but quasi-equilibrium was set in the area. The mining had a strong effect on the karst system: from the 1950's the yield of the lukewarm Tata springs in the main discharge area started to reduce and for the end of the 1960's/the beginning of the 1970's the springs disappeared.

Figure 63 is indicated the modelled hydraulic head in the Mesozoic karst aquifer: the water abstraction is similar then in the late 1980's; a quasi-equilibrium can be observed in the system. So when we produce as much as karst water than in the late 1980's an average 30 m depression can be experienced in the whole region: a huge, 60-70 m depression can be observed in the area of Tatabánya and at least 10 m depression in the Esztergom area. In the NW part of the area near Komárom and Komárno app. 30 m depression can be observed in this scenario (Figure 64). The original app. 130 mAsl water level in the Tata area was decreased below 100-90 mAsl, so such conditions the springs couldn't work.

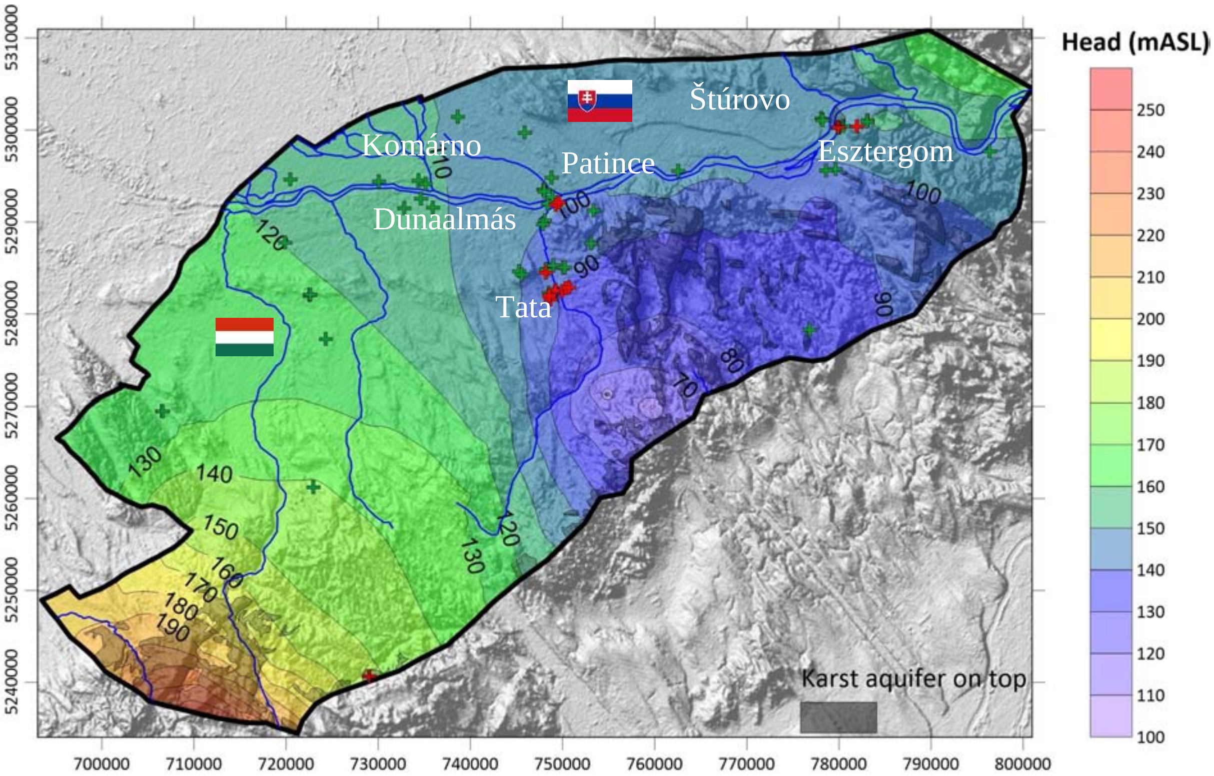


Figure 63. Modelled hydraulic head in the Mezozoic karst aquifer – water abstraction as much as in the late 1980's (Scenario 1)

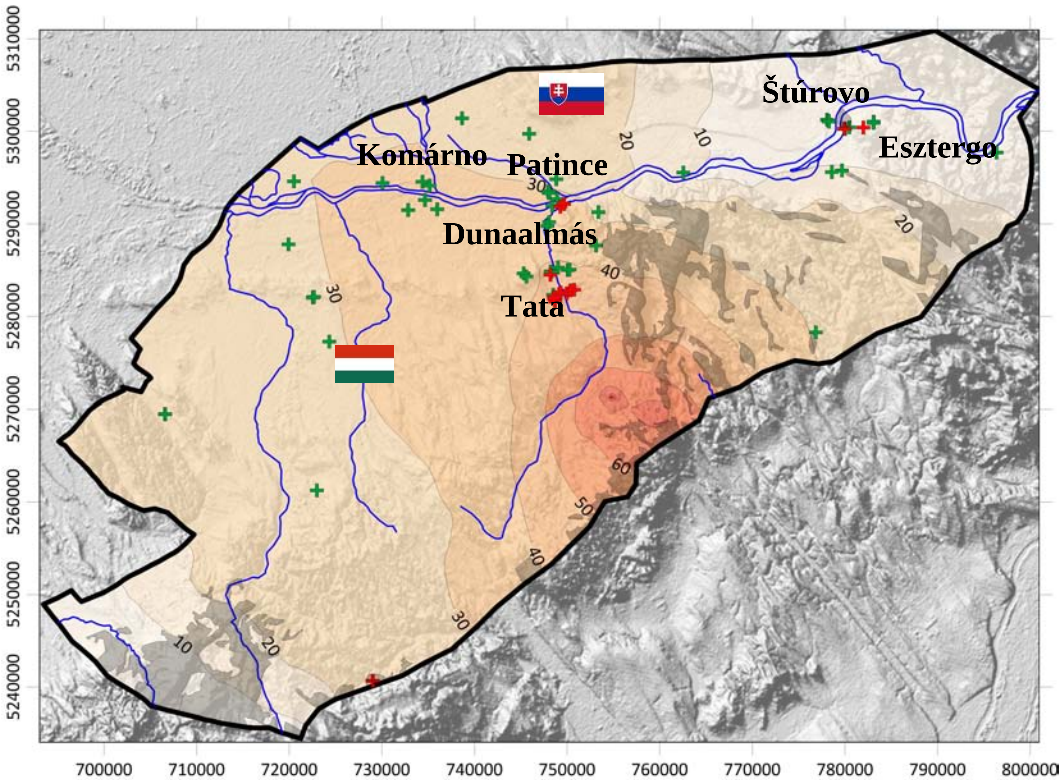


Figure 64. Modelled depressions in the Mezozoic karst aquifer (Scenario 1)

From the end of the 1980's/the beginning of the 1990's the mine closures started and the karst system started to slowly regenerate. The abstractions in the Dorog region strongly decreased also in the Tatabánya region, where only the drinking water abstractions are continued.

Figure 65 is demonstrated the modelled hydraulic head in 2000's, after the mine closures. In the main abstraction sites the wells produce as much as water than in the 2000's. At steady state conditions the 60-70 m depression (as in the late 1980's) in the area of Tatabánya decreased to 30-40 m (Figure 66), but in the Tata area the increasing of the water level is not enough that the springs work again. In the area of Komárom-Komárno we can see app. 20-25 m lower water levels than the natural levels.

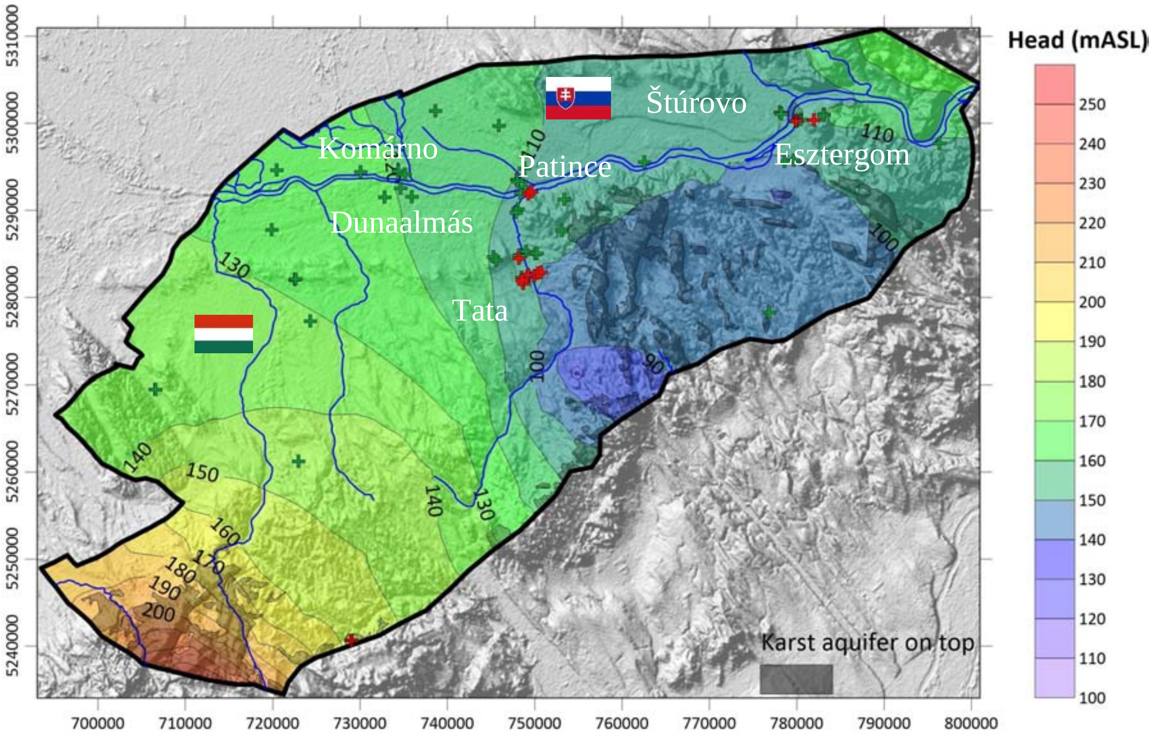


Figure 65. Modelled hydraulic head in the Mezozoic karst aquifer – water abstraction as much as in the 2000's (Scenario 2)

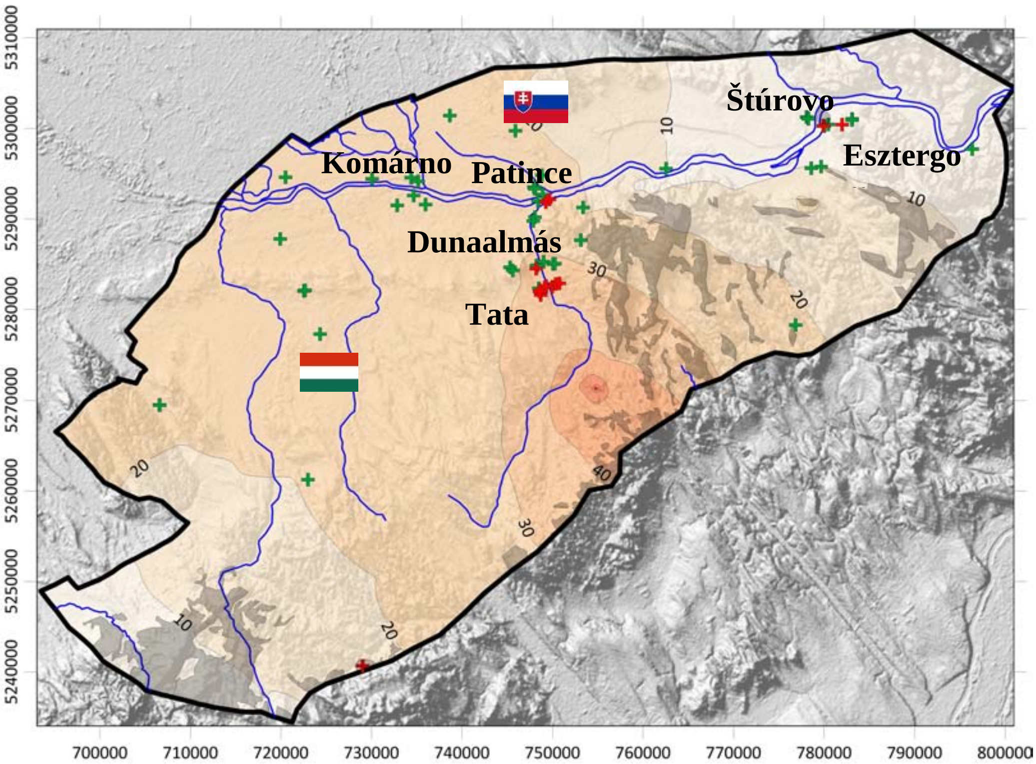


Figure 66. Modelled depressions in the Mezozoic karst aquifer (Scenario 2)

Our third scenario is the modelling of the effect of the drinking water abstractions after the mine closures (Figure 67). The main drinking water pumping sites are near Tatabánya and Esztergom. The deepest depression exists near Tatabánya, where around 30 000 m3/day karst water is abstracted; at steady state conditions the karst water abstraction results 20-30 m water level drop in the local environment, but 10-20 m depression also can be observed in the whole region also (Figure 68). In the Tata area the increasing of the water level now is enough that the springs in Dunaalmás and Tata regenerate and work again. In the area of Komárom-Komárno we can see app. 15-20 m lower water levels than the natural levels.

