



EUROPEAN UNION
EUROPEAN REGIONAL
DEVELOPMENT FUND

This project is implemented through the CENTRAL EUROPE Programme co-financed by the ERDF.

<http://transenergy-eu.geologie.ac.at>

Report on the numerical modelling of the Danube basin pilot area – scenario modelling

Authors: Miloš Gregor, Jaromír Švasta, Anton Remšík and Radovan Černák in cooperation with MFGI

Date 15-August-2013

Status final

Type Text

Description The report presents the results of the scenario modelling in the Danube basin pilot area of the Transenergy project. The modelling comprises 3D groundwater flow and heat transport simulations.

Format PDF

Language En

Project TRANSENERGY –Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia

Work package WP5 Cross-border geoscientific models

5.2.3 Detailed hydrogeological modelling

5.2.5 Detailed geothermal modelling

5.3 Scenario modelling



Table of contents

1	INTRODUCTION	6
2	HYDROGEOLOGY OF THE AREA	6
3	POTENTIAL INSTALLATIONS SCENARIOS	9
3.1	Objective of the modelling	9
3.2	Horizontal extent.....	9
3.3	Steady state geothermal modelling	11
3.4	Results	11
3.4.1	Energetic balance	15
4	BOUNDARY DOUBLET CLUSTER SCENARIOS	15
4.1	Geometry of modelled area	17
4.2	Material properties	20
4.3	Boundary conditions	22
4.4	Steady flow and heat transport modelling.....	23
4.5	Transient heat modelling	27
4.6	Long-term impacts evaluation	33
5	CONCLUSIONS	35
6	LITERATURE	35

List of Figures

Figure 1: Extend of the upper Pannonian geothermal play with hypothetical doublets (red triangles – suggested pumping wells; blue triangles – suggested reinjection boreholes). Color indicates identified geothermal resources (MW)	9
Figure 2: Localisation of hypothetical doublets: pink squares – existing utilized wells; red triangles – suggested pumping wells; blue triangles – suggested reinjection boreholes.	10
Figure 3: Temperature distribution at the base of upper Pannonian geothermal play, current state with only existing utilized wells (pink squares).....	11
Figure 4: Deformation of thermal field in upper Pannonian geothermal play caused by geothermal doublets.	12
Figure 5: Deformation of thermal field in upper Pannonian geothermal play caused by pumping wells.	13
Figure 6: Hydraulic heads field in upper Pannonian geothermal aquifer, doublets scenario.	14
Figure 7: Hydraulic heads field in upper Pannonian geothermal aquifer, pumpig wells scenario.	15
Figure 8: Localization of the investigated area.	16
Figure 9: Model area and design of the doublet cluster.	16
Figure 10: Scheme of the doublet cluster.	17
Figure 11: Horizontal definition of computing model mesh (A – general overview of the model; B – detail of nodes refinement in the place of well).	17
Figure 12: Vertikálna stratifikácia modelu (A - kvartérne sedimenty; B – terciérne sedimenty; C – geotermálny kolektor pozostávajúci z vápencov a dolomitov; D – nepriepustné podložie – kryštalínikum)	18
Figure 13: Verical definition of model (altitude values of individual layers).	20
Figure 14: Values of conductivity in X (A), Y (B) and Z (C) direction.	20
Figure 15: Parameters for heat transport modelling (A – Porosity; B – Volumetric heat capacity of solid; C – Heat conductivity of solid).	22
Figure 16: Position of defined flow boundary conditions.	22
Figure 17: Heat transport boundary condition (A – temperature boundary condition; B – Heat-flux boundary condition).	23
Figure 18: Water pressure values from steady state model of flow and heat transport modelling.....	24
Figure 19: Water temperature values from steady state model of flow and heat transport modelling..	26
Figure 20: Boundary conditions for transient heat transport modelling (A – well boundary condition; B – temperature boundary conditions	27
Figure 21: 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).	28
Figure 22: Visualization of the water heat transport within the Slovak part of the system at pumping and injecting 50 l/s of water.....	29
Figure 23: Visualization of the water heat transport on the base of carbonate colector at pumping and injecting 50 l/s of water.....	31
Figure 24: Water cooling impact in geothermal aquifer at different levels of geothermal system utilization.	32
Figure 25: 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.....	33
Figure 26: Simulation of conduction heating of geothermal waters in hydraulically closed aquifer after 35-year use i re-injection.....	34

List of Tables

Table 1: Hydraulic parameters of rock in model.....	21
Table 2: Material parameters of rocks for heat transport modelling.	21

1 INTRODUCTION

This report is an extension to the TRANSENERGY project report on steady-state numerical modelling of Danube basin, focusing on evaluation of different scenarios of possible energy extraction from the distinguished geothermal play of Danube basin – upper Pannonian sedimentary unit.

