Report on Komárom - Štúrovo Pilot Area scenario modeling

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5.2.3 Detailed hydrogeological modelling

5.2.5 Detailed geothermal modelling

5.3.1 Map series of the scenario model results

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1 INTRODUCTION

The report presents the results of the scenario modelling in the Komárom – Štúrovo Pilot Area of the Transenergy project. The modelling (in the first step) was focused on the karst aquifer of the Triassic limestones and dolomites in the NE part of the Transdanubian regional karst flow system and the changes of the flow system due to the bauxite and coal mining. After the better understanding of the system we investigated an effect of a dublet in the most perspective area near Komárom and Komárno.

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 is/was very harmful because of 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.).

But 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.

2 AIM OF THE MODELLING

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 SUMMARY OF THE PILOT AREA

3.1 Geographic settings of the Area

The Komárom-Štúrovo (Komárno-Párkány) Pilot Area of the Transenergy Project is situated in the north-eastern part of the Transdanubian Range in Hungary and its basinal part in Slovakia (Figure 1). The 84 % of the total area (4447 km^2) belongs to Hungary, the 16 % of the area belongs to Slovakia. The main importance of the area is the groundwater bodies which are divided by national boundaries and are in focus of International Commission for the Protection of the Danube River (ICPDR).

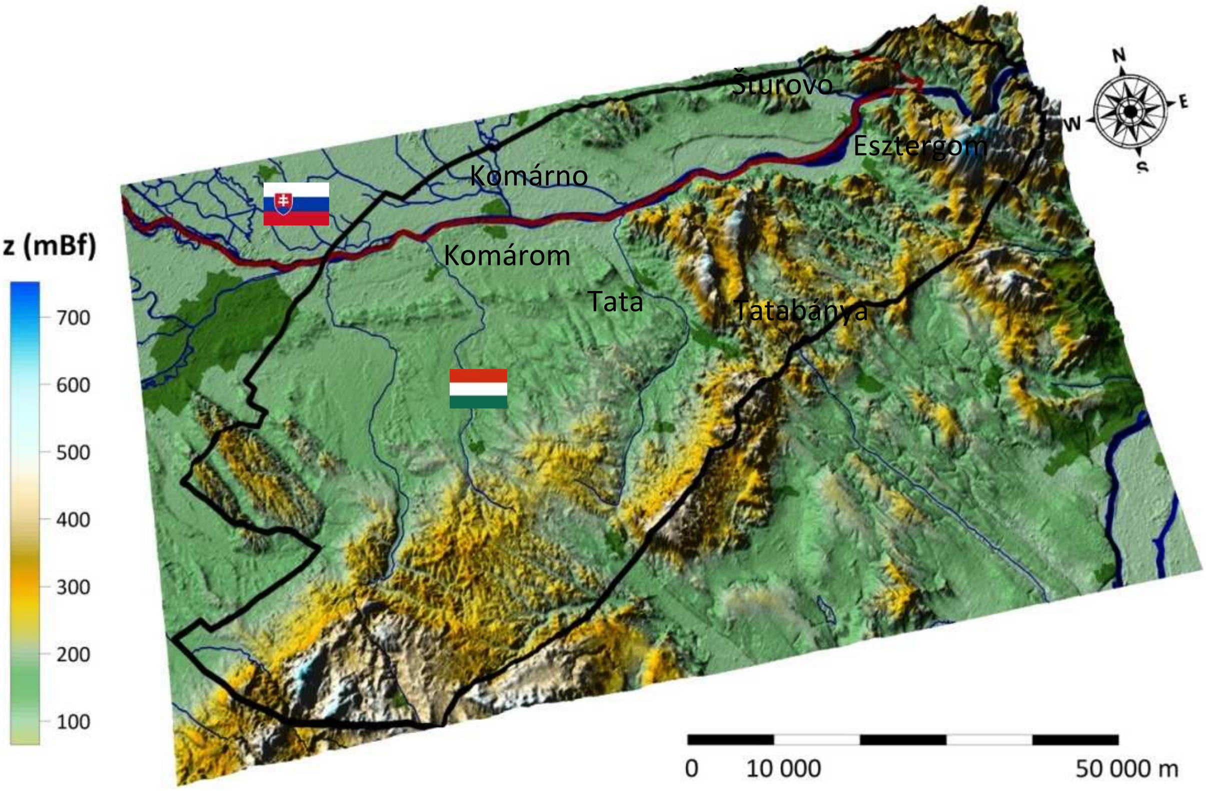


Figure 1. Geographical settings of the modelled Komárom - Štúrovo Pilot Area and the main settlements

3.2 Geological, hydrogeological and geothermal setting of the Pilot Area

3.2.1 *Geological settings*

The Pre-Tertiary basement in the modelled area is build up shallow-water Middle to Upper Triassic platform carbonates (Main, or "Haupt" dolomite, Dachstein Limestone). The Triassic carbonates are overlying by pelagic Jurassic limestones, marls and cherty limestones with Lower Cretaceous clastic sequence in the Transdanubian Range and in the middle of the Slovakian part of the model area. In the western foreland of the Gerecse and Vértes Hills, the succession continued with Middle and Late Albian with terrestrial clastics, shallow-water limestones and finally turned to open-marine marl (Figure 2).

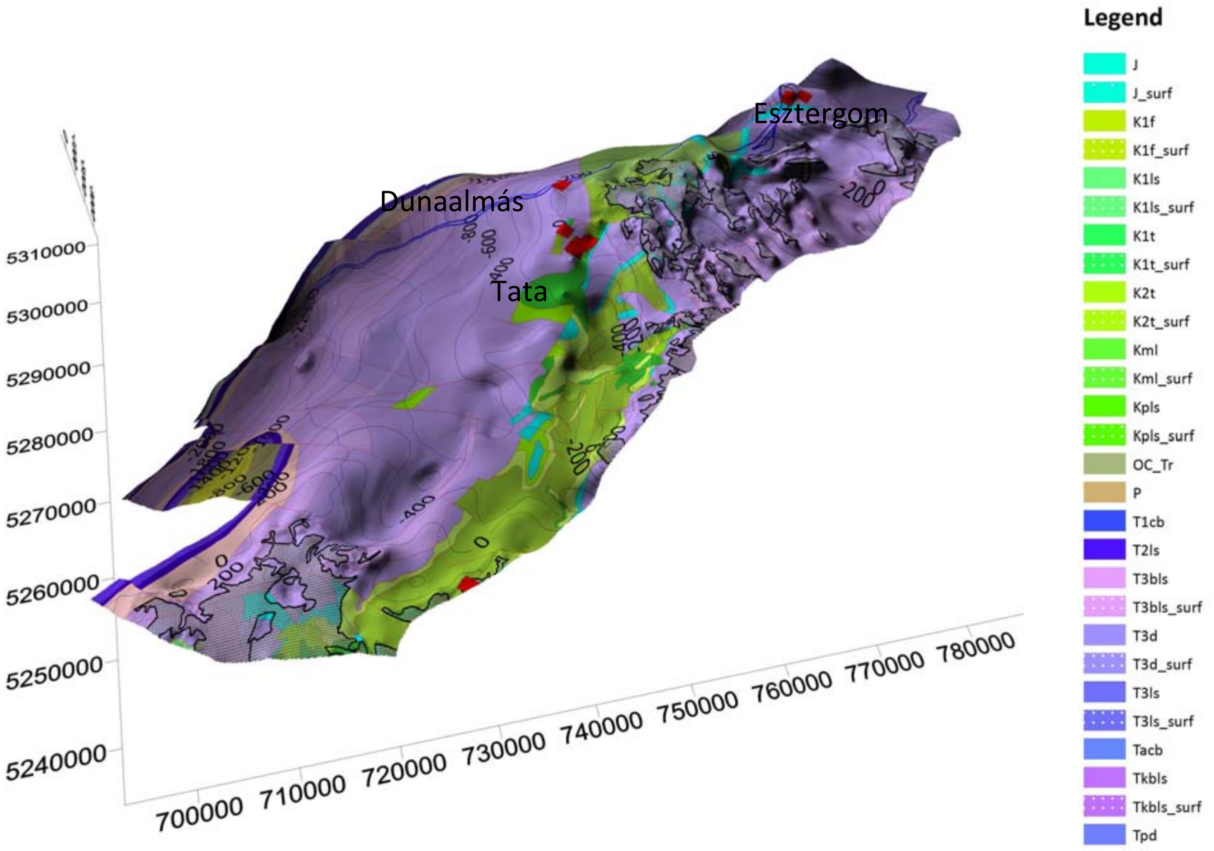


Figure 2. The geology and the depth (m a.s.l and b.s.l.) of the Mesozoic basement of the pilot model (black bold line – basement on the surface, red dots – lukewarm springs)

In the denudated and strong karstificated surface cavity of carbonates some karst-bauxite deposits were formed during the Late Eocene.

In the area of Hungarian Palaeogene Basin (NE part of the area) Eocene-Oligocene sequence is deposited on the Mesozoic basement.

The late Early Miocene sedimentation in the western part of the Gerecse Hills resulted in fluvial-limnic successions with thin coal layers, while the subsidence of the Danube Basin started at the end of the Early and the beginning of Middle Miocene. Karpatian and Badenian sediments consist of transgressive conglomerates, sandstones and volcanoclastics overlain by neritic calcareous clays, siltstones and subordinately sandstones. In the southern part of the Pilot Area terrestrial Miocene sediments occur only. Shoreline shallow-marine Sarmatian sediments deposited on the Karpatian and Badenian layers which covered by Late Miocene lacustric and delta and fluvial sediments have small thickness along the Mesozoic outcrops of the Transdanubian Range thickening towards the Danube Lowland. In the northeastern part of the Pilot Area some Neogene volcanic–volcanosedimentary rocks exist.

Quaternary is mainly represented by fluvial sediments, loess, and slope deposites.

3.2.2 Hydrogeological and geothermal settings

The main and the most important aquifers in the Pilot Area are the Upper Triassic platform limestones and dolomites (Dachstein Limestone and Main Dolomite). The Middle Eocene denudation caused strong karstification in the more than 1500 meters thickness carbonate sequence. These well karstified conduits and fractures along the tectonic elements determine the groundwater (karst-water) flow system: due to the karstification the upper part of the system has higher permeability so the groundwater flow take place in this zone.

From the area of outcrops of the Upper Triassic rocks (North-Bakony, Vértes, Gerecse, Pilis mountains) the precipitation flows towards the deeper regions to NW and W. From the NW edge of the aquifer the water turn towards N-NE and in the slovakian parts towards E. The natural discharge areas of the lukewarm system (>20°C) are Tata, Dunaalmás, Patince, Esztergom (Figure 3).