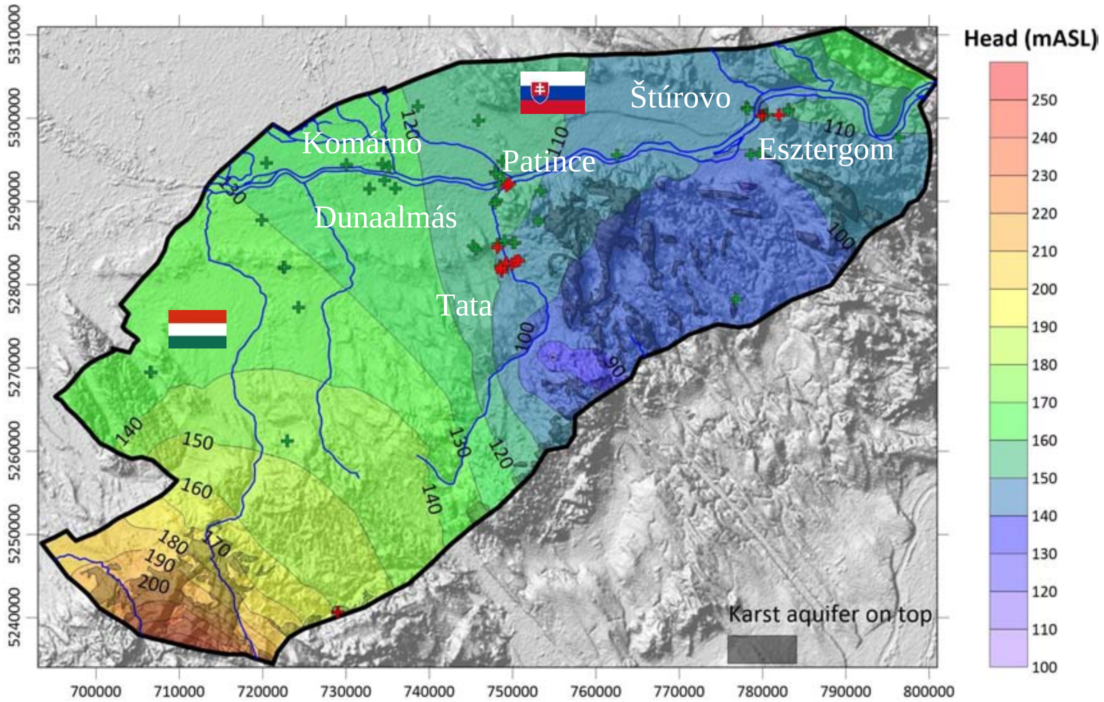


Figure 67. Modelled hydraulic head in the Mezozoic karst aquifer – drinking water abstraction as much as nowadays (Scenario 3)

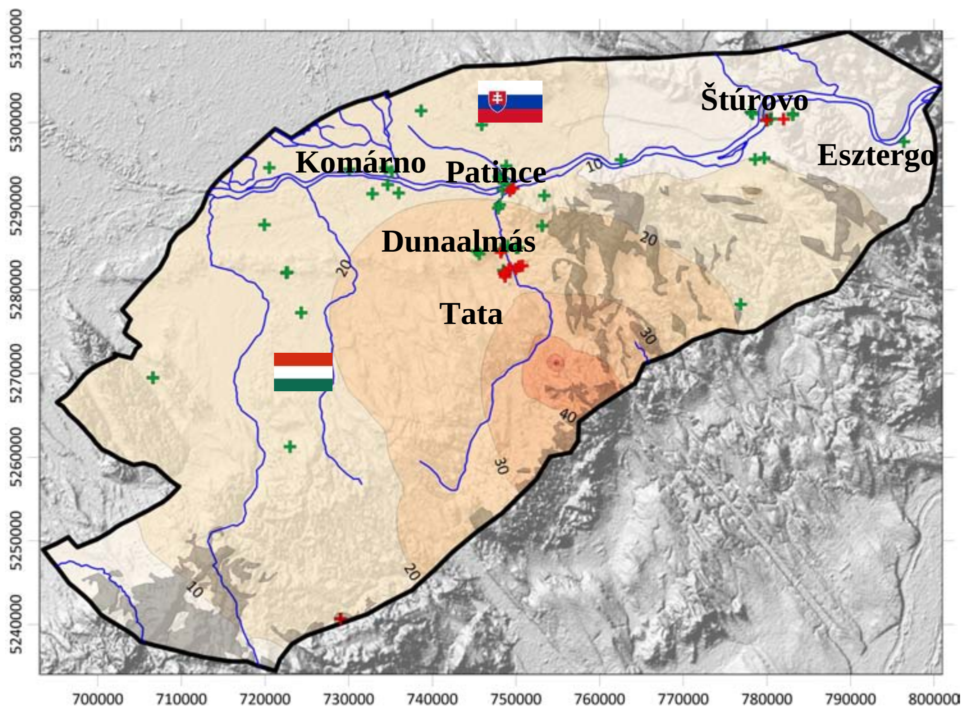


Figure 68. Modelled depressions in the Mezozoic karst aquifer (Scenario 3)

3.4.3.2 The effects of the hypothetical geothermal utilization(s)

In order to investigate the thermal effects of an operating geothermal utilization, theoretical geothermal well doublets were set in the area of Komárom-Komárno close to the national border (Figure 69). The scenario 4 – 9 represent the operation of the geothermal system with and without reinjection well(s) in one of or both countries assuming infinite operation time. In both countries two reinjection well locations were modelled. In this step we investigated 6 scenarios:

- Scenario 4: Geothermal utilization without reinjection in Slovakia,
- Scenario 5: Geothermal utilization with reinjection in Slovakia,
- Scenario 6: Geothermal utilization without reinjection in Hungary,
- Scenario 7: Geothermal utilization without reinjection in Hungary,
- Scenario 8: Geothermal utilizations without reinjection in both countries,
- Scenario 9: Geothermal utilizations with reinjection in both countries.

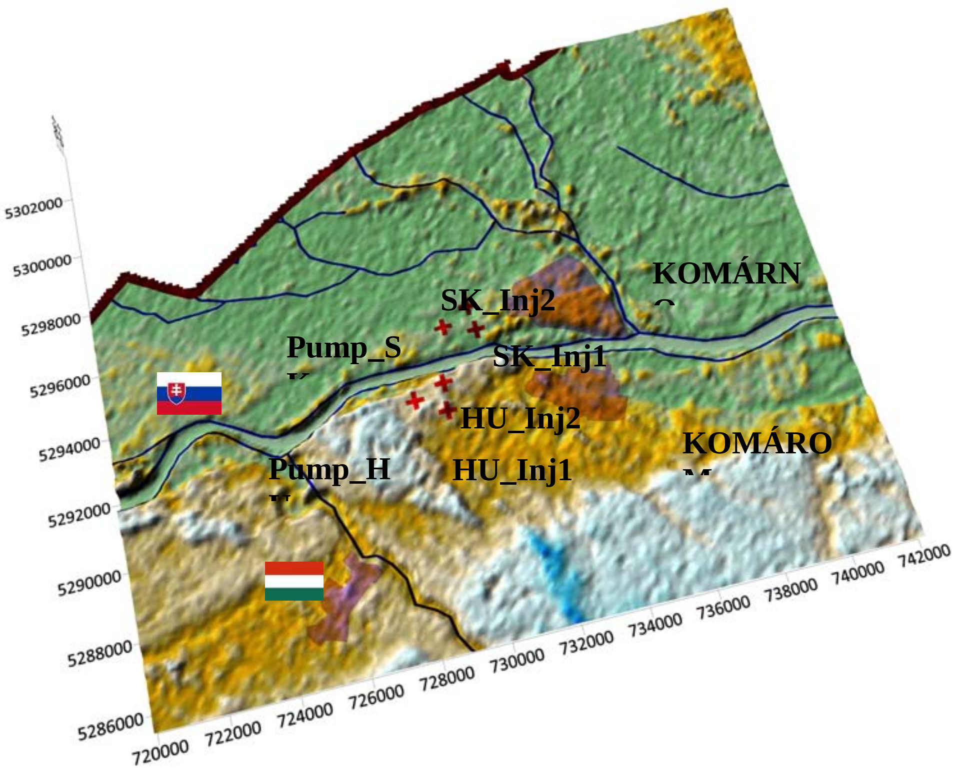


Figure 69. Theoretical well doublets in the area of Komárom - Komárno

The parameters of the investigations were the following (Table 8):

Table 8. Model parameters during the scenario modeling

Parameter	Value
Q_{term}	1 500 m^3/day
Q_{inj}	1 500 m^3/day
T_{inj}	15 °C
Well distance	1 000 m
Reservoir	T_3 karstic aquifer/reservoir
Reservoir depth	1 100 – 1 600 mBf

3.4.3.2.1 Geothermal doublet in Slovakia

Scenario 4 - 5 included the simulation of a geothermal utilization in Slovakia with (scenario 4) and without (scenario 5) reinjection well. For the purpose of determining the effects of planned utilization near Komárno two different reinjection locations have been developed.

In order to investigate the effects of the reinjection first the “pure” depression was modelled (pumping without reinjection). On the next Figure (Figure 70) we can see the steady state drawdown around the pumping well installed west from Komárno. According to the simulation results, the pumping well had more than 7 m depression without reinjection. The depression extends Hungary and dropped to 4.5 – 5 m around Komárom. If the reinjection well was operating, the maximum depression around the pumping well dropped to 2 m, while a maximum pressure increasing around the reinjection well is 2.2 m; the reinjection well also had a thermal influence in a circle of app. 4 km radius around the well (Figure 71-Figure **72**).

From the modelled depression we can see the positive effects on the depressions: the original depression (without reinjection) decreased more than 5 m around the pumping well (with reinjection). By the help of the reinjection no significant transboundary effects existed on the potential and temperature distribution. At the same time we have to pay serious attention to the location of the (reinjection) well(s) to minimalize the transboundary effects.

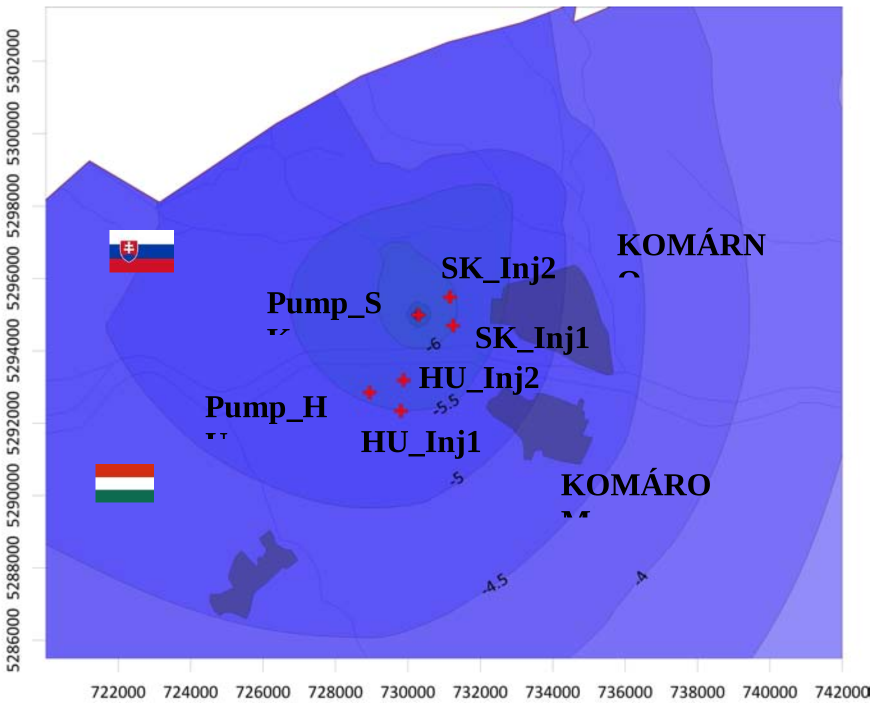


Figure 70. Steady state depression around a theoretical well near Komárno. No reinjections well exists.

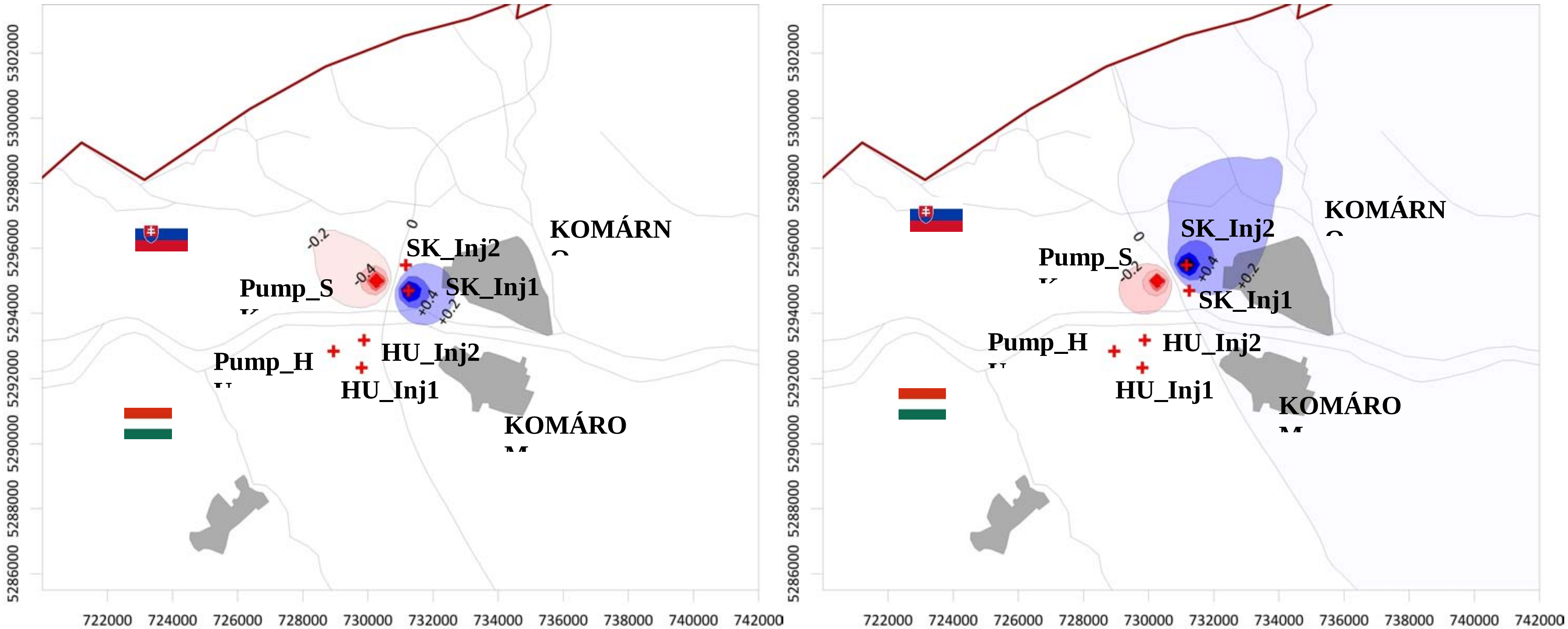


Figure 71. Steady state depression and pressure increasing around a theoretical doublet near Komárno (Scenario 5a).