As was shown in the previous report on numerical modelling, the area of Danube basin offers significant potential for geothermal utilization, what is under interest of investors on energy market. To foresee effects of new geothermal installations, in the first part of this report two principal scenarios of geothermal utilization were investigated: single wells and geothermal doublets. Secondly, a detailed study on interstate cooperation on geothermal energy exploitation was performed as well.

Because sustainable use of thermal groundwaters is promoted in all three countries within the pilot area, first scenario tested was additional heat harvesting by means of geothermal doublets. But due to technical limits of water reinjection in upper Pannonian sands, which is the main geothermal aquifer in Danube basin, also traditional direct use of geothermal energy by means of single exploitation wells was examined.

Second part of the report deals with 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 aim 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.

2 HYDROGEOLOGY OF THE AREA

The crystalline basement has no significant influence on the groundwater flow system. It has fissure-type permeability. It differs in stratigraphy, but the main features are the same. Usually the rocks can be characterized by intensive heterogeneity, decreasing fissure aperture closing downwards causing the decreasing of permeability, and improved hydraulic conductivity due to tectonic effects.

Except the Mesozoic aquifer system of the Danube Range only some smaller blocks of carboniferous basement aquifers appears.

The Levice block is located in the Northeastern part of Danube Basin. It composed of Mesozoic rocks of the higher nappes, is locally underlain by the remnants of the Mesozoic envelope of the crystalline complex (Fusan et al. 1979). This Mesozoic plateau dips first smoothly and then more steeply westwards. It has only westward continuation. The aquifer layer is formed by mainly Triassic dolomites together with the basal Badenian clastics. The temperature of the water is 69-80°C, and the mineralization reaches around 19 g/l.

The Dubnic depression is a special type of basement aquifers. It is filled mainly with Miocene sediments underlain by crystalline shists and granitoids of the Veporicum. The aquifer formed by basal Badenian clastics (conglomerates, sandstone) at a depth between 1000-2000 meters. It represents a closed reservoir, with temperature of 52-75°C, and mineralization ranges from 10-30 g/l.

The Komárno block extends between Komárno and Štúrovo. It is fringed by the River Danube in the south and by E-W Hurbanovo fault in the north with the latter separating it from the Veporic crystalline unit. The southern limit along the Danube is tectonic as well and therefore the Komárno block is a sunken tract of the northern slope of the Gerecse and Pilis Mts. The surface of the pre-Tertiary substratum plunges towards the north from a depth of approximately 100 m near the Danube to as much as 3000 m near Hurbanovo fault. The pre-Tertiary substratum of the Komárno block consists largely of Triassic dolomites and limestones up to 1000 m in thickness. These are underlain by a very thick Lower Triassic shale formation. Paleozoic units were revealed by drilling in the northwestern section of the Komárno block. These include Permian conglomerates, sandstones, graywackes and shales and Devonian limestones and lydites. From a hydrogeothermal point of view, the area is divided into 1a high and marginal block. The geothermal activity of the high block has partly been known for long because of thermal springs at Sturovo and Patince 39 and 26°C warm. The structure has a fast water circulation and is considerably cooled (water temperature is 20-22°C at a depth of 600-800 m, 24.5-26.5°C at 1,100-1,300 m, and around 40°C at 3000 m). The Komárno high block is encircled by the marginal block in the west, north and east. The latter contains ground waters whose temperature exceeds 40°C (highest so far noted temperature is 68°C). T in the high block varies from 1.54×10^{-4} to $1.28 \times 10^{-3} \text{ m}^2\text{s}^{-1}$. T in the marginal block ranges from 5.07×10^{-5} to $2.21 \times 10^{-4} \text{ m}^2\text{s}^{-1}$.

The representative block of Graz Palaeozoicum (part of the Upper Austroalpine nappes) in Bükk-Sárvár region shows other type of the carboniferous basement aquifers. Although the known spatial extent of the aquifer formed by Devonian dolomite is not too big, the hydrogeological character is not uniform. Conductive areas can be found only related to wider open fractures. They are most often along the elevated blocks of the dolomite basement. Two separated fractured flow systems were explored by boreholes. The reservoir of Rábasömjén together with the directly covering Miocene aquifers (limestone and sandstone layers) forms a significant closed system. The reservoir of Bükk is separated from the reservoir of Rábasömjén at northwest along tectonical zones. It is supposed that the Bükk reservoir has got its recharge area in the foreground of Wechsel Mts.

The Danube Basin and the Neogene sub-basins of Kisalföld filled with several thousand meters thick porous sediments.