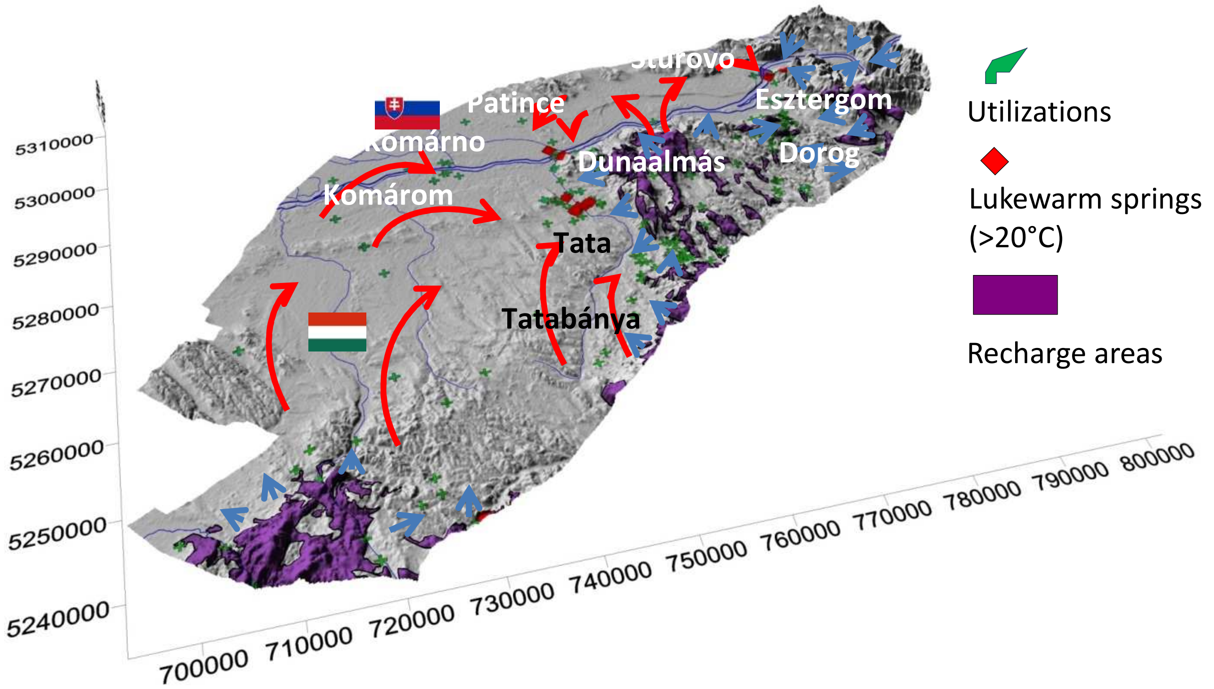


Figure 3: The main flow paths, natural discharge and recharge areas, and the utilizations in the last 75 years in the Pilot Area

The area is strongly affected by intensive groundwater abstraction connected to the coal and bauxite mines, which effected regional depressions and changed flow system (Figure 4). From the 1950's and 1960's the lukewarm springs along the Transdanubian Range also started to destroy and. after some years most of them were disappeared (Esztergom, Sárisáp, Dunaalmás, Tata, Patince). 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.).

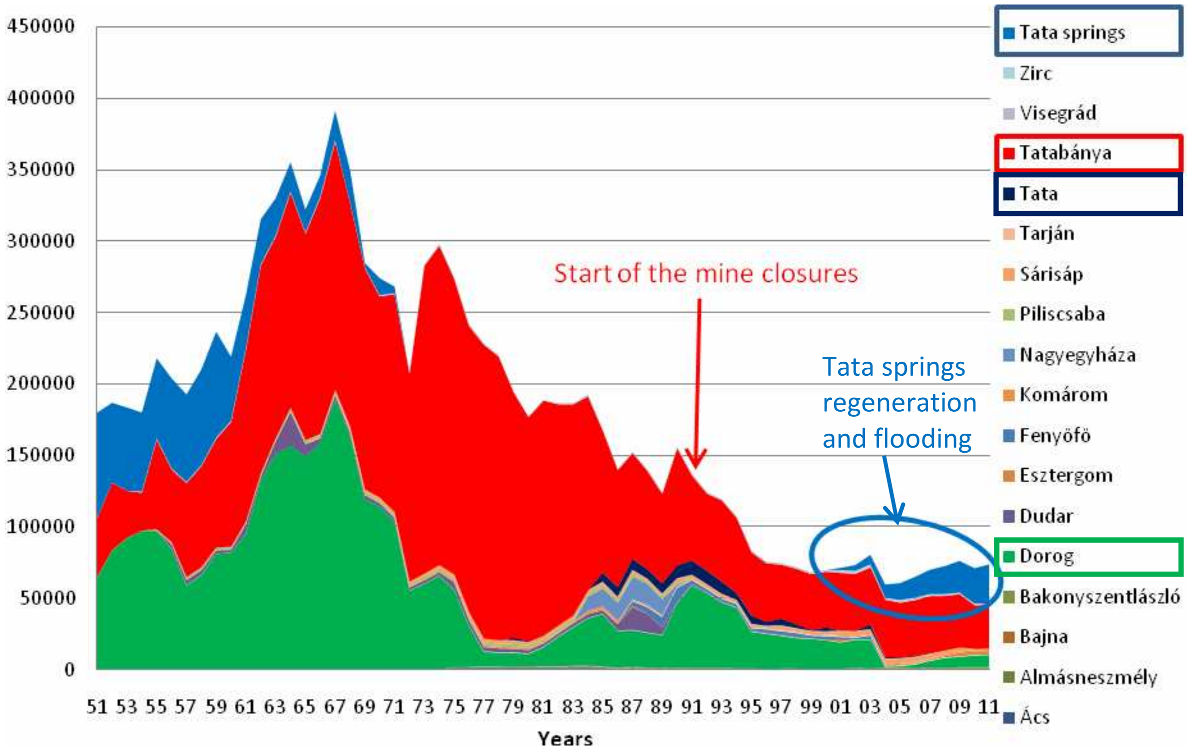


Figure 4: Karst water abstractions (m^3/d) in the Hungarian part of the Pilot Area

The main current users are the baths in both countries in the NE part of the area (Esztergom, Štúrovo). In Patince and Dunaalmás (historical) balneological and drinking water utilizations also exist. Near Komárom and Komárno balneological and agricultural utilizations take place. The most users utilize the lukewarm or thermal water of the Triassic karst aquifer, but some Miocene and Cretaceous local aquifer near Komárom and Komárno. The main current utilizations can be seen in the Table 1.

Along the margin of the mountains (Tata, Dunaalmás, Patince, Esztergom) - according to the flow system - we can find lukewarm (~20-27 °C) karst springs: Esztergom springs: 26-29 °C, Tata springs have 20-22 °C, Dunaalmás-Patince sprigs have higher, 23-24 and 25-27 °C water temperatures.

The marginal (W, NW, N) and deeper part (<-1600 m asl) of the Upper Triassic carbonate aquifer caracterized by higher temperatures which also part of the flow system ended at natural discharge points, but smaller amount: these thermal (40-60 °C) karst water produced by deep wells in the NW and N part of the area (near Bábolna, Ács, Komárom, Komárno, Štúrovo). Near Komárom and Komárno and also Štúrovo we can find thermal waters with the temperature exceeding 40 °C.

The higher (~40 °C) water temperatures in Štúrovo (against ~28 °C in Esztergom) can only be explained by longer flow pathes from NW, W direction.

Table 1. Current utilizations in the Pilot Area

*„Allowed amount for production in the water permits is much higher in several cases than the actual annual production“.

Site	**Number of wells**	**Aquifer**	**Usage**	**Actual production* (m^3/year) (2009)**
Ács (HU)	1	Lower Pannonian	agriculture	77 916
Almásneszmély (HU)	3	Upper Triassic	drinking water	223 580
Bábolna (HU)	3	Upper-lower Pannonian, Upper Triassic	balneology, agriculture	out of operation
Bakonyszombathely (HU)	1	Lower Jurassic, Upper Triassic	agriculture	388
Dunaalmás (HU)	2	Upper Pannonian, Jurassic	drinking water, agriculture	1050
Esztergom (HU)	6	Upper Triassic	balneology, drinking water	1 776 309
Komárom (HU)	2	Late Eocene	balneology	548 623
Pannonhalma (HU)	2	Upper Pannonian		No data
Szomód (HU)	1	Upper Triassic	agriculture	1825
Szomor (HU)	1	Upper Triassic	agriculture	13 589
Tata (HU)	9	Upper Triassic, Middle cretaceous	balneology, drinking water, industrial	63 343
Visegrád (HU)	1	Upper Triassic	balneology	142 112
Komárno (SK)	1	Lower Pannonian	balnelogy	10 274
Nová Stráz	1	Upper Pannonian	agriculture	out of operation
Patince (SK)	2	Upper Triassic	balneology	202 570
Stúrovo (SK)	3	Upper Triassic	balneology	440 059
Zlatná na Ostrove (SK)	2	Upper Pannonian	agriculture	105 290

4 SHORT SUMMARY OF THE STEADY STATE NUMERICAL MODEL

The description of the steady state modelling are described in the Pilot Area report (Gáspár et al 2013), only short summary is provided below.

The aim of the steady state modelling was to simulate and better understand the natural hydrogeological and geothermal conditions in the cold and geothermal water body of Mesozoic carbonate rocks near the surface in the Transdanubian Range and in the deep towards the Danube basin. In this phase one of the main goals was to reconstruct the pre-abstraction state of the system before the bauxite and coal mining.

4.1 Model geometry

To investigate the natural flow system a 12-layered numerical model was constructed which simplify the complex geological and hydrogeological system. The model layers follow the geological settings: the pinched out layers exists towards E, SE which were taken to consideration during the model building. Six main hydrostratigraphic units were defined this way in twelve numerical layers (Figure 5). The tenth layer represents the uppermost 100 meters of the cavernous Triassic carbonate unit.

Model layer	Hydrostratigraphic unit
1	Quaternary
2-5	Upper Pannonian
6-7	Lower Pannonian
8	Miocene (Sarmatian, Badenian)
9	Paleogene
10-12	Mesozoic basement

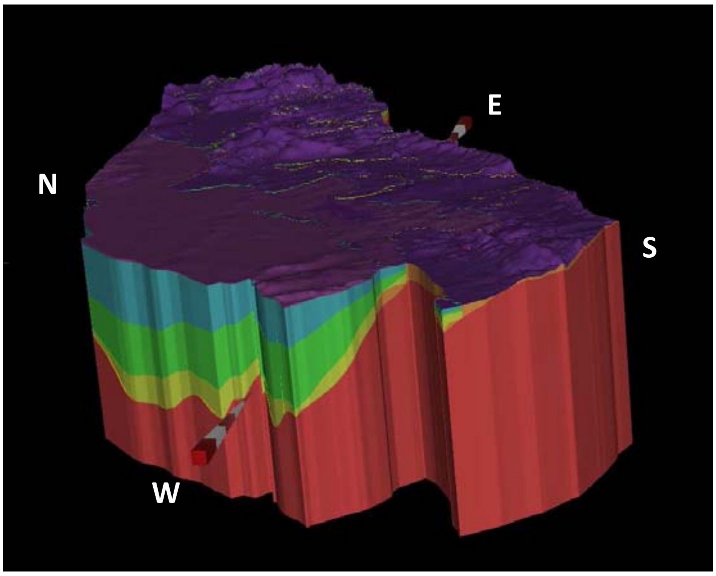


Figure 5. The main hydrostratigraphic units of the model

The main (Triassic) karst aquifer is outcropped in the southern and the south-western part of the model area. The bottommost part of the aquifer was settled down in the north-western and northern part of the pilot model area. At these locations the top of the Triassic aquifer is lower than 2500 m mASL (Figure 5).

4.2 Boundary conditions and material properties of the numerical model

We try to follow the rule to choose borders along "no-flow" boundaries, thus only the SW and the NE boundary of the model is artificial and on the model layer 10 we used fixed hydraulic head boundary conditions derived from the available hydraulic head maps of the Transdanubian karst system (Alföldi 2007). The Danube represented as a fixed head boundary condition in this model phase on the model top. The bottom of the model also represented with no flow boundary condition. A Dirichlet boundary condition with uniform temperature was set at the top of the model (11 °C) and at the model bottom 80 mW/m^2 heat flux was added.

The applied K values are based on well hydraulic tests, well measurements, literature data and previous observations and modelling experience. The conductivity zones of the model layers are based on and determined, or assumed according to the hydrogeological characterization of the geological formations. In one layer to represent the different formations parameters change was used (Figure 6).