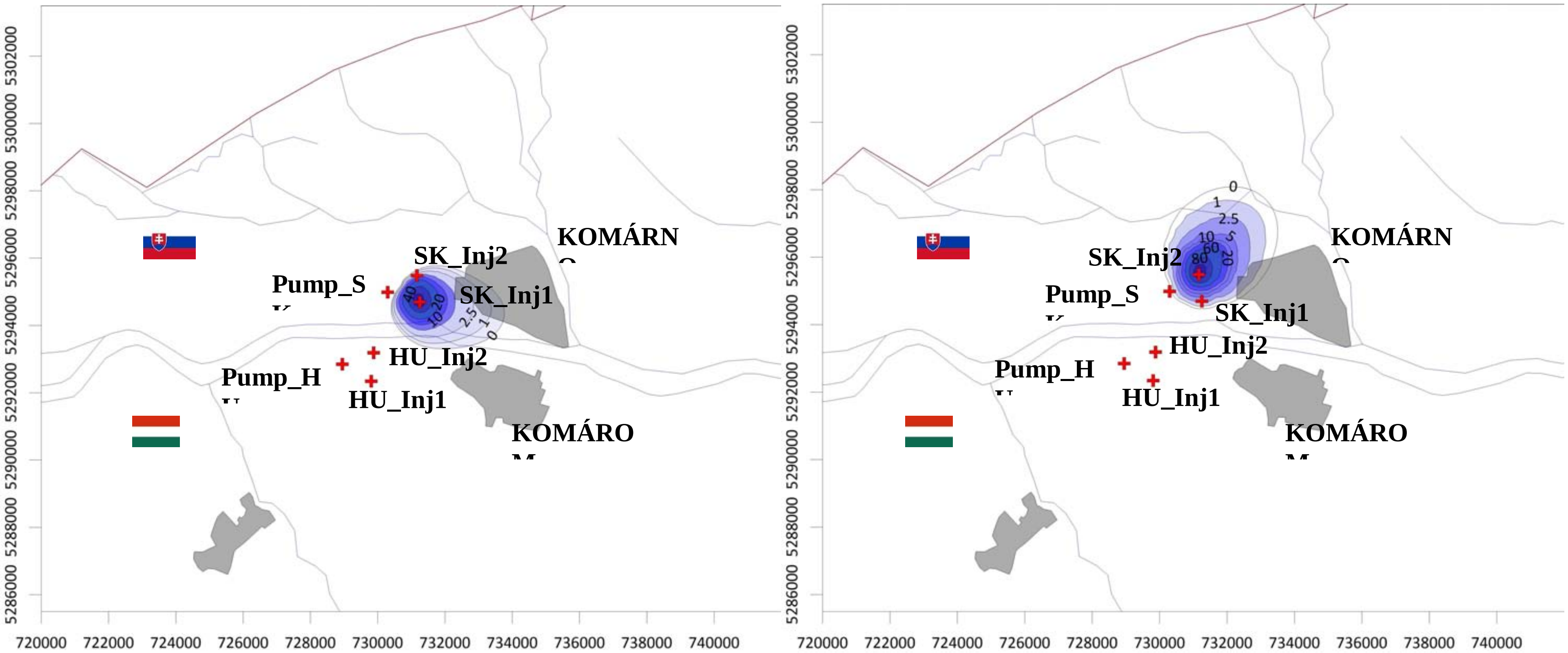


Figure 72. Steady state modelled thermal influence around a theoretical reinjection well near Komárno (Scenario 5b).

3.4.3.2.2 Geothermal doublet in Hungary

The next two scenarios simulated the effects of a theoretical geothermal utilization in Hungary with (scenario 6) and without (scenario 7) reinjection well(s). In the first step we simulated the depression in the pumping well west from Komárom (Figure 73). The modelled depression around a pumping well is app. 6.5 m (without reinjection). When the reinjection well was operated the maximum depression decreased and dropped to 1.5 m at steady state conditions (Figure 74). The thermal influence of the reinjection well is a circle of app. 2.5 km radius around the well (Figure 75).

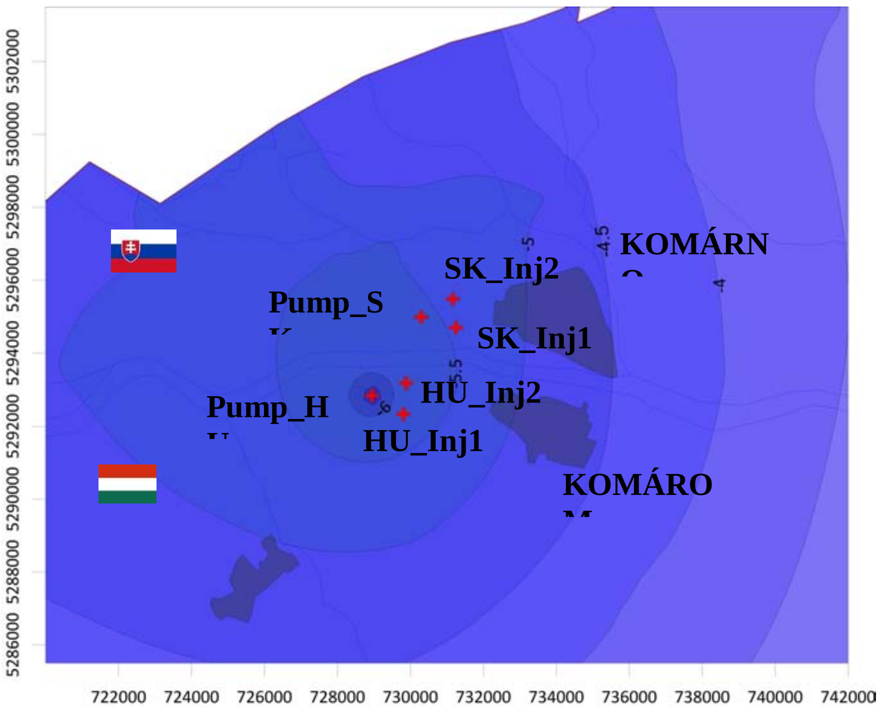


Figure 73. Steady state depression around a theoretical well near Komárom. No reinjections well exists.

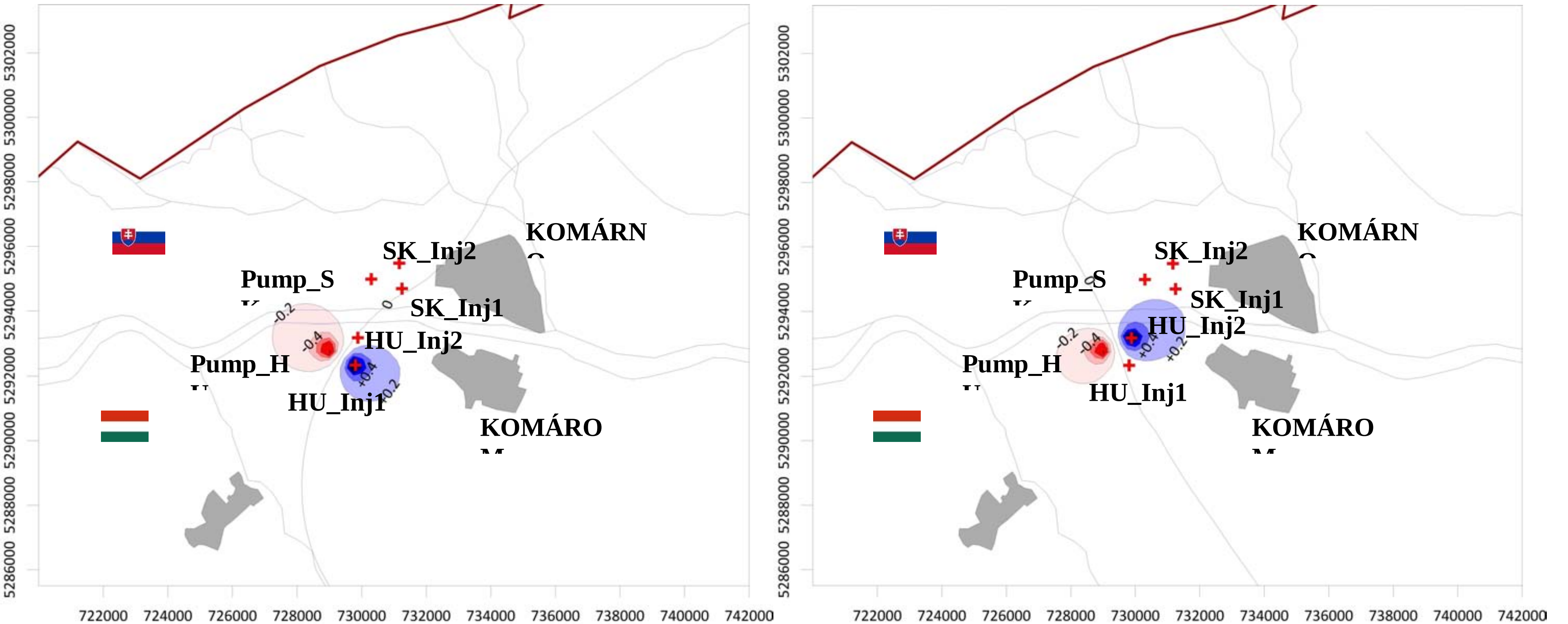


Figure 74. Steady state depression and pressure increasing around a theoretical doublet near Komárom (Scenario 7a).

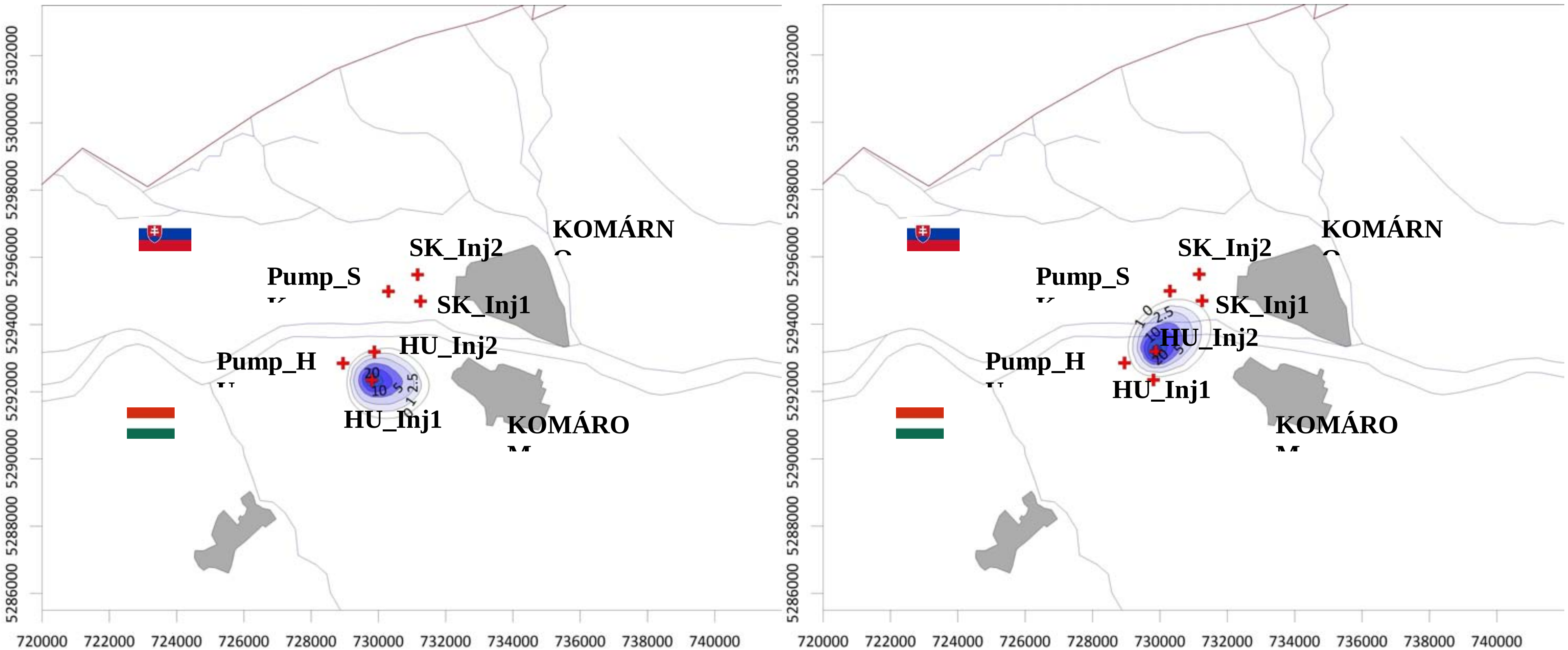


Figure 75. Steady state modelled thermal influence around a theoretical reinjection well near Komárom (Scenario 7b).

3.4.3.2.3 Geothermal doublets in both countries

Scenario 8 - 9 included the simulation of a geothermal utilization in both countries with (scenario 8) and without (scenario 9) reinjection well. The pumping scenario (scenario 8) resulted more than 12 m depression around the pumping wells in both countries (Figure 76). To decrease this great depression we operated reinjection wells in the model. The hydraulic impacts of the pumping wells significantly decreased due to the reinjection: the app. 12 m drawdown dropped to maximum 2.5 m (Figure 77). Due to the natural flow system the Hungarian pumping well and the Slovakian reinjection well had the more extensive impact areas (Figure 77). The thermal influence of the reinjection wells (Figure 78) was more extensive than in the previous scenarios: a 5*6 km ellipse shaped area around the wells (Figure 71-Figure 72).

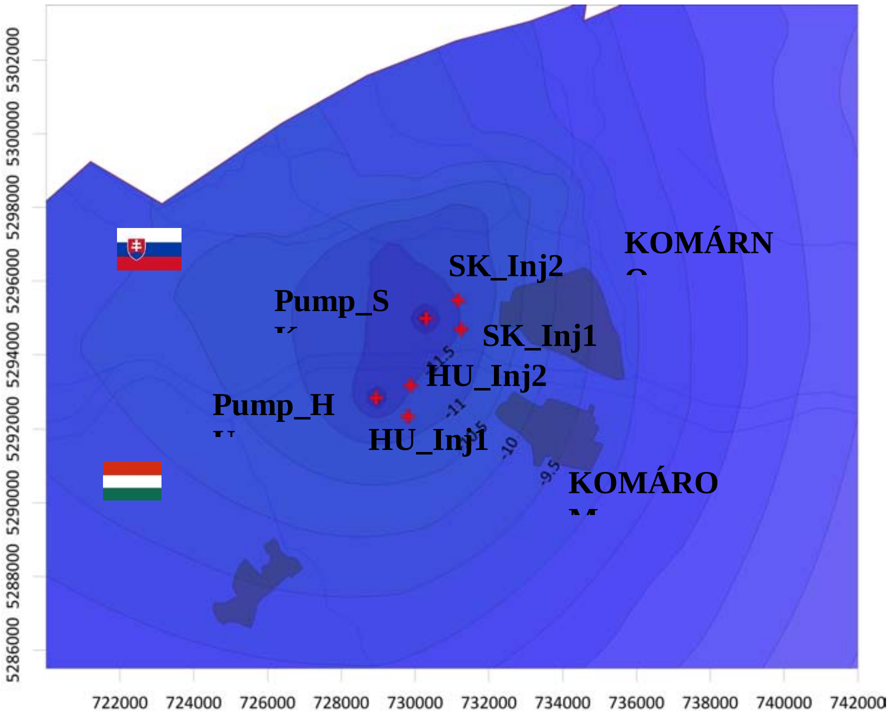


Figure 76. Steady state depression around a theoretical wells near Komárno and Komárom. No reinjections well exists.