The northern part of the territory is situated in the dish-like shaped Danube Basin. The more than 6000 meters deep basin has brachysynclinal structure. The older layers which outcrop at the edge of the basin can be found at gradually deeper position toward the centre of the basin. Miocene and Pannonian complex are composed mostly of unconsolidated strata of gravels,

sands and clays. These are locally cemented by calcium carbonate to form conglomerates, calcareous sandstones, or organogenic limestones.

The Miocene aquifers are connected in every case to the basement aquifers, especially to highs of the basement and form a single flow system. They are represented by Badenian or Sarmatian sands and limestones. They contain fossil waters with high salinity.

The upper Miocene low permeable and thick marl and clay sequences together with the lower Pannonian layers act as regional aquiclude. They separate the flow system of the basement from the deep (usually thermal water) flow system of the porous formations characterized the Pannonian reservoir.

The structure of the lower part of the upper Pannonian formation is likely to have interlayer leakage, intergranular permeability and confined groundwater level. It contains thermal waters 42–92°C warm which are bound mainly to sands to sandstones aquifers. The aquifer layers of the central part in the thermal water system outcrop at the edges of the depression. Towards the interior part of the basin the number of sandstone aquifer layers increases but simultaneously thickness, porosity and permeability decrease as a result of sediment compaction within the young sedimentary basin. Commonly, the sand bodies are lens-shaped and cannot be followed laterally for long distances. The sandy aquifer layers vary with aquitard clay, sandy clay layers. The vertical and lateral extent of the aquifer layers are varying quickly. Commonly, the up to 10 meters thick sand bodies are lens-shaped which cannot be followed for long distances laterally.

The covering Quaternary layers represented by gravel and sands. The maximum thickness (520-600 meters) occurs in the region of Gabčíkovo and Baka. Quaternary sediments form a common unconfined reservoir. The flow system of the cold groundwater represented in this sequence with hydraulic connection with the Pannonian flow systems. The groundwater regime depends on the discharge from the Danube. At Gabčíkovo region the surface regime, with all signs of common groundwaters from Quaternary alluvia, takes effect to a depth of 30 meters. Below this limit the influence of deep regime becomes evident with all its dynamic features.

The alluvial aquiferous Quaternary formation has special hydrogeological importance. The thick gravel and sand layers represent a great amount of good quality water. The dynamic discharge in some places exceeds 8 m³/s of water. It has great potential for the future drinking water resources.

With respect to lithology of the sedimentary fill of the Danube basin, the aquifer and overlying beds have been divided into six hydrogeological units in Central depression of Danube basin. Each represents a complex with different ratio of aquifers and aquiclude. The waters in the Central depression are either marinogenic or petrogenic and are divided into five chemical types (Franko et al. 1995).

3 POTENTIAL INSTALLATIONS SCENARIOS

3.1 Objective of the modelling

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.

3.2 Horizontal extent

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 (Figure 1).