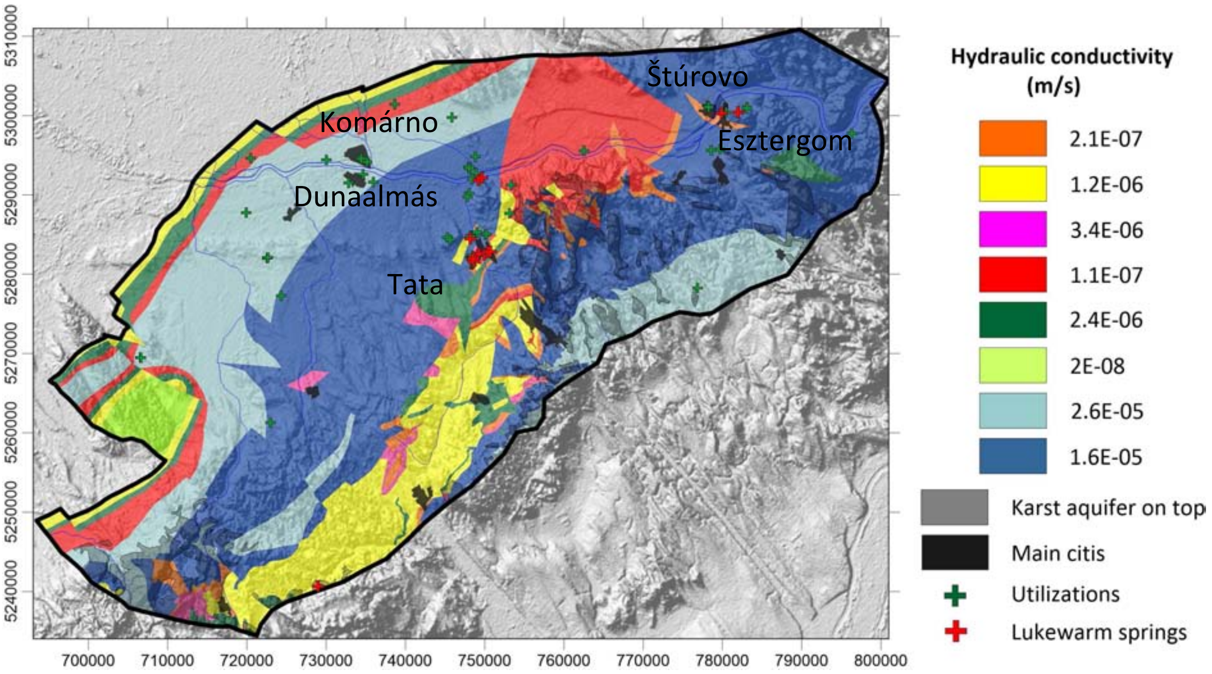


Figure 6. Hydraulic conductivity zones of the model layer '10', represented the Mezozoic basement

Porosities can derive from laboratory measurements, geophysical logs, analogies and experiences from previous models, giving a possible range of values for regional hydrogeological modelling. In the first step a general effective porosity value (0.15) was determined but during the calibration phase the value changed and the finally used porosity values are shown in Table 2.

The main heat transport parameters are evaluated by measured and literature data; default data of the FeFLOW® software were accepted for the thermal conductivity of fluid, the volumetric heat capacity of fluid and solid. The heat conductivity of the model layers is used from literature and the supra geothermal model data (Table 3).

Table 2. Hydraulic conductivities and geothermal properties of the model

Hydrostratigraphic unit	**Kxx = Kyy (m/s)**	**Vertical anisotropy (Kh/Kv)**	**Heat conductivity of solid [W/mK]**	**Porosity**
Quarternary	8×10^{-6} - 2.5×10^{-4}	10	1.5	0.25
Upper Pannonian	4×10^{-6}	100	1.8	0.1 - 0.15
Lower Pannonian	1×10^{-9}	1000	2	0.05
Miocene (Sarmatian and Badenian)	1×10^{-8} - 1×10^{-6}	10 - 1000	1.5 - 2	0.01 - 0.1
Paleogene (Eocene – Oligocene), and low permeable createceous	1×10^{-7} - 1.5×10^{-5}	10 - 100	1.5 - 2.1	0.1 - 0.5
Triassic basement weathered zone	2.6×10^{-5} - 2×10^{-8}	10 - 100	2.2 - 3.8	0.01 - 0.1
Triassic basement non-weathered, fresh zone	2.6×10^{-6} - 2×10^{-9}	10 - 100	2.2 - 3.8	0.01
Lower non-weathered zone of older Mesozoic layer	1×10^{-8}	10	3.5	0.01

4.3 Natural state of the aquifer

The coupled groundwater flow and heat transport model provided information on the hydraulic head and temperature distribution. The simulated karst water table and temperature distribution plots are shown in Figures 7-8. The simulated groundwater head distribution distribution indicate that the main flow direction within the model domain is from SW to N and then towards E. Subsurface water and heat flow has no limit along national borders. The simulated results are well reproduces this situation.

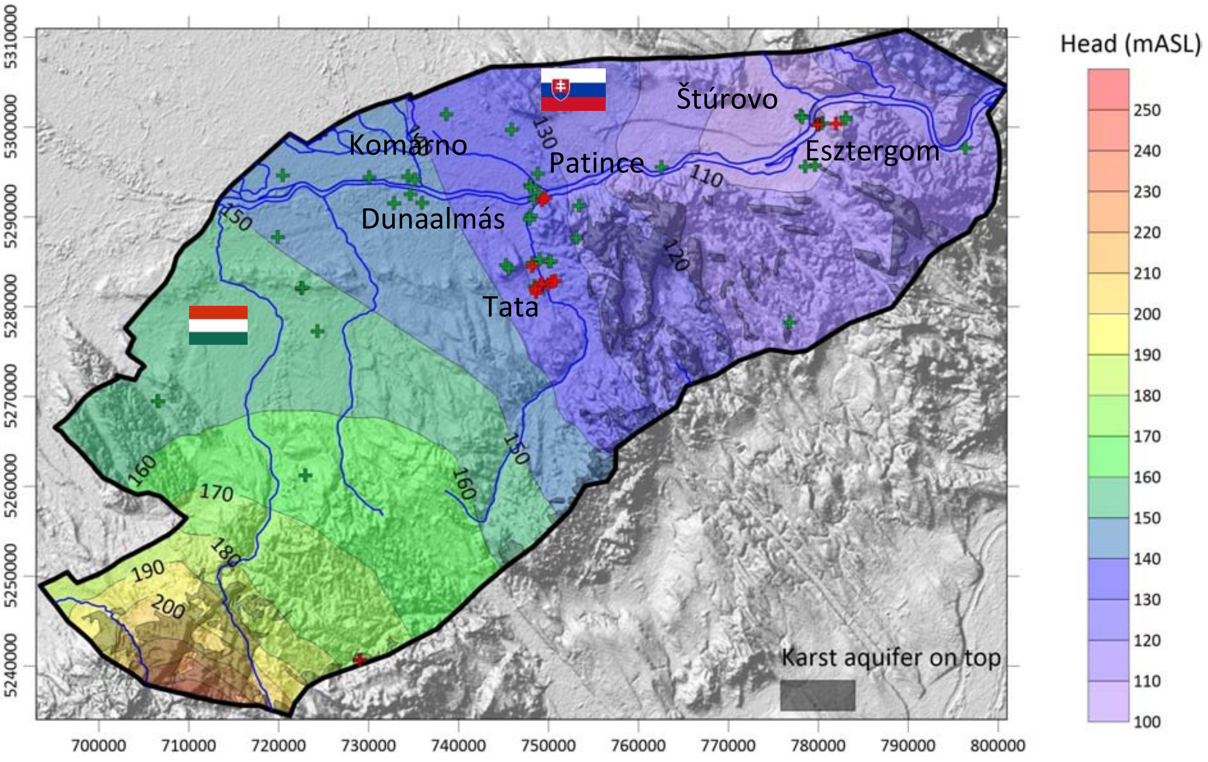


Figure 7. Modelled hydraulic head on the model layer ‘10’, represented the Mezozoic karst aquifer

The temperature distribution of the Transdanubian karst flow system is mainly affected by forced heat convection. In the karstified dolomites and limestones the water can flow deep down the surface without any barrier: the recharged precipitation water cool down the system even at high depths. Due to the intensive flow system, this cooling effect can observed also far from the recharge areas (Figure 8).

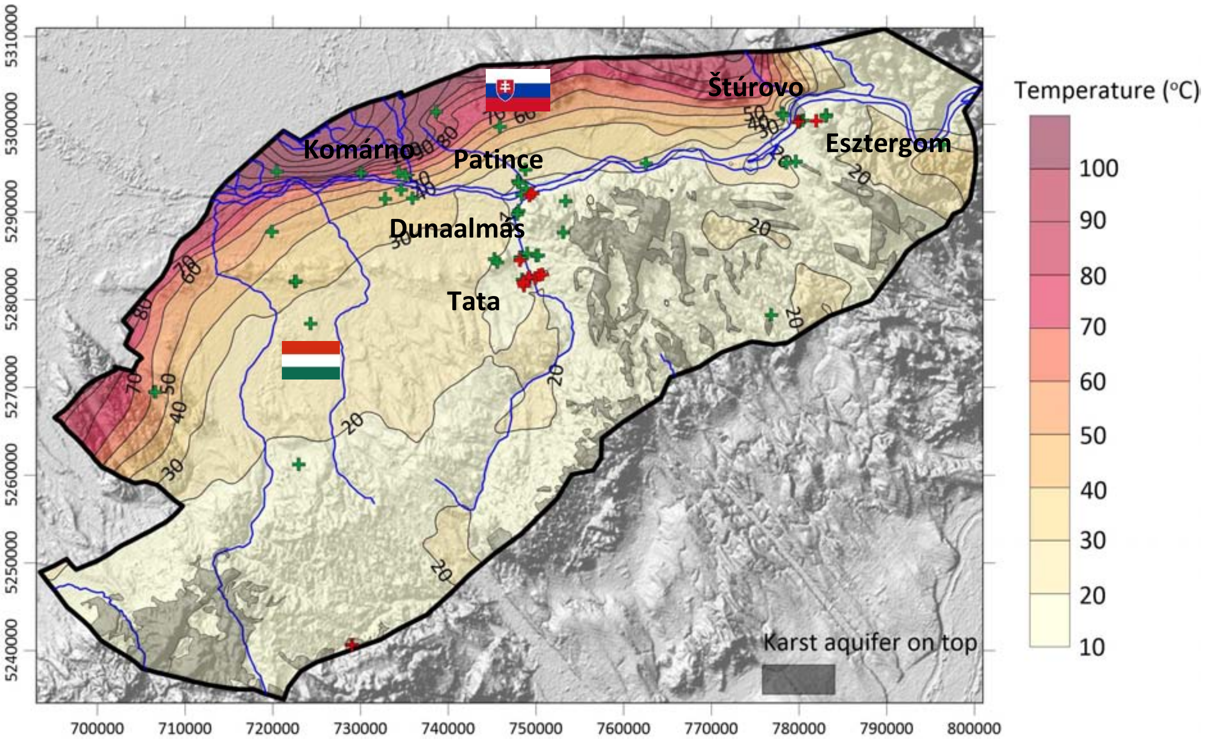


Figure 8. Modelled temperature distribution in layer ‘10’ (top of Mesozoic basement)

5 MODEL SCENARIOS

The simulation of the different scenarios is based on the existing steady state flow and coupled heat model. 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.

6 RESULTS

6.1 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) (Summary in chapter 4).

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) (Figure 4). 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 9 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 10). 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.