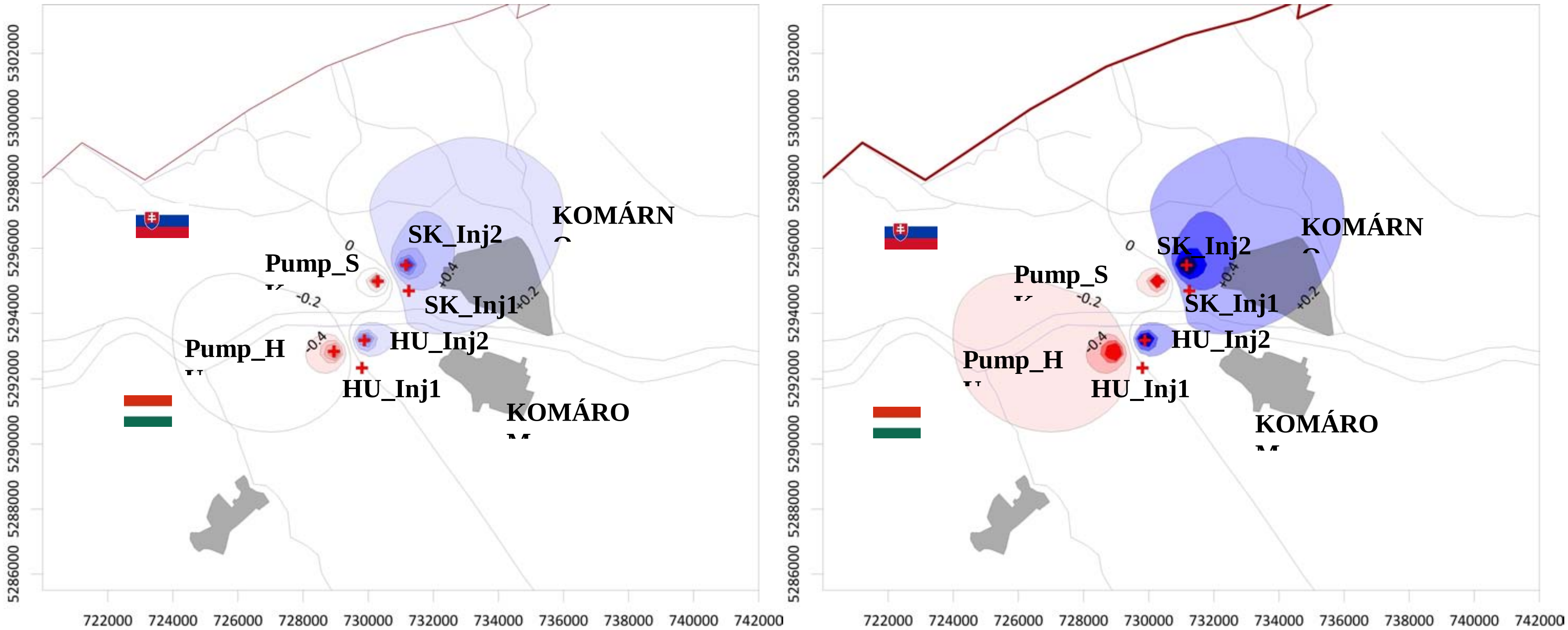


Figure 77. Steady state depression and pressure increasing around a theoretical doublets (Scenario 9a).

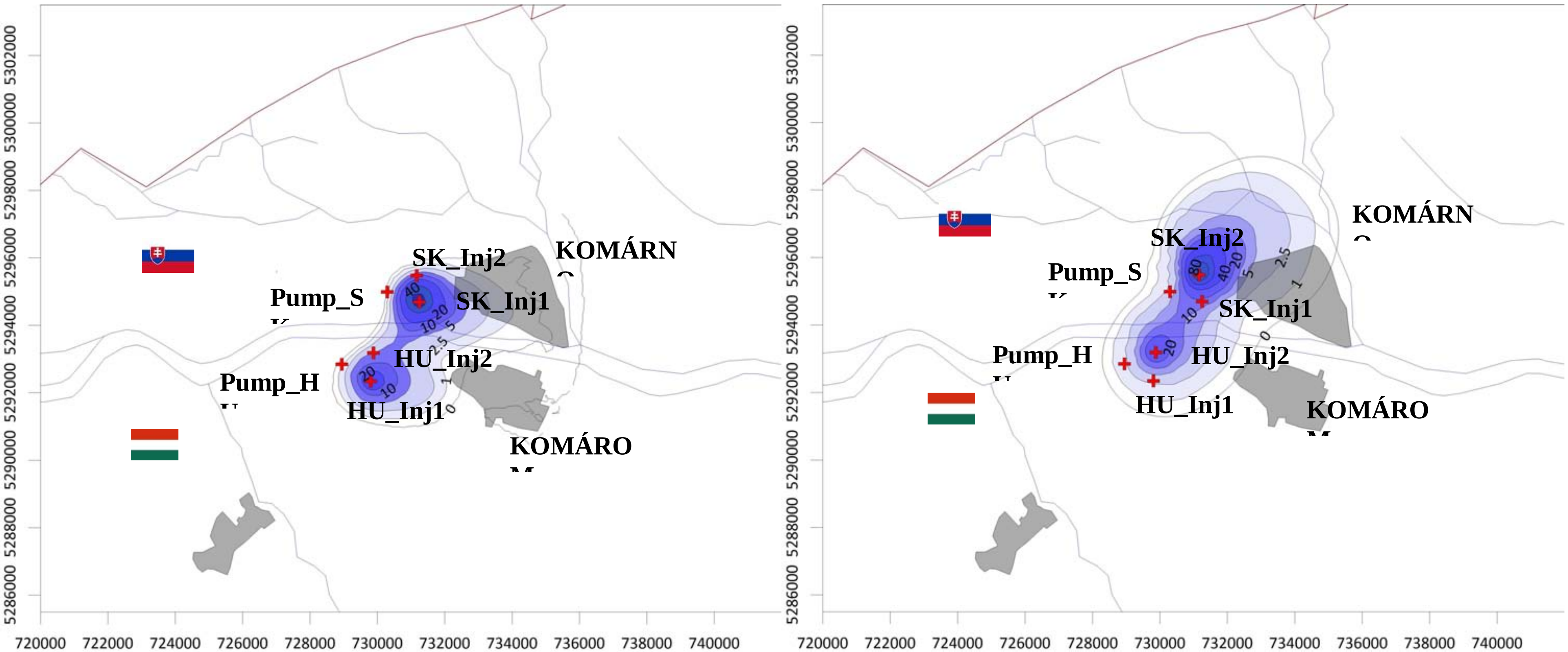


Figure 78. Steady state modelled thermal influence around a theoretical reinjection wells (Scenario 9b).

3.5 Vienna Basin model area

Located at the north-eastern part of the Transenergy region the Vienna Basin pilot area is shared by the involved countries Austria and Slovakia. Currently the use of natural thermal water does not play an important role in the pilot area. energetic use of the existing thermal water in the central and northeastern part of the Vienna Basin has not been implemented yet, although there are great resources estimated. In contrast the subsurface of the Vienna Basin has been extensively used for the production of hydrocarbons since decades. However, as the production of crude oil continuously decreases since the past 40 years it offers future possibilities for hydrogeothermal utilization in the Vienna Basin. Increasing future geothermal use may also offer challenges and risks of conflicts due to:

- Competitive subsurface use between hydrocarbon production and geothermal heat recovery
- Over-exploitation due to intense use especially at near border regions due to a lacking trans-boundary management of natural thermal water.

In order to avoid future conflicts and assist a reasonable and sustainable future use of natural thermal water in the Vienna Basin a coupled groundwater flow and heat transport model was developed.

The Wetterstein-Dolomite geothermal reservoir has been figured out to be the most promising trans-boundary geothermal reservoir pilot area. Because of the high salinity of the thermal waters of this aquifer the trapped thermal water is not suited for balneological purposes. Hence, the only possible utilisation can be a pure energy usage, realized by a doublet installation with complete reinjection of the thermally deployed brine. As this Hydrogeothermal Play has not been used for geothermal use yet, the scenario modelling is focusing und possible future near-boundary utilization schemes.

3.5.1 Model objectives

The main objectives of the detailed scenario modelling are represented by:

- Analyses of the hydraulic influence of (i) fault systems and (ii) the geometrical shape of the reservoir on the coupled hydraulic and thermal conditions of different doublet-use scenarios, represented by different locations and operational settings.
- Estimation of the technically extractable amount of heat by assuming several hydrogeothermal doublets.

3.5.2 Modelling methodology

The area of interest shows a lateral extension of about 15 km x 3 km, striking approximately along a SE-NW direction (Figure 79). The river March and the Austro-Slovakian boarder crosses the body right in the middle in N-S direction. On the Austrian side, large parts of the watersides of the river March are protected by “Natura 2000 - European Nature Reserve”. Hence no surface hydrogeothermal installations, such as wells or heating facilities are considered to be legally allowed in this area. In opposite “Záhorie Protected Landscape area” is situated on the Slovakian side along the river Morava / March. Despite of this fact, the location of the Slovakian hydrogeothermal doublets has been set within this protection area

nearby the village of Visoká pri Morave. This was done in order to investigate possible trans-boundary hydraulic flow and thermal influences at the reservoir.
On the Austrian side of the reservoir three abandoned hydrocarbon wells (SCH-T1, SCH-1 and BG-4) could possibly be used (re-entry) for geothermal usage and supply the Gänserndorf / Strasshof area (approx. 20.000 inhabitants) with energy (heat and electric power). At least the above mentioned drillings have proofed the evidence of thermal water at the investigated reservoir. On the Slovakian side we considered the Zohor – Láb – Záhorská Ves triangle containing about 10.000 inhabitants as a plausible area for geothermal supply of heat.

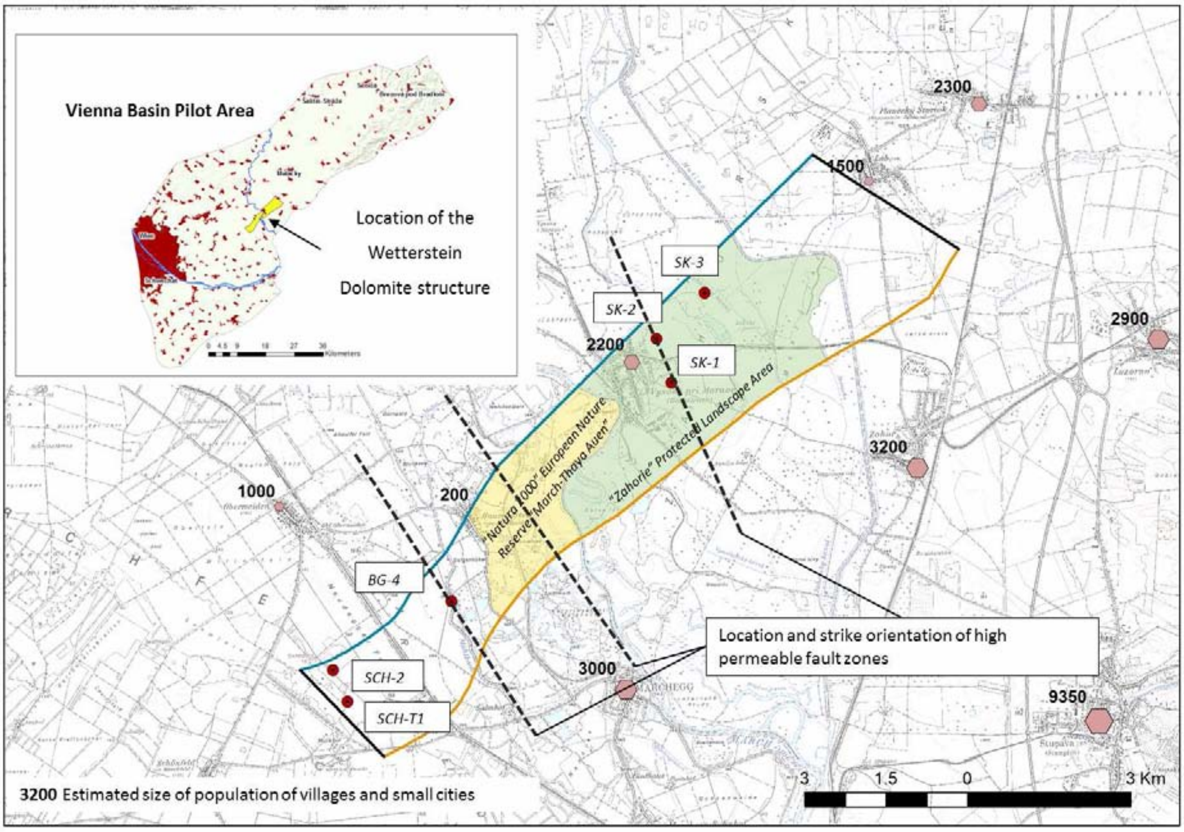


Figure 79. Outline of the scenario model „Schoenfeld-Láb". The red dots show possible well locations, the size of the hexagons display the population of the bigger settlements in the vicinity of the hydrogeothermal play 'Wetterstein-Dolomite'.

Two of the three selected wells on the Austrian side of the model-block drilled the Wetterstein-Dolomite complex at a tectonically undisturbed position, while one well hits a known fault zone. Since there is no information about fault systems on the Slovakian part of the Aquifer, one exemplary fault is assumed, where two of the three hypothetic wells are located. Hence all different 'fault'- 'no fault scenarios' have been considered by combination of different wells in terms of geothermal doublets. The applied matrix of combination is shown in (Figure 80). Previous studies have shown that a geothermal exploitation can only be economically viable with a minimum yield of 100 l/s, a production temperature of at least 100 to 120 ° C and (regarding the investment costs and return of investment) the drilling depth. In order to fulfil these "rule of thumb" criteria, the depth of the well screens is ranging between 3 and 4 km and the yield is assumed constant (100 l/s). To include the fractured character of the reservoir, the well screens are realised using five point sources/sinks each.

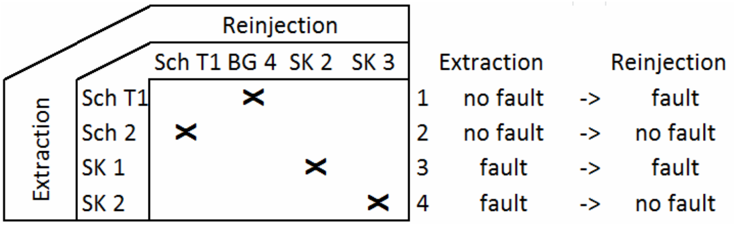


Figure 80. Compilation of the considered doublets.

The thermal parameters can be adopted from the steady-state model of the pilot area (Goetzl et al. 2013a). In addition flow properties have to be added to the model. In this context the following assumptions have been applied: The Wetterstein Dolomite is a typical fractured reservoir. Hence, the flow behaviour is, strictly speaking non-Darcy. A common approximation for fractured reservoirs is the tensor form of the Darcy equation, where it is possible to incorporate the conductivity as anisotropic values. Log interpretations done in previous studies indicate a main fracture orientation of the Wetterstein Dolomite of 110/70 (strike/dip-Notation) towards North-Northeast.

Inside the fault zones crossing the Aquifer the conductivity is expected to be elevated. No exchange between the Neogene Sediments and the Dolomite is expected, so a very small conductivity is assigned for the sedimentary layers above. There is an evidence for an approximately 50 metres thick layer of Breccia at the base of the Neogene.