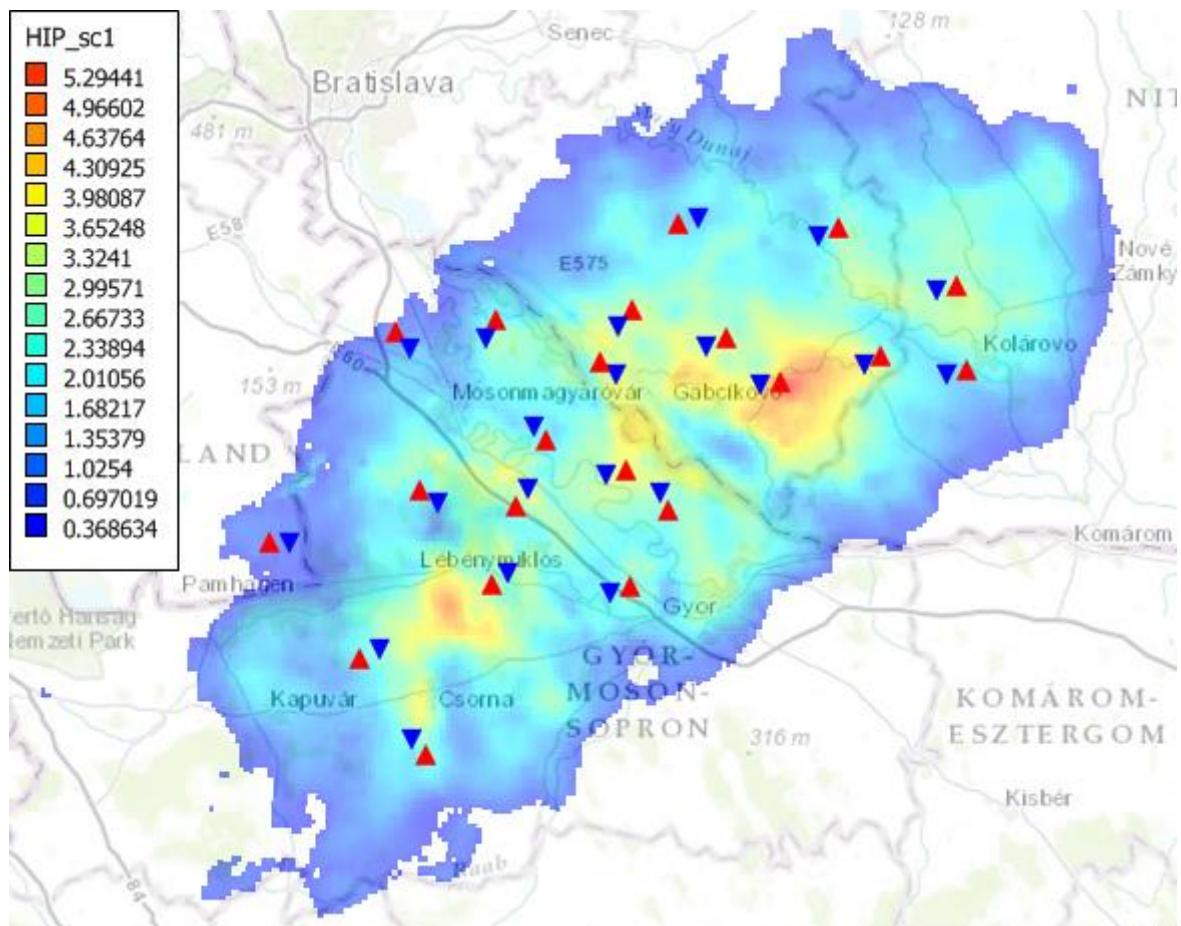


Figure 1: Extend of the upper Pannonian geothermal play with hypothetical doublets (red triangles – suggested pumping wells; blue triangles – suggested reinjection boreholes). Color indicates identified geothermal resources (MW).

New 21 geothermal doublets were placed randomly in areas with higher identified resources away from existing geothermal installations (Figure 1 and 2). Pumping and re-injection wells are separated by a distance of 2 km.