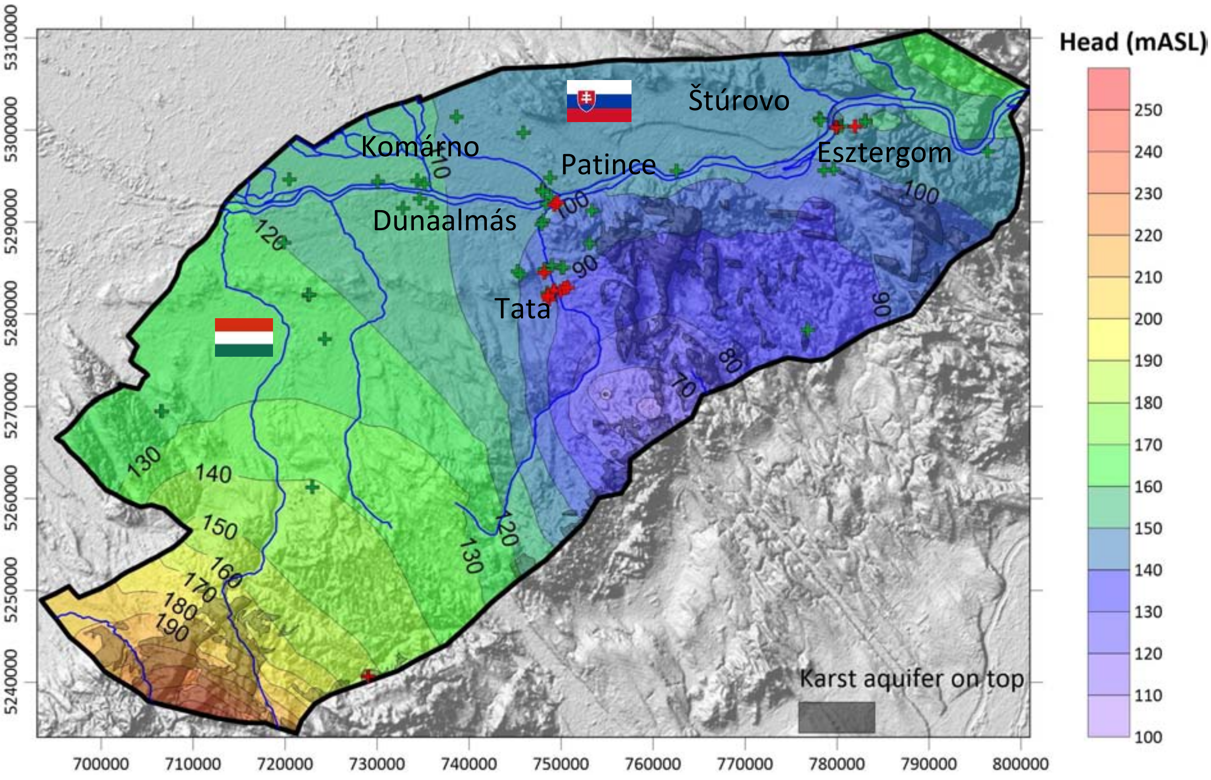


Figure 9. Modelled hydraulic head in the Mezozoic karst aquifer – water abstraction as much as in the late 1980's (Scenario 1)

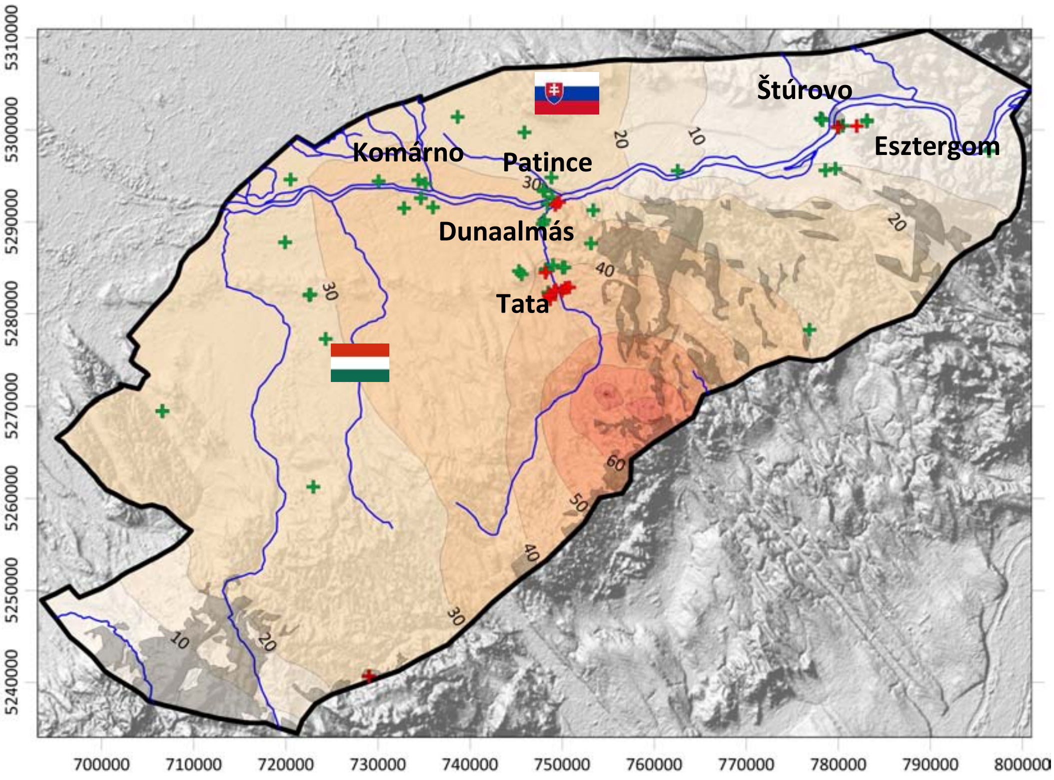


Figure 10. Modelled depressions in the Mezozoic karst aquifer (Scenario 1)

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 11 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 12), 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.

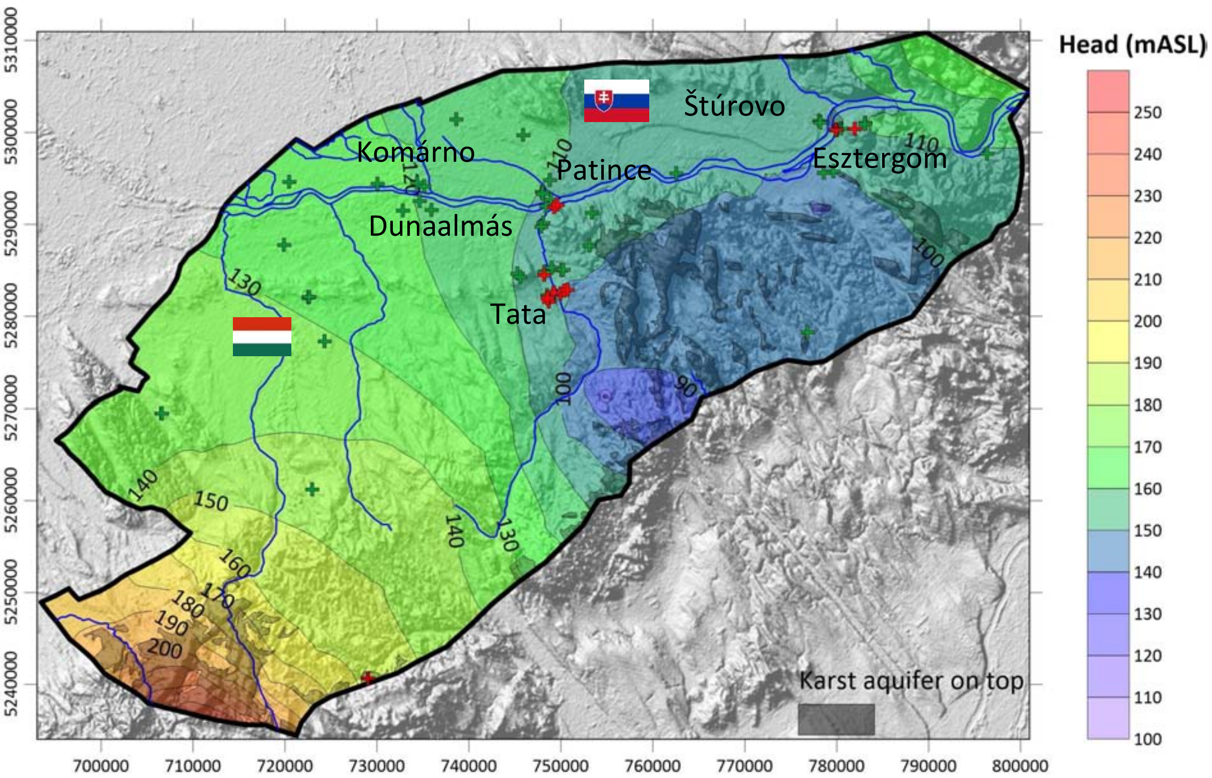


Figure 11. Modelled hydraulic head in the Mezozoic karst aquifer – water abstraction as much as in the 2000’s (Scenario 2)

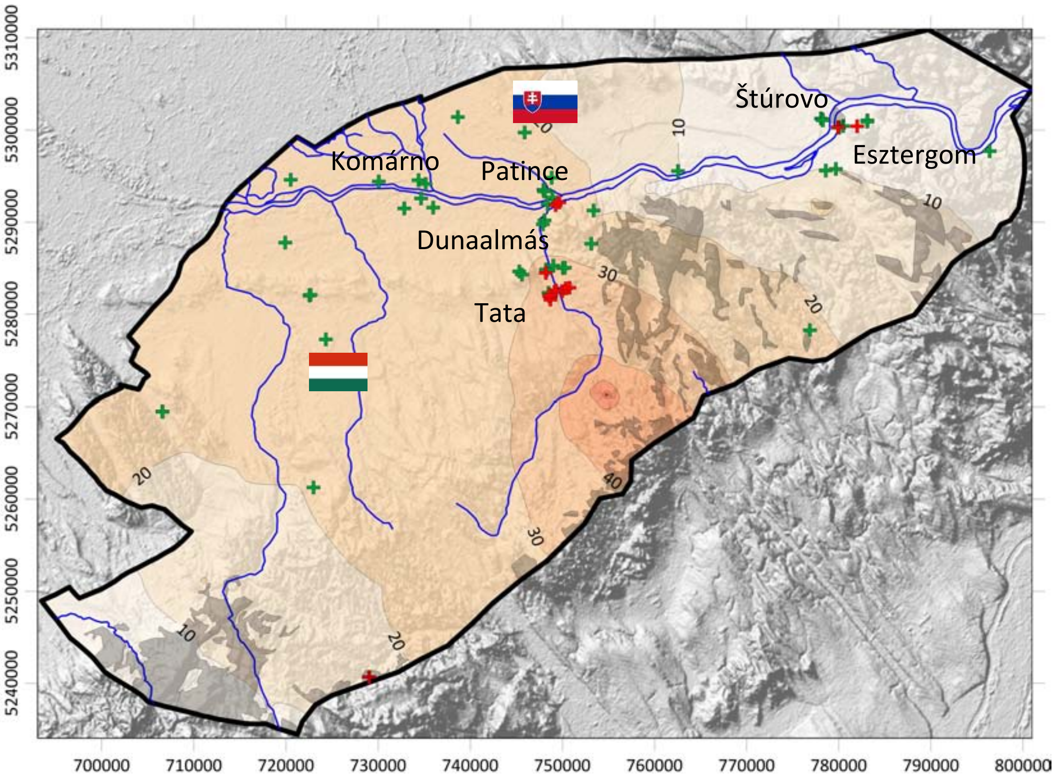


Figure 12. Modelled depressions in the Mezozoic karst aquifer (Scenario 2)

Our third scenario is the modelling of the effect of the drinking water abstractions after the mine closures (Figure 13). The main drinking water pumping sites are near Tatabánya and Esztergom. The deepest depression exists near Tatabánya, where around 30 000 m^3/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 14). 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.