At each modelling run two doublets - one on the Austrian and one on the Slovakian side of the reservoir - are simulated at a time, so basically two runs are sufficient to simulate the combinations described in chaper **Hiba! A hivatkozási forrás nem található.**. Doublette [1] and [3] (Figure 80, Table 9) were considered in 'scenario 1' and the doublettes [2] and [4] in 'scenario 2'. Additionally, the influence of a 50 metres thick layer of Breccia at the base of the neogene Sediments was surveyed in 'scenario 3'.

As no hydrogeothermal utilization has been developed yet for this Hydrogeothermal Play, the applied scenario modelling is focussing on the coupled hydraulic – thermal influence of the anisotropic shape of the reservoir (low ratio of lateral- to the longitudinal extension of the reservoir) and assumed high permeable discrete fault zones, which may act as flow channels for the injected cold water. In addition hydrocarbon drillings in the vicinity and partly within the Hydrogeothermal Play itself show the evidence of a high hydraulically conductive porous aquifer at the lowermost 50 meters of the Neogene deposits, which are directly overlaying the target reservoir. This assumed porous sedimentary layer would lead to an coupled hydraulic – thermal interflow between the wells of the doublet, which may be different to the fault related interflow. As the fault related interflow acts as a discrete flow channel, the porous layer interflow may act as a volume related interflow, which may lead to a later but smoother thermal breakthrough at the production well of a doublet. In contrast a channel related interflow is, in the worst case (both wells are located at the same conductive fault zone), expected to lead to a short thermal breakthrough time and an massif decrease of the temperature at the production well.

Table 9.: Overview on the investigated scenarios

Scenario	Involved Doublets	Description
1	Austria: Sch2 (P) – BG4 (I) Slovakia: SK1 (P) – SK2 (I)	**High influence of fault zone**: At the Austrian doublet the injection well is located at the fault zone, which may lead to a fast propagation of the cold water plume. In contrast it also may reduce the technical effort of the water injection. At the Slovakian side both wells are influenced by a high permeable fault zone, which may strongly enhance both hydraulic and thermal short-cuts.
2	Austria: Sch2 (P) – Sch (I) Slovakia: SK2 (P) – SK3 (I)	**Moderate influence of fault zone**: Both wells of the Austrian doublet are located at tectonically undisturbed positions of the reservoir, which may on one hand lead to enhanced hydraulic resistivity at the wells but on the other hand inhibits thermal short-cuts. At the Slovakian doublet the production well is located within a high permeable fault zone. As the injection well is located at an assumed tectonically undisturbed position of the reservoir, the thermal breakthrough may be inhibited on the one hand, but the effort in order to inject the used water may be raised on the other hand.
3	Austria: SchT1 (P) – Sch 2(I) Slovakia: SK2 (P) – SK3 (I)	**Influence of high permeable porous layer**: Existence of a highly conductive layer at the lowermost 50 meters of the Neogene sedimentary deposits upon the reservoir, which may lead to thermal shortcuts. Additionally, the well screens on the Austrian side are set directly underneath the brecciated high permeability layer to demonstrate a quick thermal breakthrough.

P... Production well, I... Injection well

It is also making a difference which of the two wells of a doublet is located at the fault zone. There are 3 different schemes, which can be distinguished:

i. <u>Both wells are located within the fault zone</u>: Strong directive, channel like interflow between the two wells of the doublet leding to a fast and massive attenuation of the temperature at the production well. From a hydraulic point of view the efforts for production and injection of thermal water (pumping effort) is reduced due to lowered hydraulic transfer resistance between the screen of the wells and the reservoir. This situation was assumed at the Slowakian doublet at scenario 1.

ii. <u>The injection well is located within the fault zone</u>: From a technical point of view the reinjection of (thermal) water is more sensitive to hydraulic and technical failures and more likely to be non-successful than the production of water (e.g. scaling due to temperature changes of the used thermal water). Therefore the hydraulic transfer resistance between the screen of the well and the reservoir should be as low as possible. This in turn is a strong argument for placing an injection well within a high permeable fault zone. From a thermodynamic point of view a channeled water interflow at the reservoir may lead to two different effects: (1) Shortened thermal breakthrough periods due to reduced heat-transfer surfaces between the flow channels (bearing cold injected water) and the surrounding hot rock matrix. (2) In contrast cold water has a higher density than hot water and therefore is tending to sink towards the deeper parts of the hydraulically connected reservoir due to gravitational forces. As a consequence of this, hot water is displaced to shallower parts of the reservoir, which may lead to a rise of the water temperature in the production well. This scheme is represented at the Austrian doublet in scenario 1.

iii. The production well is located within the fault zone: As described above the technical and consequently economic gain of placing the production well in a fault zone is less than placing the injection well in the fault zone. On the other hand, the risk of enhanced or interflow leading to uncontrolled or hardly predictable changes of the temperature at the production well is lower than at scheme 2. This scheme is represented at the Slovakian

Taking into account all possible effects and transport phenomena described at the three different schemes, it can be summarized, that scheme (ii) is assumed to be the preferred doublet scheme of a geothermal doublet located in a fault zone affected reservoir.

All the model parameters and boundary conditions and detailed description of the scenario model are described in the "Report on the numerical modelling at the Vienna Basin pilot area model; Step 2: Scenario modelling" (Goetzl et al 2013 b).

3.5.3 Results of the Vienna Basin scenario models

3.5.3.1 Temperature history of production

Apart from the possible yield, that is considered (and consequently presumed) at a constant value of 100 l/s, the production temperature is the most crucial factor for the economic viability of a geothermal installation.

The susbequent Figure 81 shows the results of the coupled thermal – hydraulic scenario modelling in terms of the predicted water temperature at the production wells of the Austrian as well as the Slowakian doublet for an overall time period of 100 years.

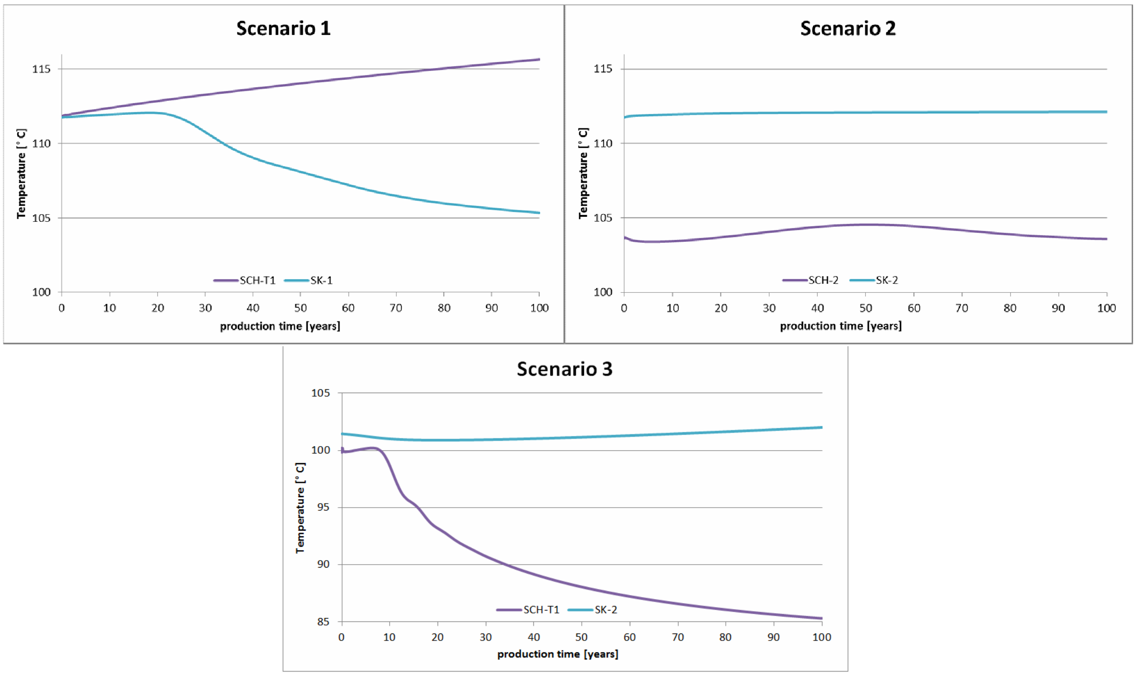


Figure 81. Time series showing the predicted temperature at the production wells of the Austrian and Slowakian doublets.

Scenario 1, which has been labeled as highly influenced by a high permeable fault zone, is showing significant changes due to convective heat transport within the assumed high permeable fault zones. The temperature at the production well of the Austrian well is continuously rising during the production period of 100 years. As described at scheme (ii) in the previous chapter this temperature rise is related to hot thermal water from the deeper parts of the reservoir, which has been replaced by sinking injected cold water. In contrast the thermal evolution of the production well at the Slovakian doublet is smoothly falling after an operational period of approximately 25 years due to enhanced interflow during the fault zones, where both wells are located. This scenario is presenting scheme (ii) described in the previous chapter.

Scenario 2 is represented by minor influences on both the Austrian and Slovakian doublets. While at the Austrian doublet both wells are located at tectonically undisturbed parts of the carbonate reservoir (lack of high conductive fault zones), only the production well of the Slovakian doublet is located within the fault zone. The interflow between the wells of the Austrian doublet is dominated by anisotropic volume flow through a moderate conductive reservoir. Therefore no thermal breakthrough has been observed for an operational period of 100 years at a well distance of approximately 1 kilometer. The temperature history at the Slovakian production well shows a slight temporally confined temperature-rise, which is assumed to be related to upstream of thermal water from deeper parts of the reservoir due to pressure decrease as a consequence of water production. It can be summarized, that both doublets simulated at scenario 2 (low influence of fault zone) are leading to stable temperature conditions at the production well.

Scenario 3 is investigating the influence of a highly conductive porous sedimentary layer on the top of the fractured basement. Such basal breccia and conglomerates, which are hydraulically connected to the fractured basement below, are widely spread over the Vienna Basin. In order to investigate a so called worst case scenario the wells of the Austrian doublet have been set in tectonically undisturbed locations within the Wetterstein Dolomite structure. Therefore the resulting flow paths are forced to pass the overlaying conductive porous layer. In contrast to the situation at the Austrian doublet the production well of the Slovakian well has been set on a highly conductive fault zone. The modelling results show a strong interference between the injection and the production well of the Austrian doublet. After a time period of approximately 10 years there is a massive temperature decline observed at the production well of almost 15°C as the cold water plume is preferentially passing the highly porous sedimentary layer at the top of the reservoir. In that case the Austrian doublet would fail. In contrast the production well of the Slovakian doublet does not show any interference, although the injected cold water plume also passes the highly conductive sedimentary layer above the reservoir. This is due to the fact, that the water pathways associated to the production well are preferably located within the highly conductive fault zone. This in turn reduces the pressure gradient within the overlaying, highly conductive porous layer and inhibits the propagation of the cold plume.

3.5.3.2 Temperature slices at depths of reinjection

To evaluate the thermal anomaly caused by geothermal exploitation, Figure 82 shows the lateral extent of the thermal plumes of the different scenarios. This can be used to estimate the maximum number of possible doublets.

3.5.3.3 Hydraulic head distribution at base of Neogene

For estimation of far field effects of a geothermal exploitation the head distribution can be evaluated (Figure 83). While the effect on the temperature field is spatially limited, the pressure distribution is affected over the whole reservoir. For all these simulations the transition to the Neogene is assumed to be perfectly sealed. If this is not the case, it could be possible that waters from structural higher levels penetrate the reservoir or vice versa.

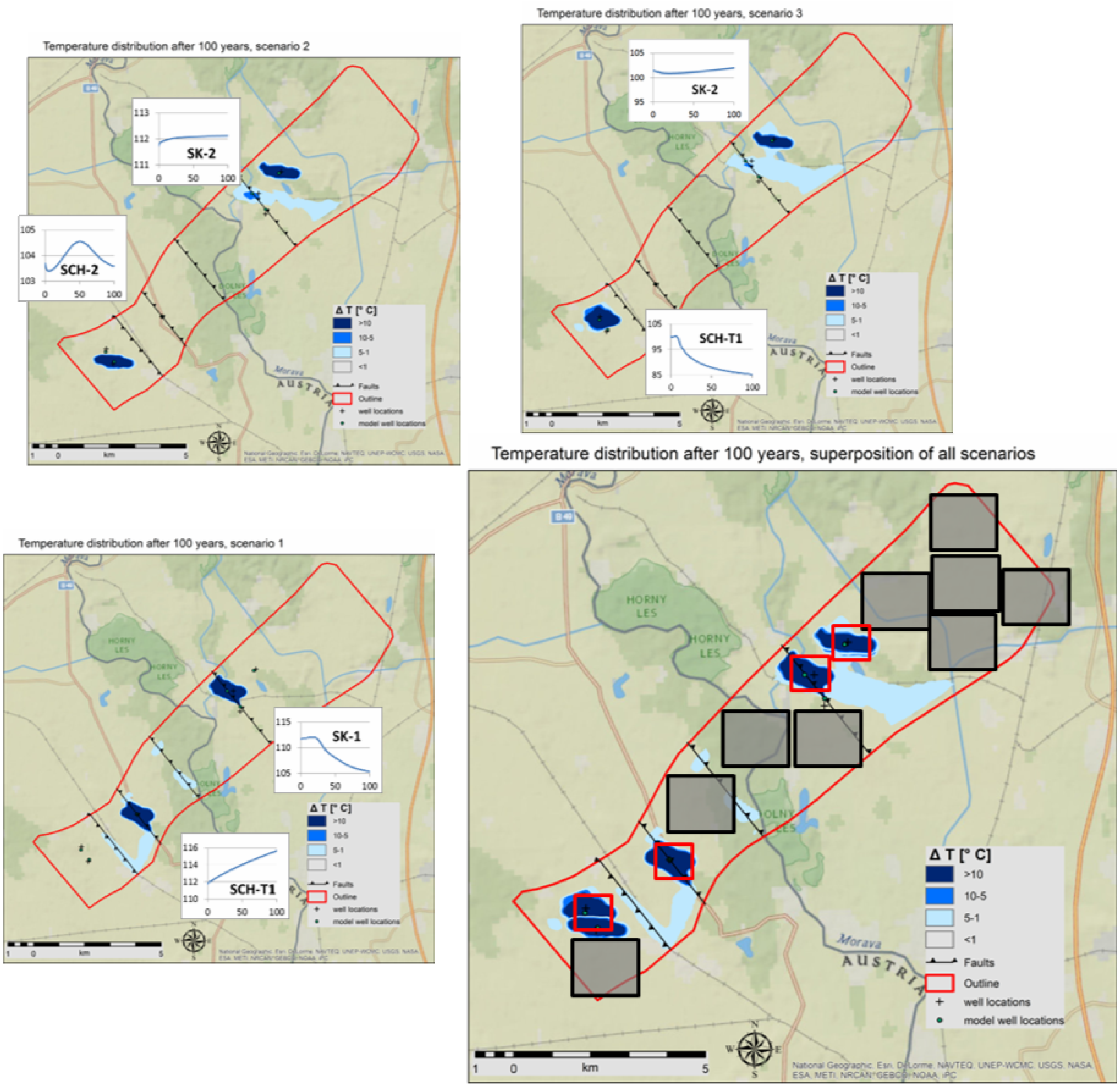


Figure 82: Temperature distribution at the depths of maximal plume at the reinjections. The overlain diagrams show the temperature evolution of the produced water.