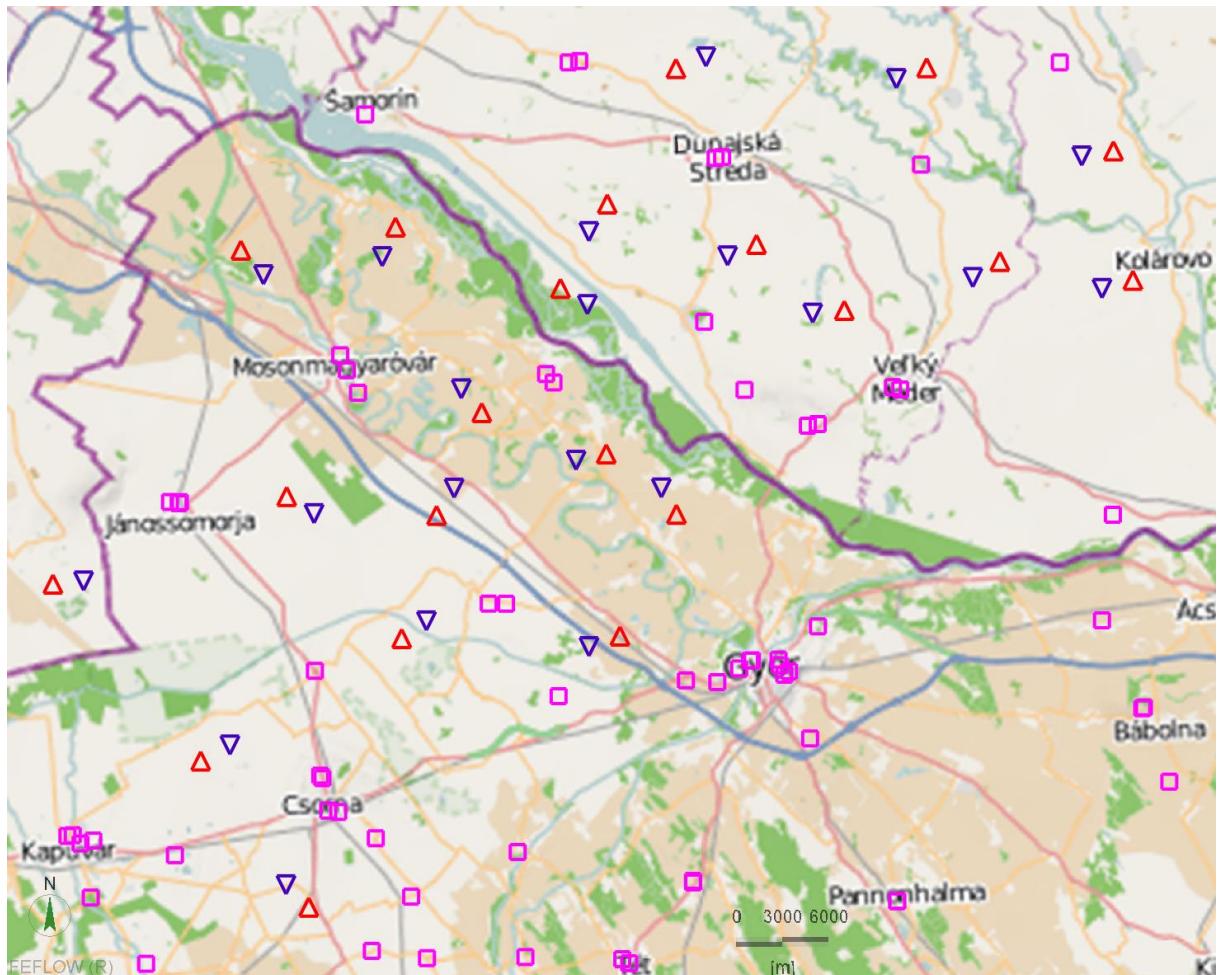


Figure 2: Localisation of hypothetical doublets: pink squares – existing utilized wells; red triangles – suggested pumping wells; blue triangles – suggested reinjection boreholes.

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 Steady state geothermal modelling

As a basis for scenario modelling a fore-mentioned regional steady state model of whole Danube basin was adopted (Figure 3). This model already includes all existing geothermal utilizations.

New geothermal doublets were introduced by means of Neumann boundary conditions with prescribed flow rate, and in the case of re-injection wells, also Dirichlet thermal boundary condition with constant temperature of infiltrated water was set.