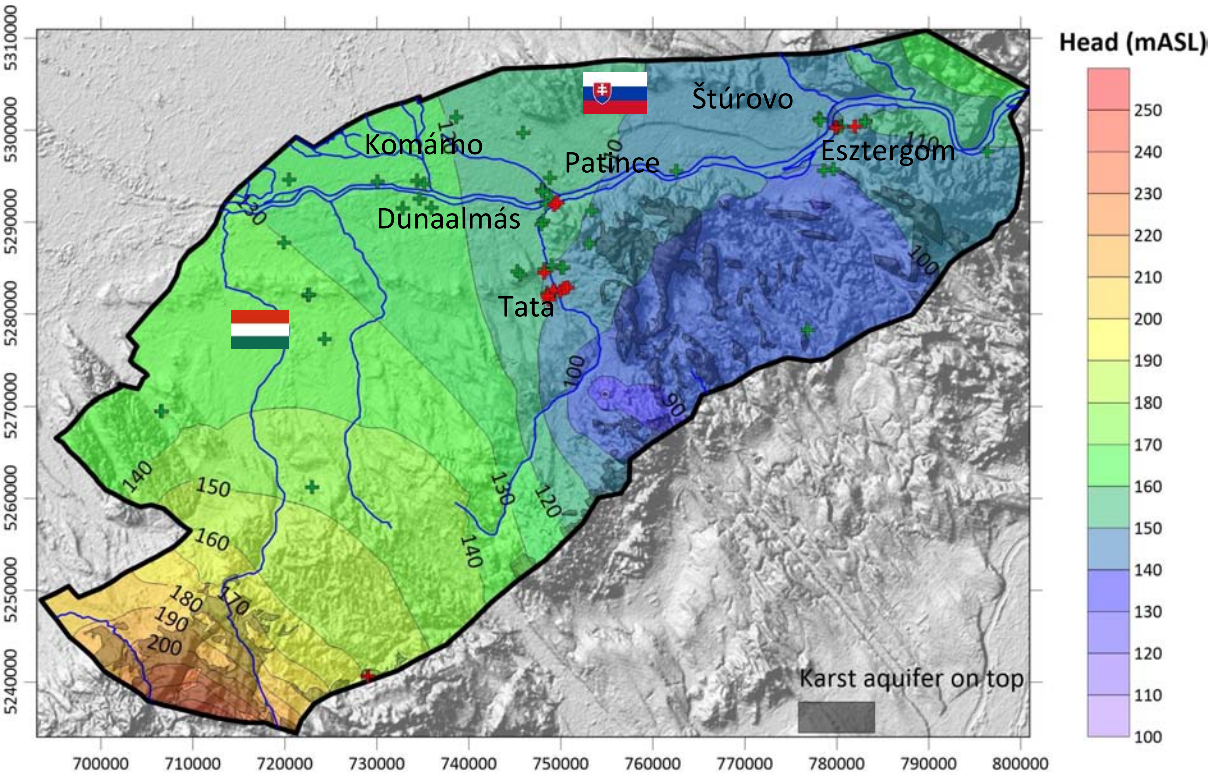


Figure 13. Modelled hydraulic head in the Mezozoic karst aquifer – drinking water abstraction as much as nowadays (Scenario 3)

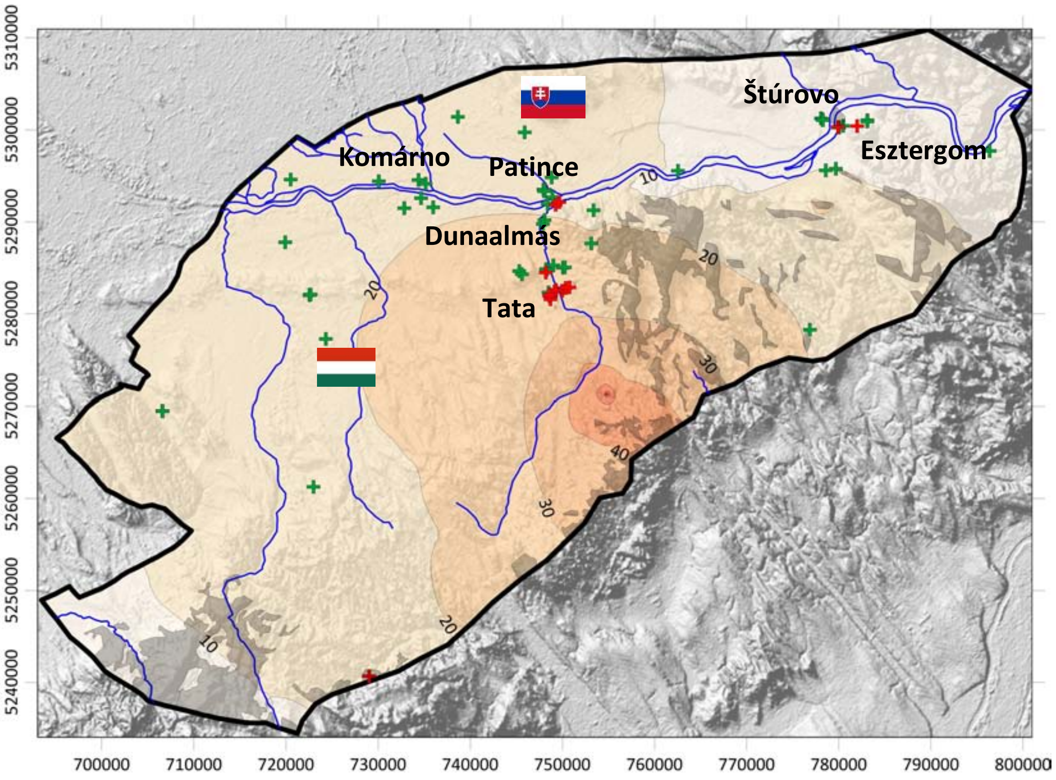


Figure 14. Modelled depressions in the Mezozoic karst aquifer (Scenario 3)

6.2 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 15). 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.

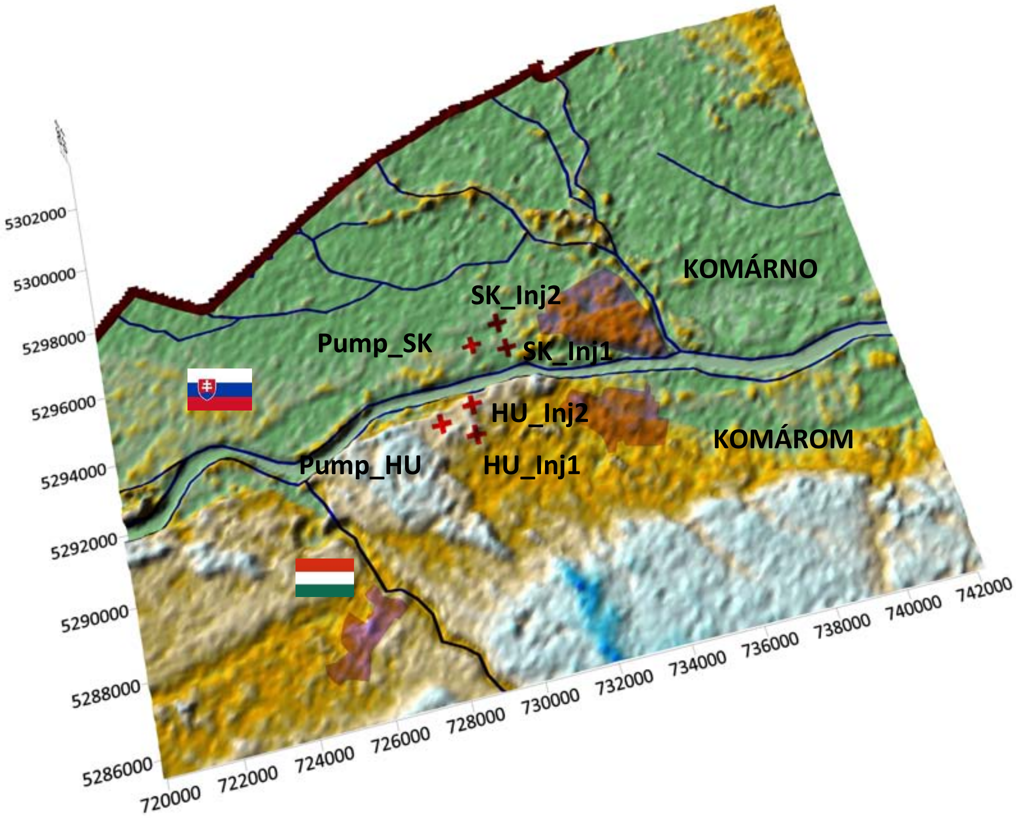


Figure 15. Theoretical well doublets in the area of Komárom - Komárno

The parameters of the investigations were the following (Table 3):

Table 3. 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

6.2.1 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 16) 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 17-18).

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.

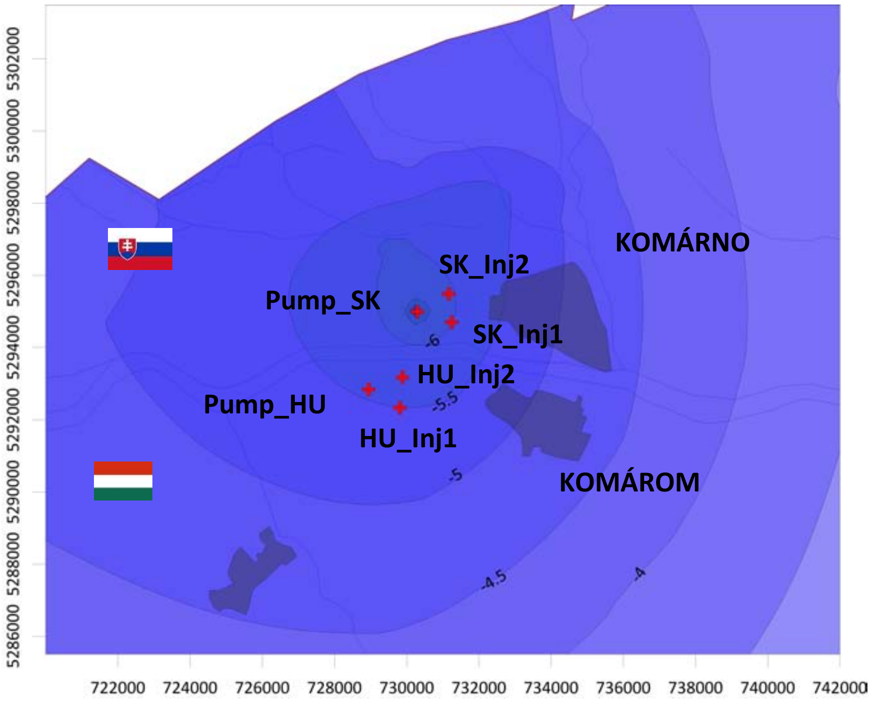


Figure 16. Steady state depression around a theoretical well near Komárno. No reinjections well exists.

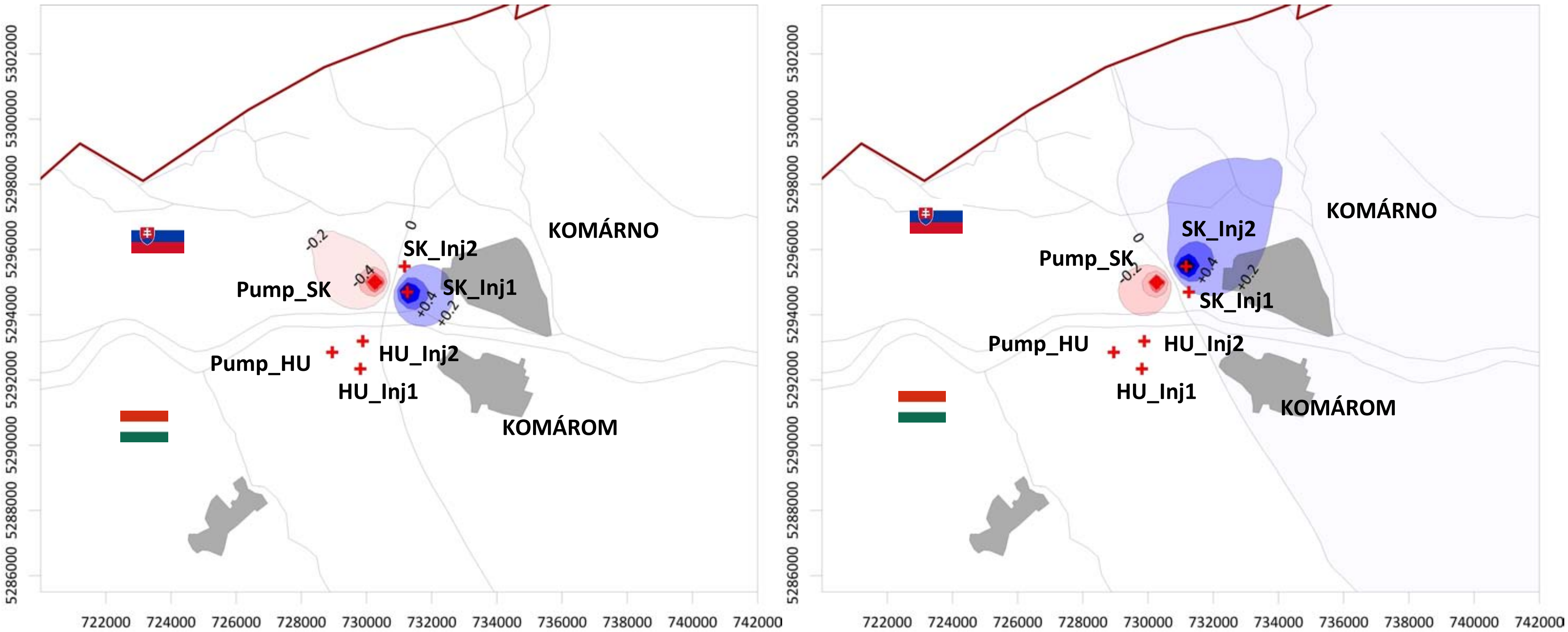


Figure 17. Steady state depression and pressure increasing around a theoretical doublet near Komárno (Scenario 5a).