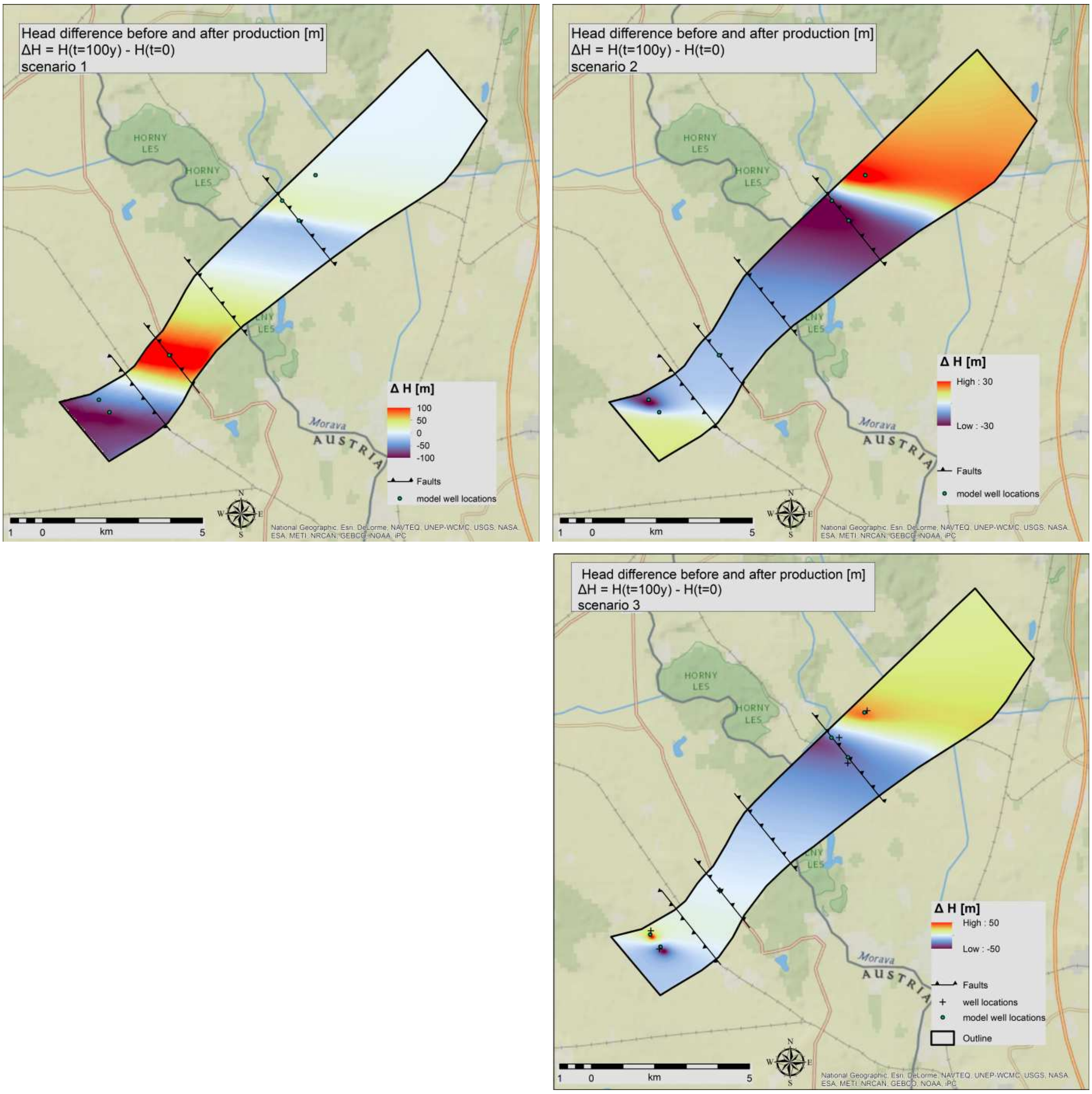


Figure 83: Head differences at the base of the Neogene sediments.

4 RESULTS OF THE HYDREGEOTHERMAL RESOURCE ASSESSMENTS

Harmonized resource assesment were carried out at all the pilot ares (Goetzl 2013c). Harmonized terminology and assessment workflow was established at all the pilot areas relying on the "Canadian Geothermal Code for Public Reporting" (http://www.cangea.ca).

In general it has to be distinguished between 3 different main levels of hydrogeothermal assessment:

The most general level covers the hydrogeothermal potential, which delimits the theoretically available heat content in a specific subsurface volume. The resource level confines the share of stored heat, which can be extracted by known technical measures, irrespective of economic constraints. The reserve level in turn also considers economic constraints and therefore delimits the economically feasible share of resources.

The term “Hydrogeothermal Play” covers a distinctive subsurface rock volume (in this case a geological reservoir complex) where natural thermal water is supposed to be occurring and may be utilized in at least one distinctive reservoir.

Table 1 is giving an overview on the different levels of hydrogeothermal assessment considered at Transenergy. It does not cover all levels of resource assessment described at the above mentioned reporting codes. However, the chosen selection covers all aspects, which are needed to fulfill the goals of Transenergy and should be seen as a first attempt towards a future joint resource management. Further diversifications of levels of hydrogeothermal assessment can be realized on demand.

It has to be considered, that the amount of assessed energy available for utilization is in general attenuating towards a higher confidence of the assessment level. As shown in Figure 84 the lowest level of confidence is provided by “Heat in Place” (potential) and in contrast the highest level of confidence provided by “Measured Resources” and already “Installed Capacities”.

Table 10. Overview of the different levels of hydrogeothermal assessment considered at Transenergy

Potential	Resource	Reserve	Definition used at Transenergy
Heat in Place			*Heat stored in a subsurface volume. This term delimits the theoretically available geothermal potential, which could only be utilized by cooling down the entire rock volume of the specific Hydrogeothermal Play. In practice it won’t be possible to extract the entire amount of heat stored by technical measures.*
	Inferred Resources		*Technically extractable amount of Heat in Place at a low level of confidence. The assessment of Inferred Resources mainly bases on modelling results and simplified assumptions at a regional scale.*
		Probable Reserves	*Share of Inferred Resources, which can be developed in an economic way (e.g. considering maximum drilling depths or maximum distances to areas of settlement).*
	Measured Resources		*Technically extractable amount of Heat in Place at a high level of confidence by relying on direct measurements at wells.*
		Installed Capacities	*Already installed hydrogeothermal power.*

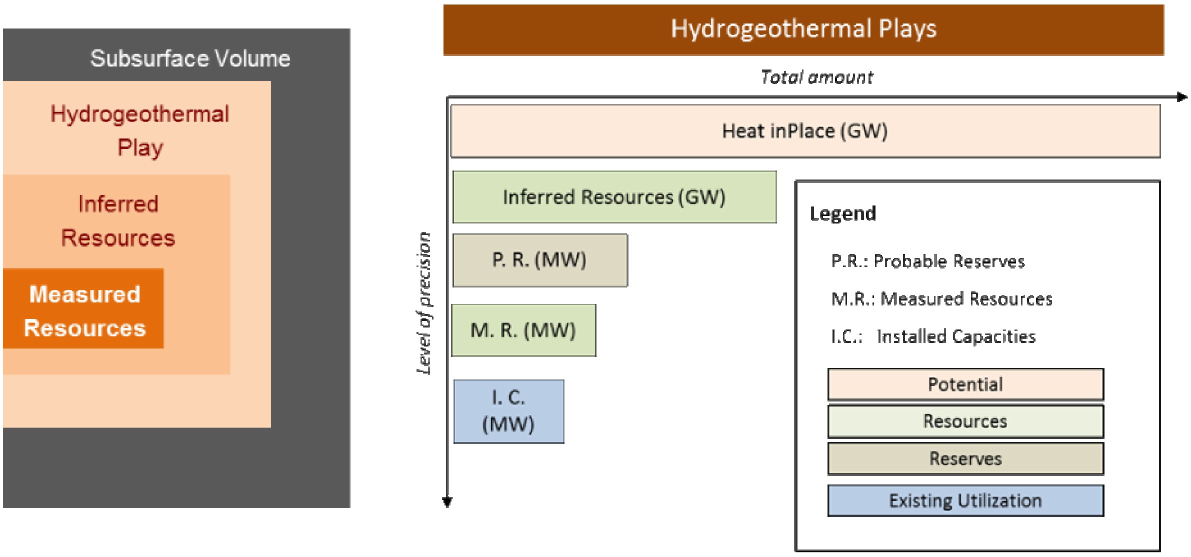


Figure 84. General scheme of the resource assessment scheme applied at Transenergy

At Transenergy project the harmonized hydrogeothermal assessment has been achieved for relevant Hydrogeothermal Plays at the selected pilot areas only. All calculations are basing on the data acquired and models developed during Transenergy. The assessment is limited to a regional scale (maximum resolution 1:100.000).

The assessment of resources is strongly depending on the technical utilization scheme chosen. In this context the controlling technical parameters are constituted by:

- Single well or doublet use
- The required minimum reservoir temperature
- The temperature of the injected water
- The maximum yield

In order to assess the hydrogeothermal potential (Heat in Place) the operational lifetime of all chosen technical utilization scheme was set to 50 years of full annual load. The technical utilization schemes applied for the hydrogeothermal resource and reserve assessment are listed in **Hiba! A hivatkozási forrás nem található.**.

4.1 Investigated Hydrogeothermal Plays

In total 9 different Hydrogeothermal Plays located in the 5 different pilot areas have been identified for the harmonized hydrogeothermal assessment. Except for the Vienna Basin pilot area only 1 Hydrogeothermal Play has been identified for each pilot area (Table 12).

The selected technical utilization schemes intend to cover the most important or already widely spread utilizations.

Table 11. Overview of the utilization schemes selected for hydrogeothermal resource assessment

ID	Title	Required minimum temperature	Reference temperature (discharge, re-injection)	Type of scheme	Constraints
		°C	°C	-	-
1	**Balneology** (energetic use of water for local heating)	30	10*	Single Well	None
2	**Heat Supply** (district heating as well as individual heating)	40	25	Doublet (2 wells)	Maximum flow rate 100 l/s or max. drawdown of 100 meters**
3	**Electric Power Generation** (combined with heat supply)	105	55	Doublet (2 wells)	Maximum flow rate 200 l/s or max. drawdown of 200 meters**

The main criteria for the selection of Hydrogeothermal Plays are:

- Coverage of at least one aquifer
- Relevance for present or future hydrogeothermal use
- Minimum average temperature level above 30°C

Three of the nine identified Hydrogeothermal Plays are located at the Miocene basin fillings of the Pannonian- and the Vienna Basin. They mainly constitute porous aquifers belonging to a single stratigraphic horizon. The remaining 6 Hydrogeothermal Plays are located at the pre-Miocene basement of the basins and are represented by fractured carbonate reservoirs, which are partly consisting of several different tectonic and stratigraphic structures.

The geometrical attributes of the investigated Hydrogeothermal Plays have been derived from the steady-state 3D modelling executed at the different pilot areas. The largest reservoir complexes exist in the Danube Basin (DB1) and the Vienna Basin (VB3 and VB5). While the gross- and estimated aquifer volume in the Play DB1 is resulting from the vast surface, the volumes of the Plays in the Vienna Basin are resulting from the great thickness of the reservoir complexes. The smallest Hydrogeothermal Play is located at the Lutzmannsburg – Zsira pilot area (Play LZ1). The total estimated gross aquifer volume is at 2100 km³. It has to be kept in mind that this estimation bases on the simplifying assumption of a homogeneous reservoir (Table 13).

Table 12: Overview on the Hydrogeothermal Plays selected for the hydrogeothermal assessment

ID	Name	Pilot Area	Description
VB1	*Aderklaa Conglomerate*	Vienna Basin	Conglomerates of the Miocene basin fillings (Lower Badenian)
VB2	*Deltafront Sediments (Eggenburgian - Ottnangian)*	Vienna Basin	Sandstones and sands of the Miocene basin fillings
VB3	*Tirolic Nappe System*	Vienna Basin	Dolomites and limestones of the Triassic basement of the Vienna Basin (Norian - Anisian)
VB4	*Juvavic Nappe System*	Vienna Basin	Dolomites and limestones of the Triassic basement of the Vienna Basin (Ladinian - Anisian)
VB5	*Central Alpine & Tatric Carbonates*	Vienna Basin	Dolomites and limestones of the Triassic basement of the Vienna Basin (Ladinian - Anisian)
TWB1	*Upper Triassic karbonate reservoir*	Komarno - Sturovo Area	Limestones and dolomites of the Upper Triassic basement
LZ1	*Devonian dolomite*	Lutzmannsburg - Zsira Area	Limestones and dolomites of the Paleozoic basement
DB1	*Upper Pannonian formation*	Danube Basin	Interchange of clays, marls and sands/sanstones of the Miocene basin fillings
BRH1	*Bad Radkersburg – Hodoš pilot area / Raba fault zone*	Bad Radkersburg - Hodoš Area	Carbonates and metamorphic rocks of the Pre-Tertiary basement (Triassic & Paleozoic)

The estimated range of reservoir temperatures (Table 14) has been derived from the achieved steady-state thermal models covering the pilot areas. High temperatures of more than 200°C have therefore not been proofed by direct measurements. However, the estimated maximum temperatures vary between 114°C (VB1) and 282°C (VB5). The average reservoir temperatures, which have been used for the hydrogeothermal resource assessment, are varying between 46°C (DB1) and 148°C (BRH1).

Except for the Hydrogeothermal Play TWB1, which exhibits a very high level, all estimated transmissivities vary in the range of 10-4 to 10-3 m²/s (Table 15).

Table 13: Geometrical attributes of the investigated Hydrogeothermal Plays

ID	Name	Gross Volume (km³)	Aquifer Volume (km³)	Average Thickness (m)
VB1	*Aderklaa Conglomerate*	249	37	199
VB2	*Deltafront Sediments (Eggenburgian - Ottnangian)*	124	21	182
VB3	*Tirolic Nappe System*	4,495	265	2,239
VB4	*Juvavic Nappe System*	900	31	1,937
VB5	*Central Alpine & Tatric Carbonates*	3,220	103	1,930
TWB1	*Upper Triassic karbonate reservoir*	164	2	200
LZ1	*Devonian dolomite*	120	6	600
DB1	*Upper Pannonian formation*	9,127	1,278	985
BRH1	*Bad Radkersburg – Hodoš pilot area / Raba fault zone*	1,779	356	3,100

The hydraulic transmissivity was used to calculate the Inferred- and Measured Resources, as this parameter controls the maximum yield of an individual geothermal doublet. It was calculated by combining the modelled thickness of a Hydrogeothermal Play with an averaged hydraulic conductivity, once again assuming isotropic and homogeneous conditions at the Play.