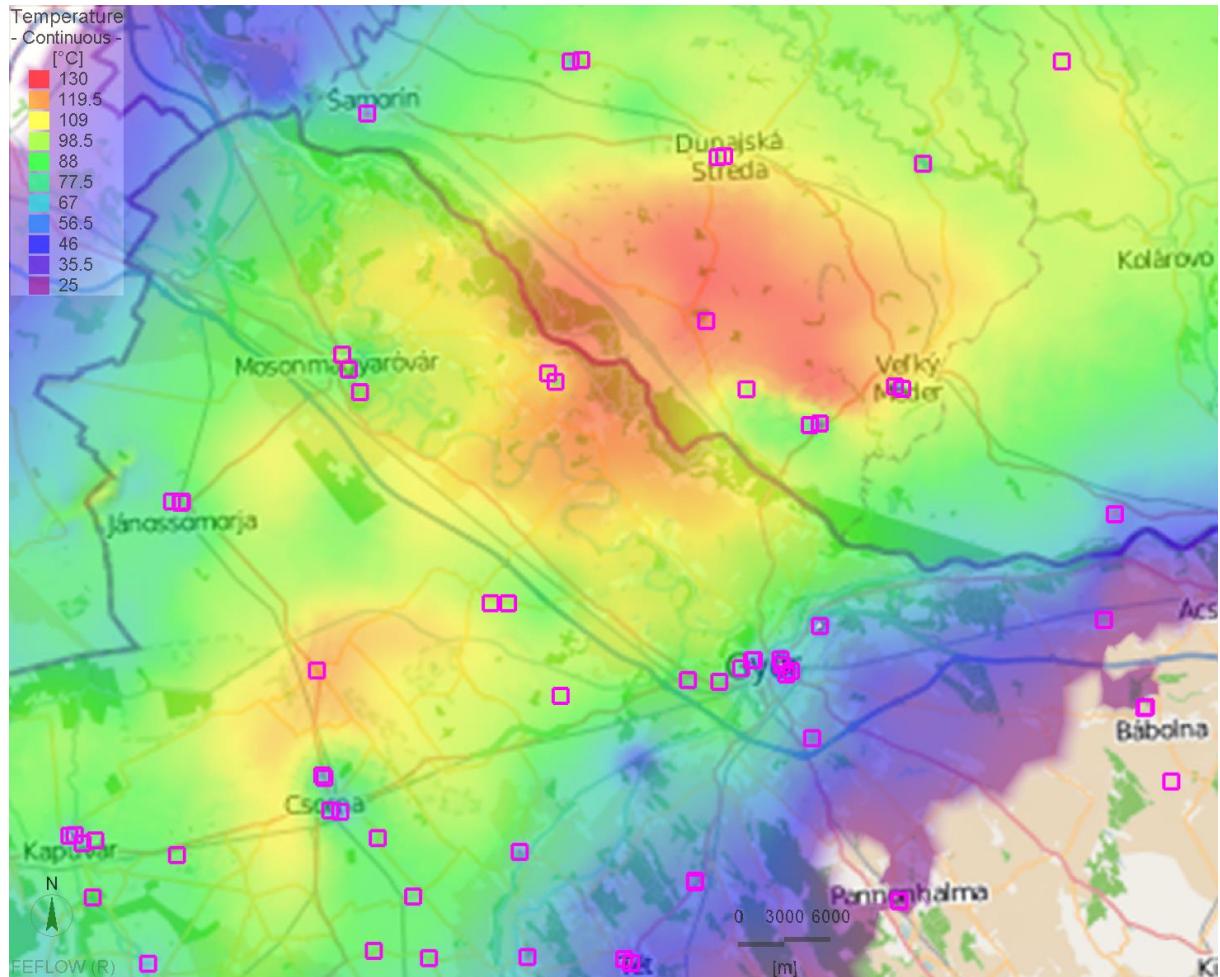


Figure 3: Temperature distribution at the base of upper Pannonian geothermal play, current state with only existing utilized wells (pink squares).

3.4 Results

Steady state simulation with additional 21 geothermal doublets revealed a significant effectiveness of the thermal energy harvesting (Figure 4). It also showed that in some areas a potential for additional installations still remains.