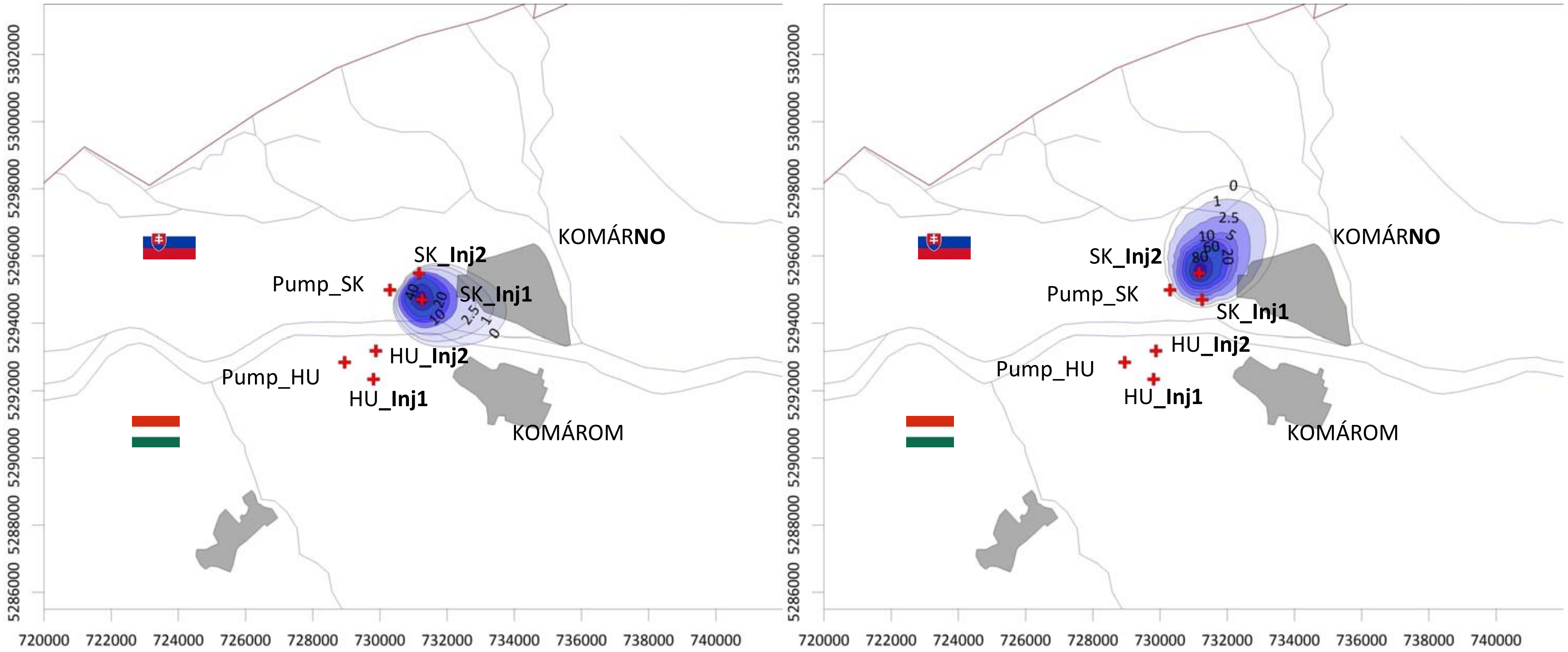


Figure 18. Steady state modelled thermal influence around a theoretical reinjection well near Komárno (Scenario 5b).

6.2.2 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 19). 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 20). The thermal influence of the reinjection well is a circle of app. 2.5 km radius around the well (Figure 21).

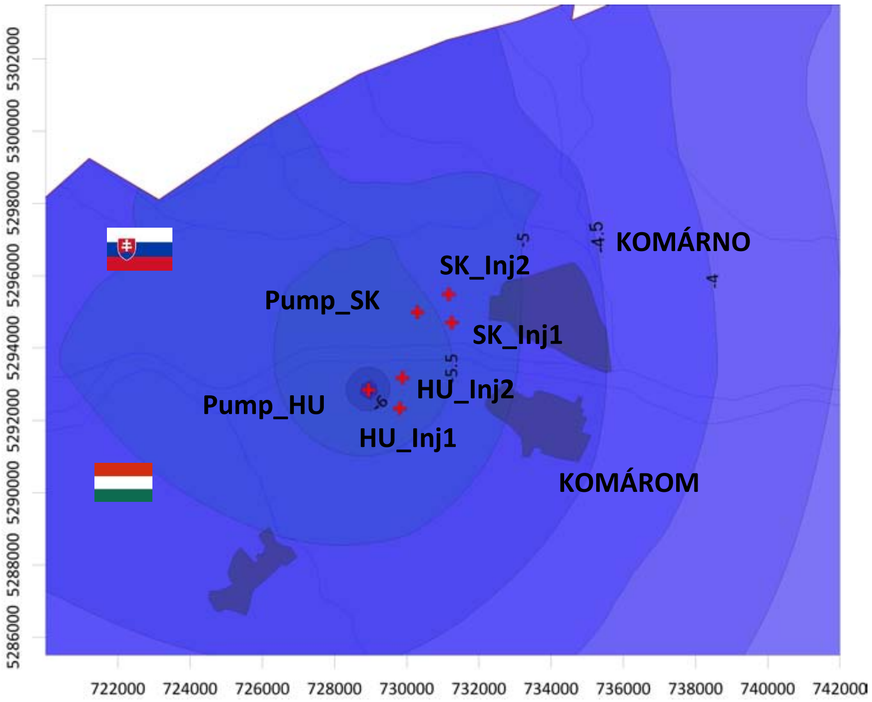


Figure 19. Steady state depression around a theoretical well near Komárom. No reinjections well exists.

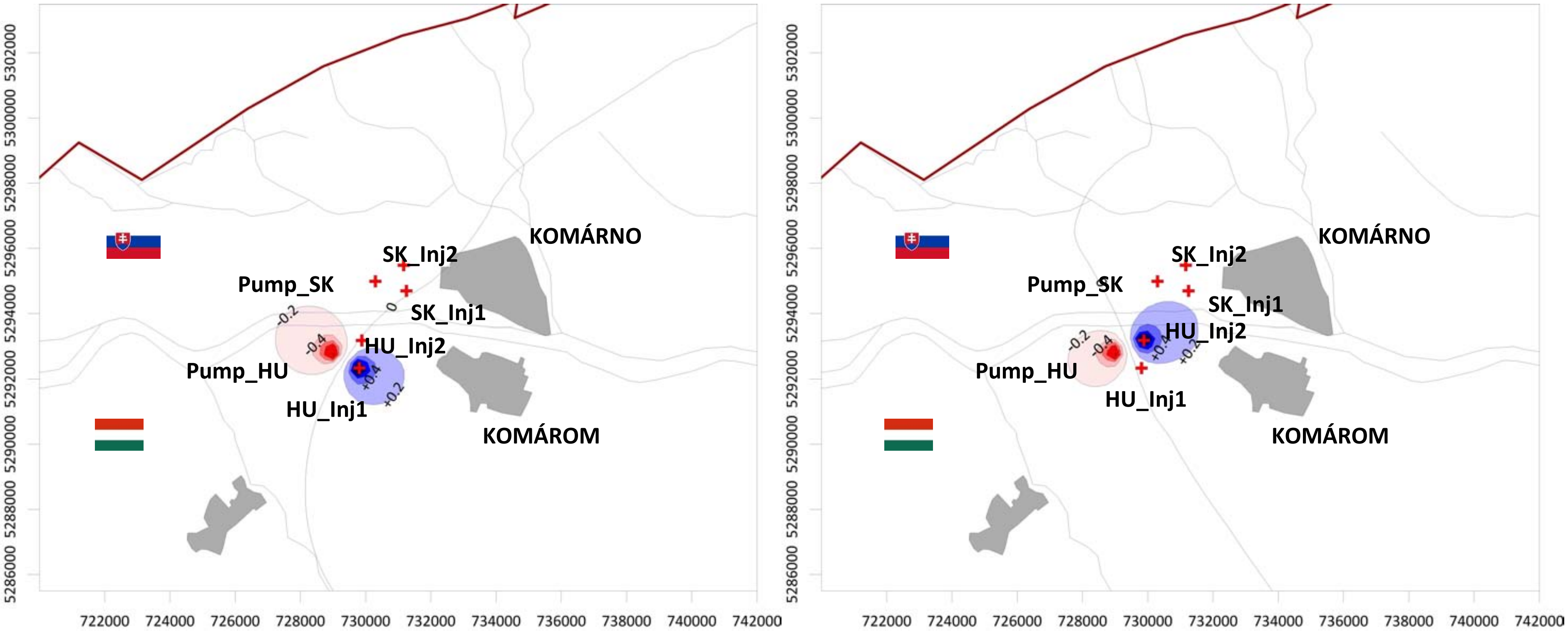


Figure 20. Steady state depression and pressure increasing around a theoretical doublet near Komárom (Scenario 7a).

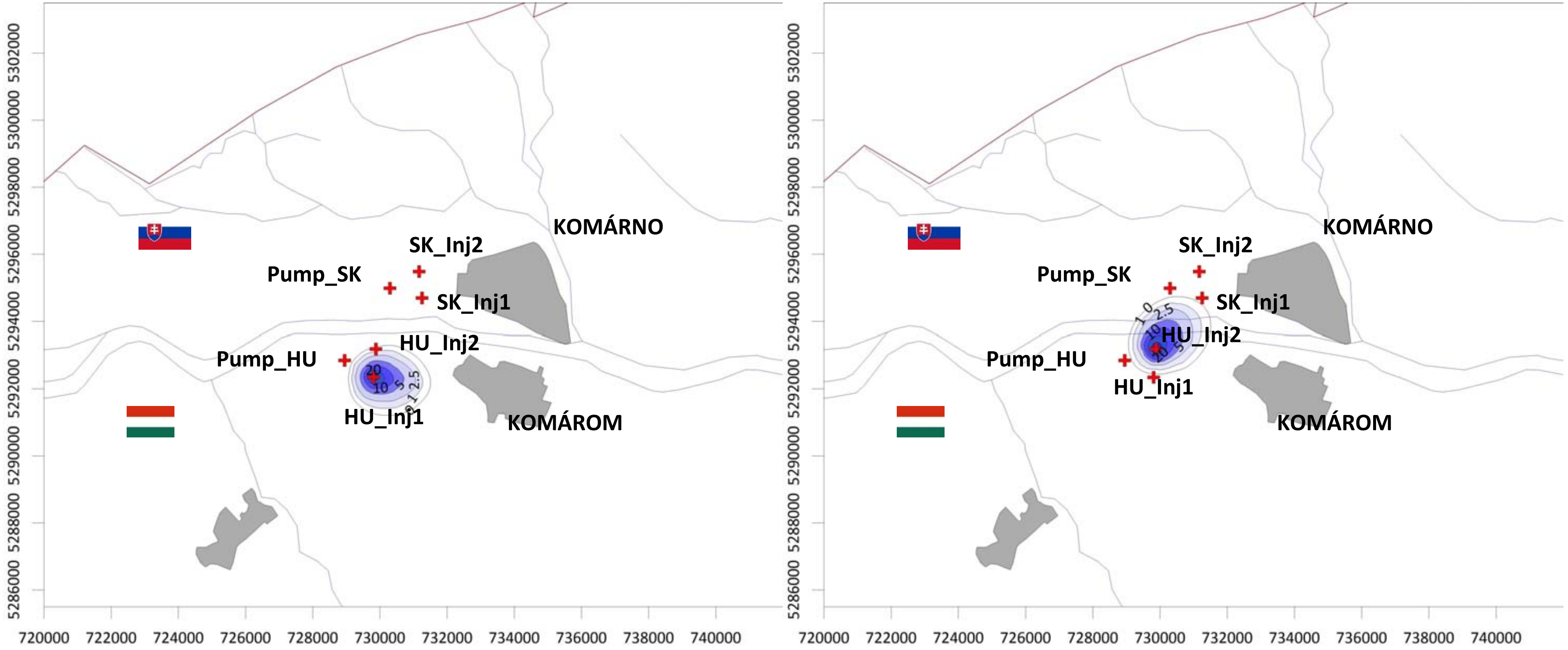


Figure 21. Steady state modelled thermal influence around a theoretical reinjection well near Komárom (Scenario 7b).