The heat exchange between the surrounding rock matrix and the circulating thermal water is controlled by the rock parameters (i) Heat Capacity, (ii) Density and (iii) Porosity as well as by the same parameters of the fluid itself. The thermal rock parameters have been generalized based on measurements done by or available at the involved geological surveys. Due to the lack of data once again simple isotropic and homogeneous reservoirs had to be assumed (Table 16).

Table 14: Range of the estimated reservoir temperatures of the investigated Hydrogeothermal Plays

ID	**Name**	**Estimated Reservoir Temperature (°C)**		
		Min	*Max*	*Average*
VB1	*Aderklaa Conglomerate*	26	114	80
VB2	*Deltafront Sediments (Eggenburgian - Ottnangian)*	10	155	58
VB3	*Tirolic Nappe System*	8	239	118
VB4	*Juvavic Nappe System*	58	193	129
VB5	*Central Alpine & Taric Carbonates*	9	282	134
TWB1	*Upper Triassic karbonate reservoir*	20	152	86
LZ1	*Devonian dolomite*	n. a.	n. a.	n. a.
DB1	*Upper Pannonian formation*	10	136	46
BRH1	*Bad Radkersburg – Hodoš pilot area / Raba fault zone*	45	243	148

Table 15: Estimated transmissivity of the investigated Hydrogeothermal Plays

ID	Name	Estimated Transmissivity 10^{-3} (m²/s)		
		Min	*Max*	*Estimated*
VB1	*Aderklaa Conglomerate*	0.002	1.219	0.325
VB2	*Deltafront Sediments (Eggenburgian - Ottnangian)*	0.020	1.305	0.356
VB3	*Tirolic Nappe System*	0.000	3.426	1.159
VB4	*Juvavic Nappe System*	0.003	2.416	1.010
VB5	*Central Alpine & Taric Carbonates*	0.274	3.328	1.006
TWB1	*Upper Triassic karbonate reservoir*	n. a.	n. a.	42.000
LZ1	*Devonian dolomite*	n. a.	n. a.	0.480
DB1	*Upper Pannonian formation*	0.072	1.544	0.423
BRH1	*Bad Radkersburg – Hodoš pilot area / Raba fault zone*	0.755	4.700	3.120

Table 16: Thermal rock parameters of the investigated Hydrogeothermal Plays

ID	Name	Bulk Heat Capacity (J/(m³ˣK)	Bulk Density (kg/m³)	Porosity (%)
VB1	*Aderklaa Conglomerate*	1380	2273	15.0
VB2	*Deltafront Sediments (Eggenburgian - Ottnangian)*	1154	2370	17.2
VB3	*Tirolic Nappe System*	1126	2681	5.9
VB4	*Juvavic Nappe System*	1028	2735	3.4
VB5	*Central Alpine & Taric Carbonates*	897	2860	3.2
TWB1	*Upper Triassic karbonate reservoir*	914	2650	3.0
LZ1	*Devonian dolomite*	1380	2273	15.0
DB1	*Upper Pannonian formation*	n. a.	n. a.	14.0
BRH1	*Bad Radkersburg – Hodoš pilot area / Raba fault zone*	1000	2850	20.0

4.2 Methodology and workflow

The assessment of hydrogeothermal potentials, resources and reserves follows a workflow developed in the frame of Transenergy. All processing steps have been in a MS Excel worksheet, which has been sent out to all partners for individual calculations. The chosen approach bases on the previously elaborated steady state models and have been performed based on 2D raster analyses using the software package Esri ArcGIS.

Doing so the entire Hydrogeothermal Play was covered with a 1 km x 1 km raster putting on individual geothermal doublet (1 production well + 1 injection well) at each cell in order to consider the utilization schemes 2 (heat supply) and 3 (electric power generation). Considering scheme 1 (balneological use) only 1 single well was put at each cell.

In the frame of the assessment harmonized nomenclature was applied (Table 17).

Table 17. The harmonized nomenclature

Symbol	Name	Unit
K	(Hydraulic) Permeability	m² (Darcy)
g	Gravity	m/s²
?	Dynamic Viscosity	Ns/m³
ρ	Density	Kg/m³
cp	Heat Capacity	J/(kg·K)
θ	Porosity	-
τ	Transmissivity	m²/s
Q	Yield	m³/s
H	Heat (Resources)	MW, (W)
T	Reservoir Temperature	°C
T_{Ref}	Reference Temperature (Injection Temperature)	°C
f	Subscript: Fluid (Water)	
a	Subscript: Aquifer (rock matrix and fluid filled pores)	
i	Subscript: Cell	

The assessment of hydrogeothermal resources is consisting of the following processing steps (see nomenclature at the end of this chapter):

(1) <u>Preparation of input data</u>

- Define the outline of each Hydrogeothermal play and cut out all relevant input data from the elaborated steady-state 3D models.
- Calculate a raster of the gross thickness of each Hydrogeothermal Play (HP).
- Calculate the gross volume of each HP by summing up the thickness of all cells.
- Calculate the average (midpoint) temperature for each cell by: $T_i = \frac{TTop_{,i} + TBase_{,i}}{2}$.

- Assign uniform Heat Capacity, Bulk Densities and Porosities (total, effective) to each HP.
- Calculate the transmissivity of each HP:
  - If no direct measurements of the hydraulic conductivity are available then transform hydraulic permeabilities into hydraulic conductivities using: $kf = \frac{K \cdot g \cdot \rho f}{\eta f}$.
- Calculate the hydraulic transmissivity by combining the hydraulic conductivity with the gross thickness for each cell.
- Calculate the gross aquifer volume by multiplying the gross volume with the effective porosity.
- Create filter considering the minimum reservoir temperature requirement for the schemes 1 to 3: Each utilization scheme has a minimum reservoir temperature required. In order to avoid negative capacities all cells, which don't fulfil the requirements, have been excluded from the calculations.

(2) Calculation of the Heat in Place

All calculations are basing on a volumetric approach assuming to cool down the entire volume of the HP to the level of the reference temperature.

- Utilization scheme 1: $HIP = \sum_{i=1}^{n}\left(6.2420E - 10 \cdot \langle cp \cdot \rho \rangle_f \cdot \theta \cdot \left(T_i - T_{Ref}\right)\right)$, unit [MW].
- Utilization scheme 2,3: $HIP = \sum_{i=1}^{n}\left(6.2420E - 10 \cdot \langle cp \cdot \rho \rangle_a \cdot \left(T_i - T_{Ref}\right)\right)$, unit [MW].

(3) Calculation of the Inferred Resources

- Scheme 1 (balneology, single well use): Follows an approach presented by Gringarten (1978): $H = \langle cp \cdot \rho \rangle_f \cdot Q \cdot v_{heat}$, where vheat is representing the heat transfer velocity between the rock matrix and the circulating fluid: $v_{heat} = \frac{\langle cp \cdot \rho \rangle_f}{\langle cp \cdot \rho \rangle_a}$. For calculating the Inferred Resources a constant yield of 10 l/s (0.01 m³/s) was assumed. The output unit is [MW].
- Schemes 2, 3: The inferred resources have been assessed using a multiplet-scheme approach (1 individual doublet per cell) based on a correlation between the maximum yield of an individual doublet and the transmissivity at the affected cell:
  - Calculate the maximum allowed yield: $Q = 150.816 \cdot \tau$. This equation also follows an approach by Gringarten (1978). A maximum yield of 100 l/s (0.1 m³/s) was set as a general constraint for each cell.
  - Calculate the thermal capacity of each individual doublet: $H = \langle cp \cdot \rho \rangle_f \cdot Q \cdot \left(T_i - T_{Ref}\right)$, afterwards the unit is transformed from [W] into [MW].
  - Sum-up all cells in order to get the total Inferred Resources.

(4) Calculation of the Measured Resources

The calculation of Measured Resources follows the methodologies for calculating the Inferred Resources. Instead of using modelled reservoir temperatures the thermal capacity of a single well or a hydrogeothermal doublet was calculated using direct measurements at hydrocarbon wells and geothermal wells only. That means only those cells have been considered, where wells with direct temperature measurements were available.

(5) Calculation of the Probable Reserves

The calculation of probable reserves has been experimentally applied on the utilization scheme 2 (heat supply) for the HPs in the Vienna Basin only. For that purpose the Inferred Resources have been calculated only for cells showing a maximum distance of 1000 meters to settlement areas. The information about settlement areas have been derived from a Corrine Landsat dataset (Eurosat©, Corrine Landcover, 2006).

(6) Calculation of already Installed Capacites

Considering the utilization schemes 1 to 3 the already Installed Capacities have been assessed based on production data: $H = (cp \cdot \rho)_f \cdot Q \cdot (T_i - T_{Ref})$.

4.3 Results

The Heat in Place, assessed for the investigated Hydrogeothermal Plays is shown in Table 18.

Table 18: Estimated Heat in Place for the investigated Hydrogeothermal Plays

ID	Name	Heat in Place ($MW_{Th,\ 50\ years}$)		
		Scheme: Single well	*Scheme: Heat Supply*	*Scheme: Electric Power*
VB1	*Aderklaa Conglomerate*	5,449	28,794	454
VB2	*Deltafront Sediments (Eggenburgian - Ottnangian)*	1,153	7,422	1,289
VB3	*Tirolic Nappe System*	52,998	858,027	587,344
VB4	*Juvavic Nappe System*	6,533	194,102	122,013
VB5	*Central Alpine & Taric Carbonates*	12,628	557,686	380,336
TWB1	*Upper Triassic karbonate reservoir*	235	15,731	3,896
LZ1	*Devonian dolomite*	412	7,014	3,603
DB1	*Upper Pannonian formation*	34,325	176,868	0
BRH1	*Bad Radkersburg – Hodoš pilot area / Raba fault zone*	29,945	374,354	250,455

In general the greatest potential has been calculated for the Heat Supply scheme, as this scheme is affected by a moderate minimum temperature required (40°C). In this context the highest amount of Heat in Place was calculated for the HP VB3 (approx. 860 GWTh) assuming an operational lifetime of 50 years for cooling down the reservoir. This high amount of the Heat in Place is strongly related to the vast volume of this Hydrogoethermal Play and therefore calculated high temperature levels in the basal sections of the Play. However, it has to be kept in mind, that this is only a hypothetical potential, which will never been realized in practice. Nevertheless using the Heat in Place we can summarize, that the maximum amount of heat stored in all investigated HPs.

A first estimation of the technically realizable share of the stored Heat in Place is given by the Inferred Resources (Table 19).

Table 19: Estimated Inferred Resources for the investigated Hydrogeothermal Plays

ID	Name	Inferred Resources (MW_{Th})		
		Scheme: Single well	*Scheme: Heat Supply*	*Scheme: Electric Power*
VB1	*Aderklaa Conglomerate*	636	14,285	229
VB2	*Deltafront Sediments (Eggenburgian - Ottnangian)*	199	4,455	835
VB3	*Tirolic Nappe System*	459	66,624	46,242
VB4	*Juvavic Nappe System*	72	15,567	10,945
VB5	*Central Alpine & Taric Carbonates*	264	60,547	41,756
TWB1	*Upper Triassic karbonate reservoir*	51	5,327	1,319
LZ1	*Devonian dolomite*	22	1,809	919
DB1	*Upper Pannonian formation*	1,075	6,205	0
BRH1	*Bad Radkersburg – Hodoš pilot area / Raba fault zone*	846	122,253	81,791
	SUM	**3,624**	**297,072**	**184,036**

The assessed Inferred Resources show an average share of the stored Heat in Place in the range of 10% considering the different technical utilization schemes. Except for the HP DB1 (Upper Pannonian formation) each investigated Hydrogeothermal Play shows resources for the generation of electric power. Considering a technical conversion factor of around 10% total resource for the generation of around 1.8 GWEl are available in 8 Hydrogeothermal Plays in the 5 different pilot areas. However, this is only a technical potential, which does not respect any economic constraints. The by far greatest amount of Inferred Resources is, once again, evident for the Heat Supply technical scheme (297 GWTh). In contrast, the single well use (Single well or Balneology Scheme) only offers limited resources. Irrespective of the environmental consequences of only using a single well for hydrogeothermal utilization only a by far smaller amount of the heat stored in a subsurface rock volume can be technically extracted by a single well in comparison to a doublet use.

The already proven resources are represented by the Measured Resources (Table 21).

Table 20: Calculated Measured Resources for the investigated Hydrogeothermal Plays

ID	Name	Measured Resources (MW_{Th})		
		Scheme: Single well	*Scheme: Heat Supply*	*Scheme: Electric Power*
VB1	*Aderklaa Conglomerate*	7	114	0
VB2	*Deltafront Sediments (Eggenburgian - Ottnangian)*	1	28	0
VB3	*Tirolic Nappe System*	36	1,007	349
VB4	*Juvavic Nappe System*	10	461	102
VB5	*Central Alpine & Taric Carbonates*	5.4	20	0
TWB1	*Upper Triassic karbonate reservoir*	0.2	17.2	0
LZ1	*Devonian dolomite*	22	434	39
DB1	*Upper Pannonian formation*	24	137	0
BRH1	*Bad Radkersburg – Hodoš pilot area / Raba fault zone*	n. a.	n. a.	n. a.
	SUM	**105**	**2,218**	**490**

The already proven resources constitute only a small share of the Inferred Resources (<1%). It has to be pointed out, that the Measured Resources do not include already Installed Capacities. Nevertheless, total Measured Resources of more than 2 GWTh (Heat Supply scheme) and around 500 MWTh (Electric Power scheme) are already verified for the Transenergy project area. In this context a great share of the Measured Resources have been identified for the Vienna Basin pilot areas, where lots of hydrocarbon wells exist.

Finally, the assessed already Installed Capacities are shown in **Table 21**.

Table 21: Assessed already Installed Capacities at the investigated Hydrogeothermal Plays

ID	Name	Installed Capacities (MW_{Th})		
		Scheme: Single well	*Scheme: Heat Supply*	*Scheme: Electric Power*
VB1	*Aderklaa Conglomerate*	0	0	0
VB2	*Deltafront Sediments (Eggenburgian - Ottnangian)*	0	0	0
VB3	*Tirolic Nappe System*	0	0	0
VB4	*Juvavic Nappe System*	0	0	0
VB5	*Central Alpine & Taric Carbonates*	4.9	0	0
TWB1	*Upper Triassic karbonate reservoir*	12.8	2.5	0
LZ1	*Devonian dolomite*	4.0	0	0
DB1	*Upper Pannonian formation*	36.7	23.9	6.8
BRH1	*Bad Radkersburg – Hodoš pilot area / Raba fault zone*	10	0	0
	SUM	**68.0**	**26.4**	**6.8**

The Installed Capacities have been assigned to the 3 different utilization schemes in order to opposite them to Measured Resources in order to estimate the degree of utilization. Of course this is a very pessimistic or conservative statement, as the Measured Resources only reflect the already proven hydrogeothermal resources. As the already Installed Capacities have been excluded from the assessment of Measured Resources and therefore reflect the remaining known resources, the following total degree of utilization (DoU) can be reported for the 3 different technical utilization schemes:

- Balneological- (single well) scheme: DoU ~39%
- Heat Supply Scheme: ~1%
- Electric Power Generation scheme: ~1%.