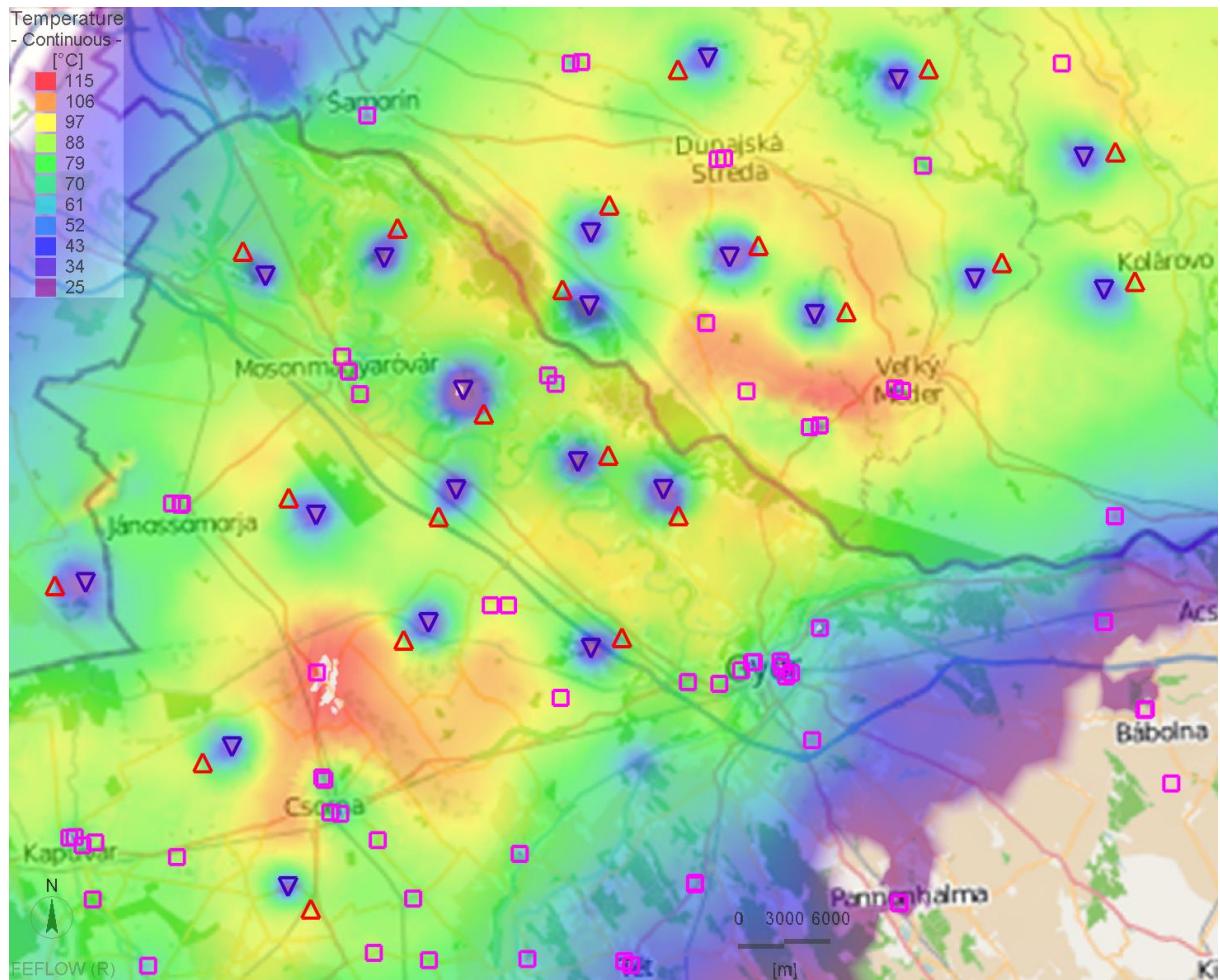


Figure 4: Deformation of thermal field in upper Pannonian geothermal play caused by geothermal doublets.

Utilization of pumping wells without re-injection also shows significant cooling of the area in broader vicinity of the wells (Figure 5). Comparing to the doublet scenario, the temperature decrease is spread much more in lateral extend.

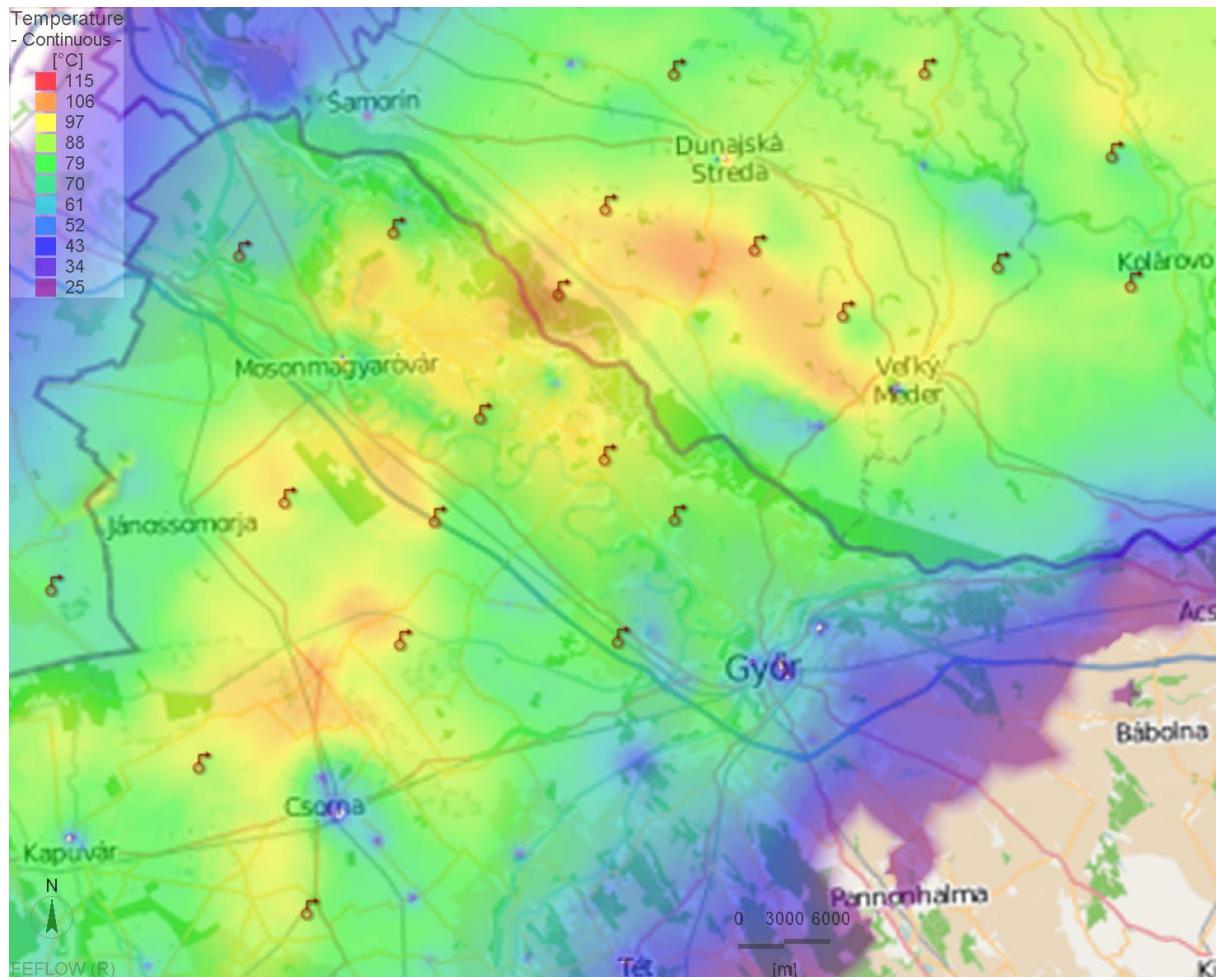


Figure 5: Deformation of thermal field in upper Pannonian geothermal play caused by pumping wells.