6.2.3 *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 22). 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 23). Due to the natural flow system the Hungarian pumping well and the Slovakian reinjection well had the more extensive impact areas (Figure 23). The thermal influence of the reinjection wells (Figure 24) was more extensive than in the previous scenarios: a 5*6 km ellipse shaped area around the wells (Figure 17-18).

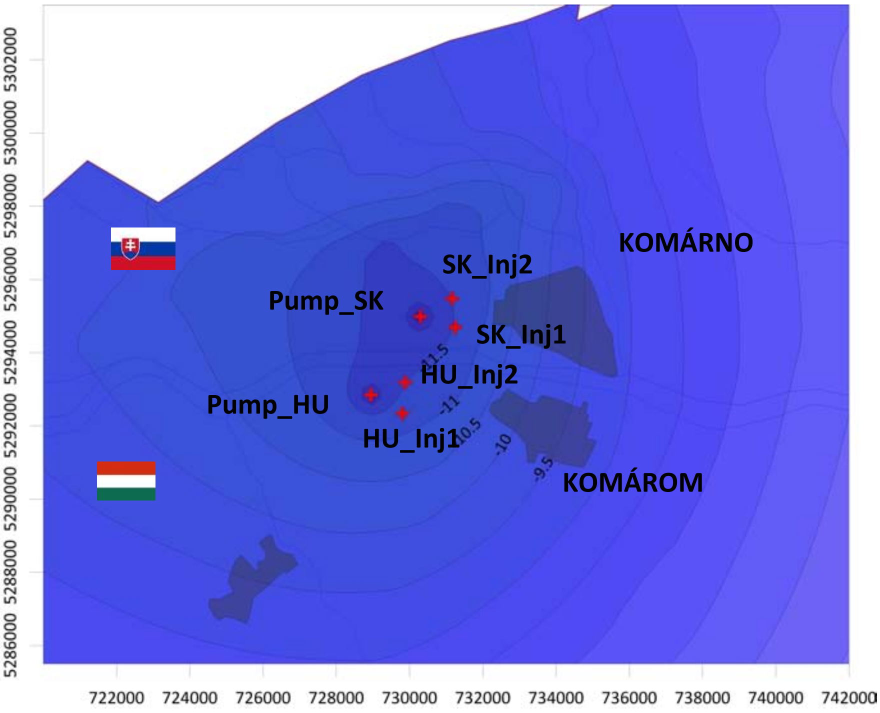


Figure 22. Steady state depression around a theoretical wells near Komárno and Komárom. No reinjections well exists.

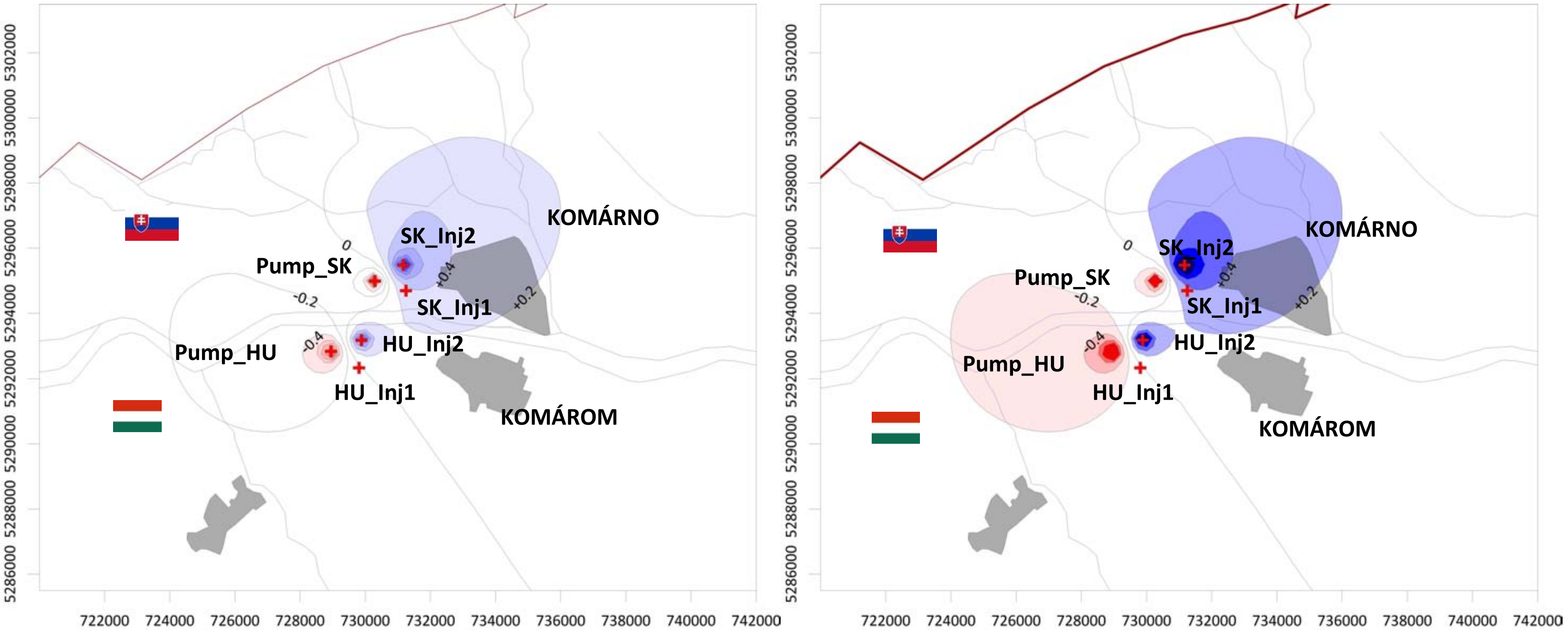


Figure 23. Steady state depression and pressure increasing around a theoretical doublets (Scenario 9a).

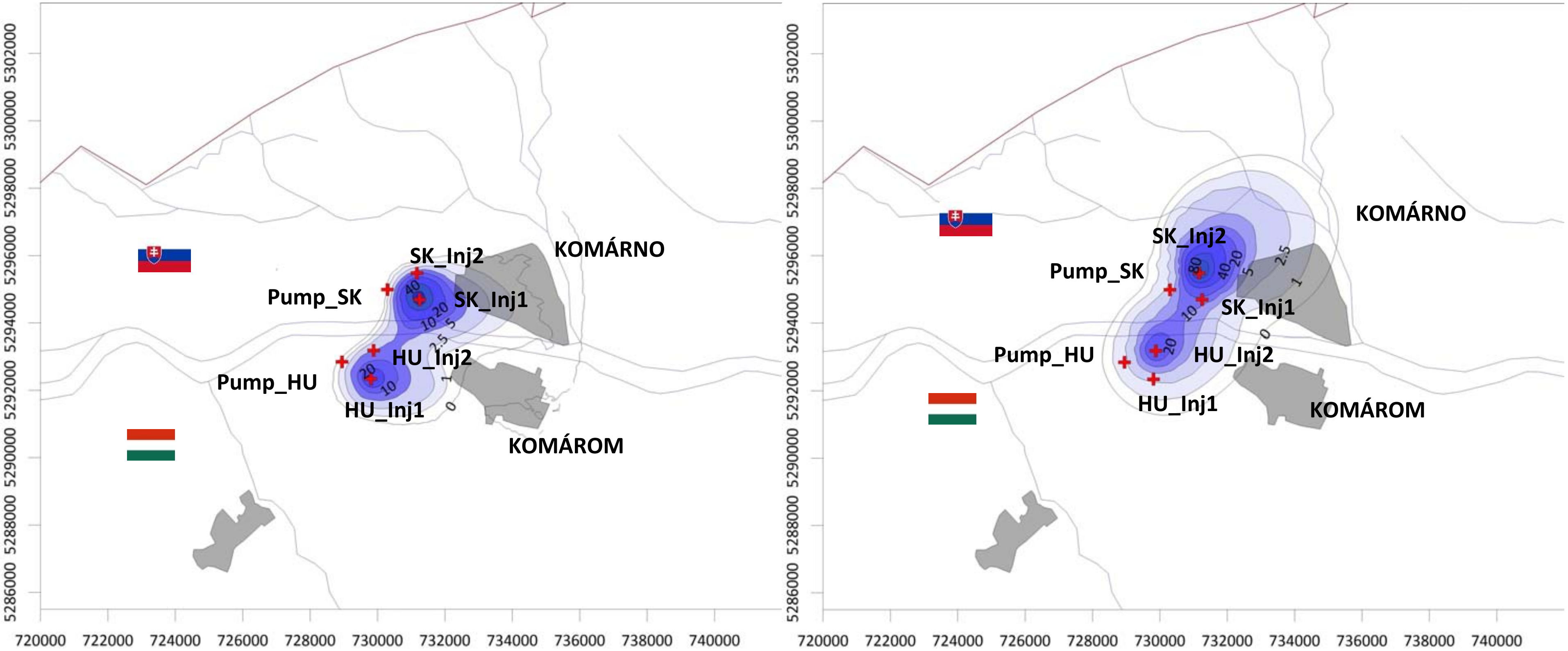


Figure 24. Steady state modelled thermal influence around a theoretical reinjection wells (Scenario 9b).

7 RESOURCE ESTIMATION

In the Komárom-Štúrovo Pilot Area numerous hydrogeothermal utilizations exist and in the future additional geothermal utilizations could be installed in the deeper, higher temperature part of the reservoirs. To estimation of (hydro)geothermal resources in the area we performed calculations to identify the potential geothermal resources. For these calculations we used 2D (1000*1000 m) grids derived from the geological and 3D coupled flow and heat transport model (convective heat transport dominated in the area). During the calculation we followed the same method in the 5 Pilot Areas, which is the following (associated to the "Canadian Geothermal Code for Public Reporting" (Deibert et al., 2010)):

The resources and reserves are calculated for identified hydrogeothermal plays:

- Description of the Hydrogeothermal Play(s) in the area and preparation of input data;
- Calculation of the Heat in Place (HIP);
- Calculation of the Inferred Resources (IR);
- Calculation of the Measured Resources (MR);
- Calculation of the Probable Reserves (PR).

In the Komárom-Štúrovo Pilot Area we performed the assessments for the Mesozoic karstic reservoir which consists of karstic, fissured carbonate rocks and high temperature karst water in the NW part of the area. The main utilizations in the Pilot Area are the balneological utilizations of the thermal wells and the lukewarm karst springs and some agricultural (heat supply) utilizations exist from the porous aquifers; but there are possibilities in this NW part for the heat supply from the Mesozoic karst aquifer also.