The term Reserves describes both the technical as well as economical extractable amount of heat stored in the subsurface. Probable Reserves correspond to Inferred Resources by outlining the share, which can be developed in an economically feasible way. There are various economic constraints controlling the feasibility of hydrogeothermal utilizations. Most of them are very site specific and are difficult to generalize (e.g. the load profile of local users). However general constraints are given by the maximum drilling depth and the distance to existing settlement zones. In order to give a rough estimation about Probable Reserves we have considered the limitations given by the distance to existing settlement areas. By assuming a maximum distance of 1,000 meters to settlements the Probable Reserves have been assessed for the heat supply utilization scheme. This assessment has only been executed in an experimentally way for the Hydrogeothermal Play VB03 Tirolic Nappe System, located at the Vienna Basin pilot area (Table 22, Figure 85).

Table 22: Probable Reserves calculated for the identified Hydrogeothermal Plays considering the heat supply utilization scheme.

ID	Title	Probable Reserves (MW_{Th})
		Heat supply scheme
VB 01	Aderklaa Conglomerate	816
VB 02	Deltafront Sediments	87
VB 03	Tirolic Nappe System	22,688
VB 04	Juvavic Nappe System	5,292
VB 05	Central Alpine & Tatric Units	20,391
	TOTAL SUM	**49,273**

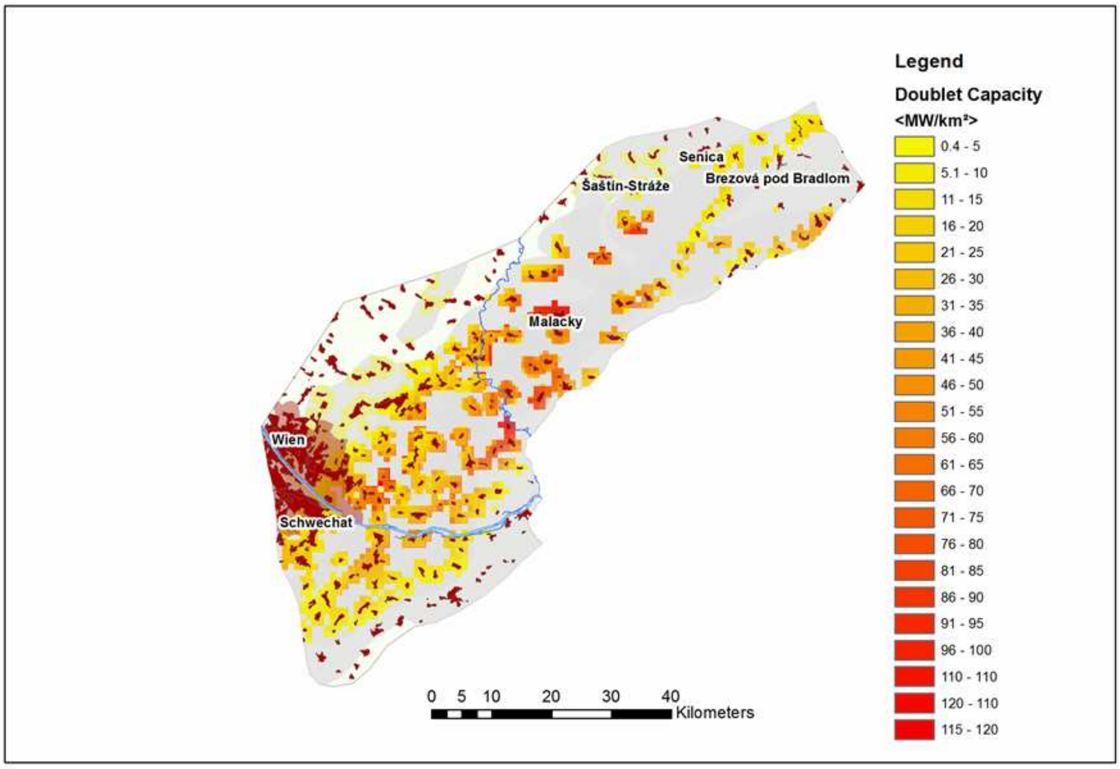


Figure 85: Probable Reserves: Hydrogeothermal doublet capacity per km² combined for all investigated Hydrogeothermal Plays. Settlement Areas: Eurosat©, Corrine Landcover (2006)

Considering a maximum distance of 1.000 meters the estimated Probable Reserves associated to the heat supply scheme are in the range of 49 GWTh. The resulting hot spots for hydrogeothermal heat supply are located at the surrounding of the capital city Vienna and at the Austrian – Slovakian border region between Malacky and Schoenkirchen / Aderklaa.

5 SUMMARY AND COCLUSION

Based on the steady steate models scenario models were developed for each pilot area. These models provide information about the possible limitations in thermal water utility, the need of protection, and describes the geothermal exploitation capacity of each region. The aim of the present modelling work was to understand and characterize the natural hydro-geothermal system of the study areas, to investigate the future effects of existing geothermal water extractions, and to make predictions on different extraction scenarios and utilization shemes. The modelling activity consists of two main parts: developing coupled flow and heat transport model and carrying out hydrogeothermal resource assessment. During modelling common approach was applied for each pilot area and principles were harmonized. The modelling methods and applied software were the same in each pilot area. Two different geothermal utilization shemes were investigated and well doublets were supposed in the transboundary zone in each pilot area, except Lutzmannsburg-Zsira region where the geothermal conditions are favourable only for balneological utility near the national border.

Although we applied the same approach in the models, due to specific features of each pilot area special model solutions were applied to investigate unique transboundary problems, which are not relevant for all pilot regions.

The results of the different scenario modelling studies and the models themselves can be used for everyday thermal water management e.g. reviewing allowance processes of new utilization.

Following the Canadian Geothermal Code for Public Reporting (CanGEA) we have assessed different levels of geothermal potential and resources for 9 selected Hydrogeothermal Plays (reservoir complexes) at the 5 pilot areas. The general aim of this task was to give an overview about the limitations and opportunities for different schemes of hydrogeothermal utilization in the Transenergy pilot areas.

The maximum level of hydrogeothermal potential is given by the calculated Heat in Place, which is in the range of several Terawatts. The assessed Inferred Resources can be seen as an upper technical limit for hydrogeothermal utilizations neglecting any economic constraints. Taking into account the different utilization schemes Inferred Resources between 4 GWTh (Single Well use) and 300 GWTh (Heat Supply scheme) could be assessed for the selected Hydrogeothermal Plays. In practice these resources are not likely to be realized by technical measures, as all the available surface space would be systematically covered by geothermal doublets in a so called multiplet scheme. In contrast the already proven resources, described by the term Measured Resources, only represent a small share of the realizable resources, as they have been derived from already drilled wells and boreholes, which have shown a significant inflow of natural thermal water. However, taking into account the already Installed Capacities only a very small share of the proven resources (less than 1%) are already realized leaving great opportunities for future development.

The realized assessment of resources at the different levels of confidence and resolution has shown that the Balneological- or Single Well scheme is the least efficient way to extract geothermal heat from the subsurface. Taking also into account environmental aspects, such as the pollution of surface streams or the attenuation of pressure in the exploited aquifers, the Transenergy group strongly advises against a single well scheme for pure energetic use of natural thermal water.

The results which are specific for the pilot areas can be summarized in the following:

The **Lutzmannsburg-Zsira** natural state model provided three-dimensional information on hydraulic head distribution, groundwater fluxes and temperature distribution. The simulated groundwater head distribution and calculated flux distribution indicated that the dominant flow direction is towards the east following a semi-radial pattern. The groundwater is recharged mainly via surface infiltration. The Marcal Valley and the Répce valley represent the regional discharge area, while the north-eastern side of the model is a cross-flow area.

The production state simulation results indicate that regional groundwater table drawdown varys between 1-15 metres in response to groundwater extraction. The largest drawdowns exists in the western side of the model domain resulting from the depression of resource bores located in Austria.

The current depressurisation of pre-neogene aquifers generally varies between 2-12 metres. The largest pressure drop is simulated to exist around the Bük extraction bores. A significant depressurisation is observed around the Lockenaus extraction bore.

With respect to the Zsira-Lutzmannsburg local system, the model scenarios indicate that both the Bük and Lutzmannsburg extractions contribute to the drawdown observed in the Zsira Zst-1 monitoring bore. The upper Pannonian extractions also contribute to the depressurisation observed in Zst-1. The contribution of the Upper Pannonian and Quaternary extractions is comparable to that of the Bük and Lutzmannsburg extractions. Both extraction groups contribute equally to the depressurisation along the borderzone. The Sarmathian extraction bores also contribute to the depressuriastion in the border zone. Both Austrian and Hungarian extractions take part in the depressurisation in Zst-1; the contribution of the Hungarian bores is slightly larger.

Simulation of a twofold increase in existing extraction rates indicates a significant increase in water table drawdown of up to 16 metres in the border zone of the pilot area. Similarly, the current depressurisation of the Sarmathian reservoir was predicted to increase by 18 metres in response to increased production rates. Predictive model results suggest, that the increase of extraction rates would put a significant stress on the groundwater system.

The steady state simulation of a geothermal bore doublet targeting the Devonian dolomite indicated that the reinjection of the extracted fluids would significantly decrease the hydraulic impacts of groundwater extraction. The cooling effect of cold water reinjection had little influence on the temperature distribution within 20 years of simulation time, and has only a local impact on reservoir temperatures in the case of long-term utilisation. Reinjection of the extracted thermal waters is thus the recommended practice for future geothermal developments in this reservoir.

Simulations of the **Bad Radkersburg-Hodos** pilot model showed no impact of abstraction in Korovci on Benedikt. The impact on Bad Radkersburg was simulated with and without reinjection well. When no reinjection is applied the expected hydraulic depression reaches Bad Radkersburg only if higher than expected hydraulic conductivity or abstraction rate are implemented in the model. The simulated 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 expected only if very high hydraulic conductivity is used in the model, in this case is noticeable after 50 years. Higher abstraction and injection rates in the model cause the breakthrough after 30 years already.

Two regional steady-state model scenarios of the **Danube Basin** revealed new geothermal energy sources in the Danube basin regions, reaching up to about 55 MW of thermal power. However, the impacts of additional pumping on existing installations as well as on global pressure field puts questions on future direct use of thermal water in the region, favorizing re-injection.

The results of a detailed transient geothermal modelling of a doublet cluster can be summarized into next points:

It was found that re-injected cooled water within a period of system lifetime does not affect pumping wells, what have a positive impact on the system efectivity.

If the input values of hydraulic and thermal properties of modelled environment are sufficiently accurate, it is possible to re-inject quantity of water in the range of 10 to 50 l/s without affecting the lifetime of system.

Parallel coexistence of two re-injection systems nearby the national border do not interact with each other.

After closing this system, although it will take a very long time until the groundwater temperature returns back to the initial conditions, this effect has in hydrogeological structure relatively small spatial extent.

The pilot model of the Komarno-Sturovo pilot area the natural system was modelled to give information about the period before the intense karst water abstractions during bauxite and coal mining and help the understanding of the natural water and heat flow system. The resulted hydraulic potential and temperature distributions indicated the natural flow paths and the natural convective heat flow system; furthermore helped to plan the sites and the scenarios of the theoretical utilizations.

In the second step the scenario modelling theoretical production strategies were investigated. These scenario models are based on the steady state modelling.

The first three scenarios were related to the karst water abstraction during and after the bauxite and coal mining. The behaviour of the karst system during intense water abstraction was investigated by the help of infinite operation time. The intensive water production resulted regional depression in the whole region: the largest, 60-70 m drawdowns exist in the area of the water abstractions in the SE part of the Pilot Area (near Tatabánya). Regional drawdown was observed not only in the Hungarian part, but also in the Slovakian part of the Pilot Area. In these transboundary regions the depression reached 10-30 m due to the natural flow system. The most adverse and best seen effect of the intense water abstractions was the disappearance of the lukewarm springs in the Tata area. The scenario of the drinking water abstractions showed lower depressuration in the karst system and in the Tata area the water levels reached again the level of the springs.

The well doublet scenarios took place in the Komárom-Komárno area, which is the most perspective geothermal area of the Pilot Area due to the energy market and the geothermal resources. To investigate the possible impacts of a planned geothermal utilization, 6 different utilization strategies were studied. The importance of the reinjection was confirmed by the simulations: the utilizations without reinjection had transboundary impacts in the neighbouring countries, the simulated depressions on the hydraulic potential was 6 - 7 m around the pumping wells and minimum 5 - 5.5 m around the theoretical wells in the neighbouring country. When reinjection wells worked the modelled depressuration rates were between 1.5 - 2.5 m around the abstraction wells and the pressure increasing around the reinjection wells were between 1.5 - 2.5 m. In these scenarios the operation of the geothermal system had no transboundary impacts. The scale and spatial extent of the impacts – in the case of theoretical doublets existed in both countries – were depended on the location of the injection wells. The thermal impacts mainly depended on the natural water flow: the Hungarian utilization had transboundary effects in the case of well located closer to the national border. When both countries had doublets, the common impact was 2.5 - 10 °C along the Danube between the utilizations assuming infinite operation time.

An easy, though reasonable, approach to assess an estimate exploitable amount of energy from a reservoir in the **Vienna Basin** is to estimate the number of possible doublets. Multiplication of power of one doublet times the number of doublets. yields the exploitable Heat in Place.

In total 9 hydrogeothermal doublets could be installed in the outlined Wetterstein Dolomite structure irrespective of natural reserve zones. The average installed power of the modelled doublets is around 25 MWTh, therefore the total sum of all installed doublets would be in the range of around 230 MWTh. This result is now compared with the outcomes of the regionals scale resource assessment in term of the so called Inferred Resources (per square kilometer) considering the electric power generation multiplet scheme.

The estimated hydrogeothermal capacities per square kilometer are varying between 9.6 MWTh and 35.9 MWTh. The average installed capacity of 29.3 MWTh is fitting quite well to the average thermal power derived by the scenario modelling studies. With raster based estimation the total Inferred Resources are in the range of 470 MWTh, which is about 2 times larger than the total available resources derived from the detailed modelling studies. The reason for this is given by a too optimistic assumption considering the needed space of a single hydrogeothermal doublet in the raster based estimation of Inferred Resources.

Taking a look at the temperature distributions and the hydraulic conditions at the reservoir a multiplet scheme consting of maximum 10 to 15 doublets, which are jointly controlled, could be most efficient way to develop the reservoir. Depending on the attainable energy price it would be possible to exploit deeper levels (> 4000 m) of the reservoir and/or apply more elaborate exploitation schemes (e.g. multiplet arrays or EGS). Taking these possibilities into account, up to 25 % of the total Heat in Place could be exploitable.

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