All resource estimation was calculated for the Mesozoic karst reservoir because this was the focus of our investigation.

3 different scenarios were used for the estimation:

- Balneological utilizations;
- Heat supply (e.g. district heating);
- Electric power generation.

Every scenario had initial parameters: minimum temperature of the thermal water (T_{min}), injection/discharge temperature of the water (thermal efficiency of the utilization) (T_{ref}) and the type of the utilization: single or well doublet (Table 4):

Table 4. Initial parameters of the scenarios

Parameter	**T_{min} (°C)**	**T_{ref} (°C)**	**Type of utilization**
Balneology	30	10	Single well
Heat supply	40	25	Well doublet
Electric power generation	105	55	Well doublet

7.1 The Mesozoic karst aquifer and the Hydrogeothermal Play

The main Hydrogeothermal Play in the Komárom-Štúrovo Pilot Area is represented a part of the main Mesozoic karst aquifer of the region. During the delineation of the Hydrogeothermal Play we have taken into consideration the well-known and the less well-known geological formations and structures which can be become thermal (karst) water reservoir and we used the geological model and the 3D numerical model of the Pilot Area (Figure 25).

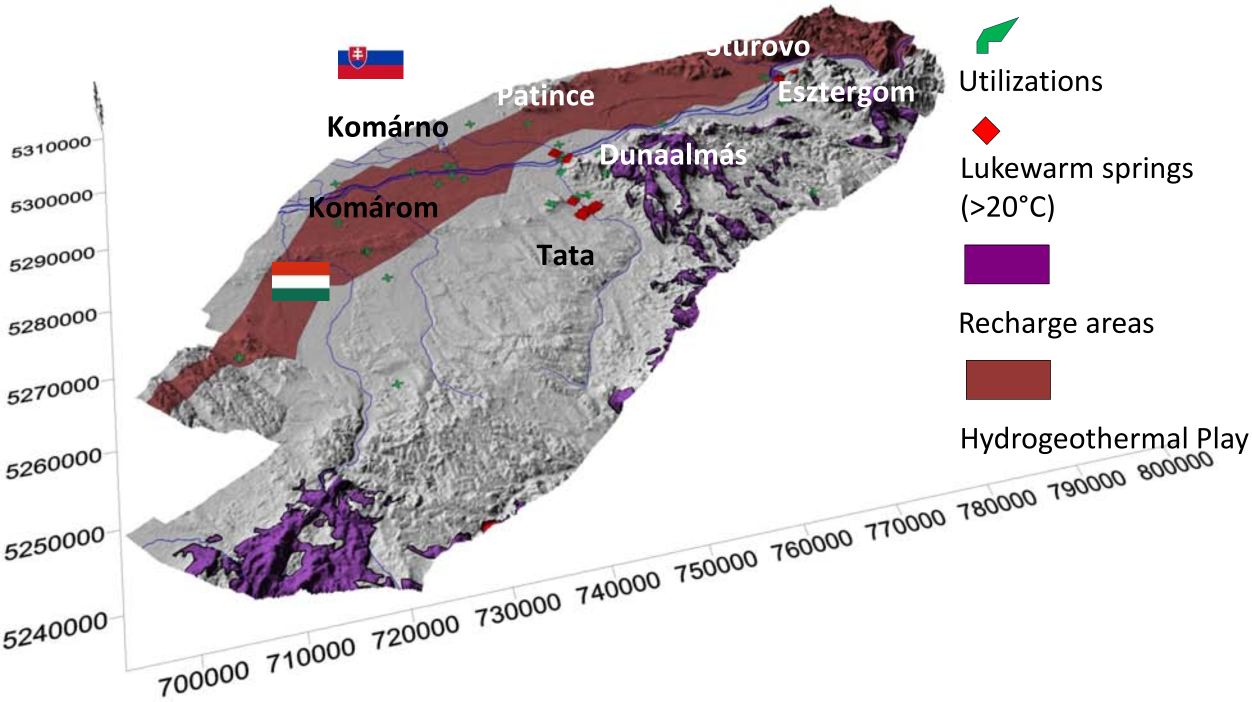


Figure 25. The main Hydrogeothermal Play of the Komárom-Štúrovo Pilot Area

Although the Mesozoic karst aquifer is presented almost in the whole Pilot Area, the investigated Hydrogeothermal Play (HP) is only a part of it and existed in the NW and N part of the Pilot Area. The karst aquifer and the HP is mainly covered by younger, Palaeogene and Neogene sediments and the aquifer is partly outcropped in the hilly region (Gerecse, Vértes, North-Bakony) of the Pilot Area. The minimum depth of the HP is app. 500 m below the surface, while the maximum depth is more than 3700 m below the surface in the NW part of the region. The thickness of the HP is evaluated;

based on the observation of the thickness of the karstified zones, literature data and our previous experiences, so we used a uniform 200 m thickness in the whole area.

For the estimation the following data were applied (Table 4):

Table 5. Input data of the resource estimation

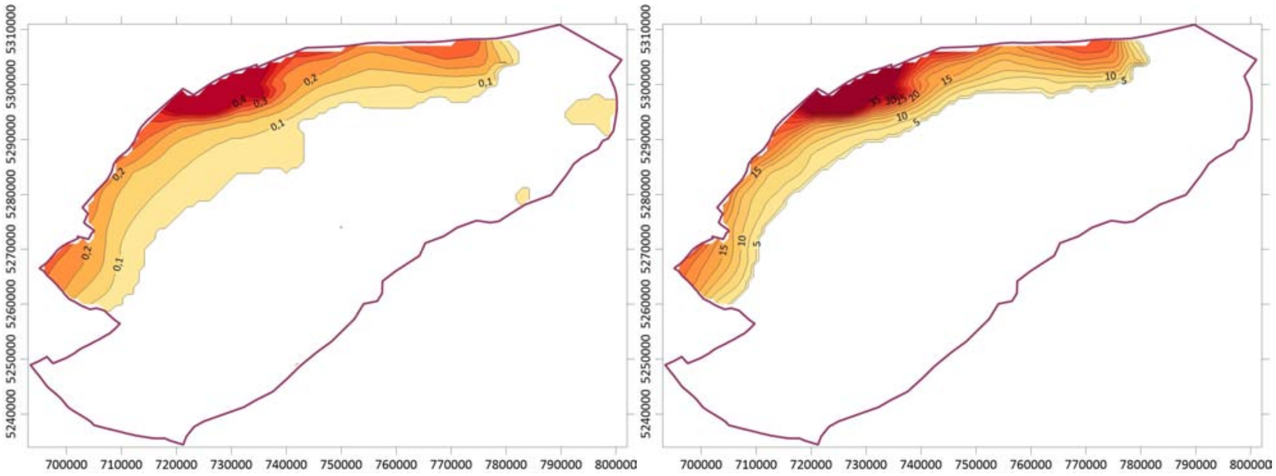
Parameter	**Value**
Average thickness (m)	200
Minimum depth (m)	500
Maximum depth (m)	3760
Gross volume (km^3)	163.71
Gross Aquifer volume (km^3)	1.6371
Volumetric heat capacity (J/m^3*K)	914
Hydraulic conductivity (m/s)	2.1E-04
Transmissivity (m^2/s)	4.2E-02
Average temperature (°C)	10
Maximum temperature (°C)	155

7.2 Result of the resource estimation

7.2.1 Calculation of the 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 (associated to Deibert et al., 2010).

HIP was calculated for three different scenarios included balneological utilization (T_{ref} 10 C°), heat supply (T_{ref} 25 C°) and electricity generation (T_{ref} 55 C°). The calculated HIP distributions are shown in Figure 26.



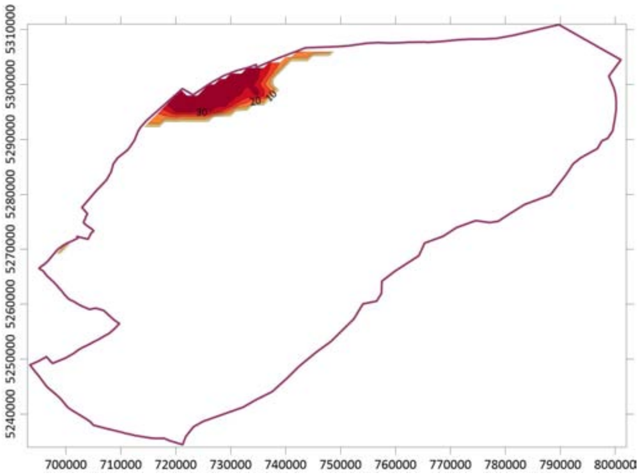


Figure 26. Heat In Place distribution, Mesozoic karst reservoir

The calculated HIP is shown in the following table (Table 9).

Table 6. Calculated resources (MW for 50 years of utilization) for the Komárom-Štúrovo Pilot Area.

Resource	**Scenario**	**Calculated value**
Heat in Place	Balneology	235.03
	Heat supply	15,730.7
	Electric power generation	3,895.8
Inferred Resources	Balneology	51.25
	Heat supply	5,326.8
	Electric power generation	1,319.2
Measured resources	Balneology (min 20°C)	0.2
	Balneology	0.2
	Heat supply	17.2
	Electric power generation	-

7.2.2 Calculation of the Inferred Resources (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.

The calculation are performed on a 1000 * 1000 m raster, assuming 1 well doublet (1 production well + 1 injection well) on each raster cell. The distance between the wells is constant, 500 m. The total thermal capacity is calculated by a sum of all raster cells.

The calculation of the Inferred Resources for the balnelogical scenario was followed a slightly different approach: the heat content of the thermal water is also used in this approach. For the calculation 1 single well set in each raster (1000 * 1000 m) cell. The extracted heat from a single well is only depending on the temperature level of an aquifer, if we assume a constant yield (Q): 10 l/, then the inferred resources can be calculated.

The calculated IR is shown in the Table 9.

7.2.3 Calculation of the Measured Resources (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.

The calculation of the Measured Resources also based on the same 1000 * 1000m raster. The raster was filtered with existing wells, which are hydrogeothermal wells in this Pilot Area. The calculation based on the measured temperature of the produced water every cells contained wells. The total amount of the Measured Resources is calculated by a sum of the raster cells.

The calculated MR is shown in the Table 9.

7.2.4 Summary of the Resource estimation

The estimation of (hydro)geothermal resources was performed to identify the potential geothermal resources in the Pilot Area. Due to the different scenarios (balneology, heat supply and electric power generation) we can determine:

- Although the Mesozoic karst reservoir has a great extent and exists almost the Pilot Area, the Hydrogeothermal Play of the Mesozoic karst reservoir has a smaller spatial extent. The “lower” temperatures caused by the natural flow system resulted the limited extent of the hydrogeothermal reservoir.
- The most perspective sites are located in the NW and N part of the Pilot Area, where the reservoir is reached greater depth, and where the thermal is come up shallower regions by the natural flow paths. Here almost 16 GW energy is stored applying heat supply utilization scenario, app. 4 GW energy applying electricity supply and app. 250 MW energy assuming balneological utilization scenario. The total HIP almost 20 GW for 50 years of utilization.
- The calculated IR, which can be represented the technical exactable amount of the stored heat assuming a multiplet well scheme, is between 50 MW and app. 5 GW (for 50 years of utilization) depends on the utilization scheme.
- The calculated MR based on the active geothermal wells is maximum 18 MW (for 50 years of utilization). It can be seen that there are few and mainly lower temperature existing utilizations on this reservoir.

8 CONCLUSIONS AND PROPOSALS

The Komárom-Šturovo (Komárno-Párkány) Pilot Area is situated in the NE part of the Transdanubian Range in Hungary and its basinal part in Slovakia. The groundwater bodies are divided by national boundaries and are in focus of International Commission for the Protection of the Danube River (ICPDR). This requires harmonized management of not only the cold water resources but also of the geothermal energy and thermal water resources for the sustainable utilization in the transboundary regions. Thus 3D flow and coupled heat flow numerical model was constructed in the Komárom-Šturovo region.

In the first step a 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.

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