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 6.

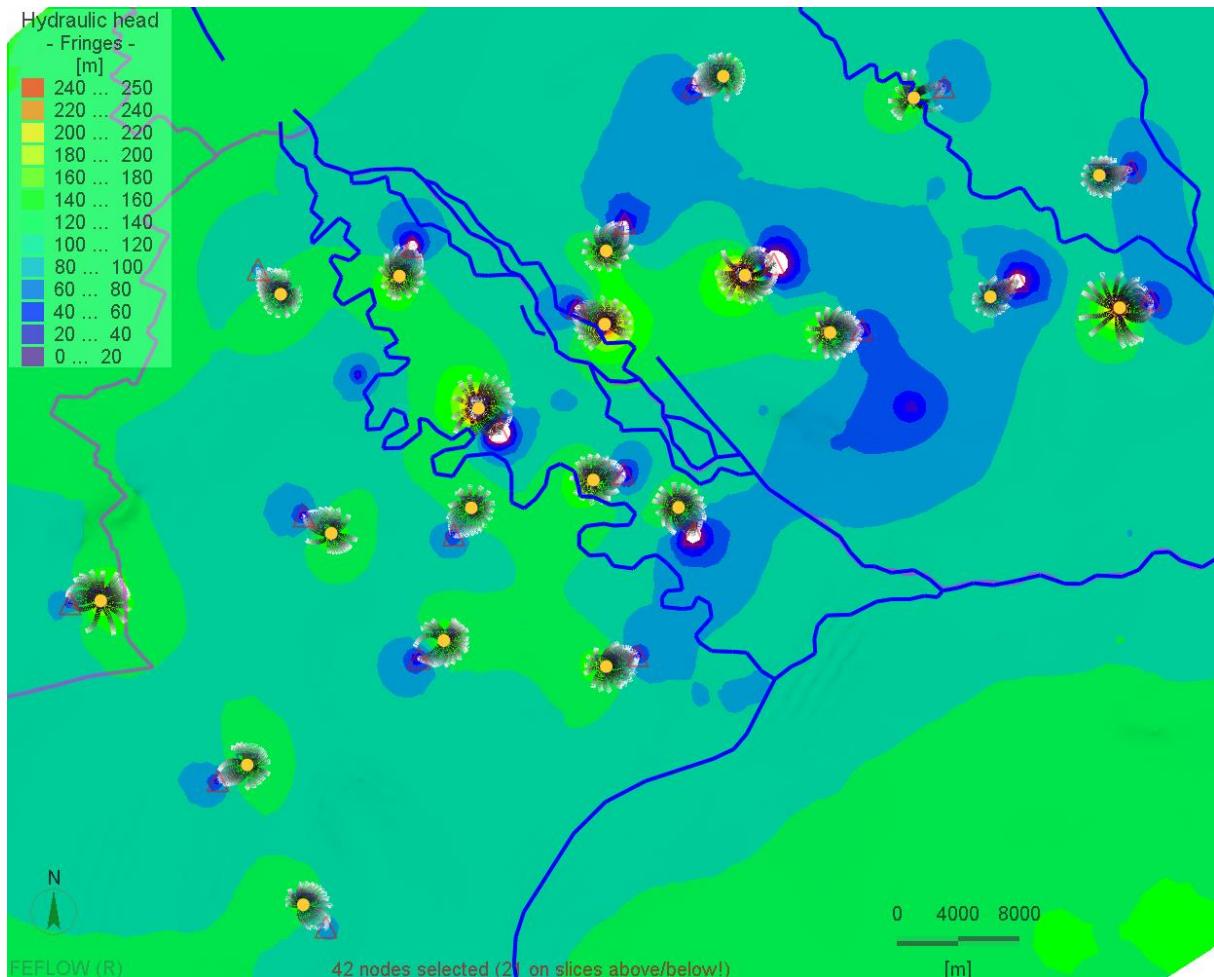


Figure 6: Hydraulic heads field in upper Pannonian geothermal aquifer, doublets scenario.

This picture is radically different from the scenario without re-injection (Figure 7), 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.

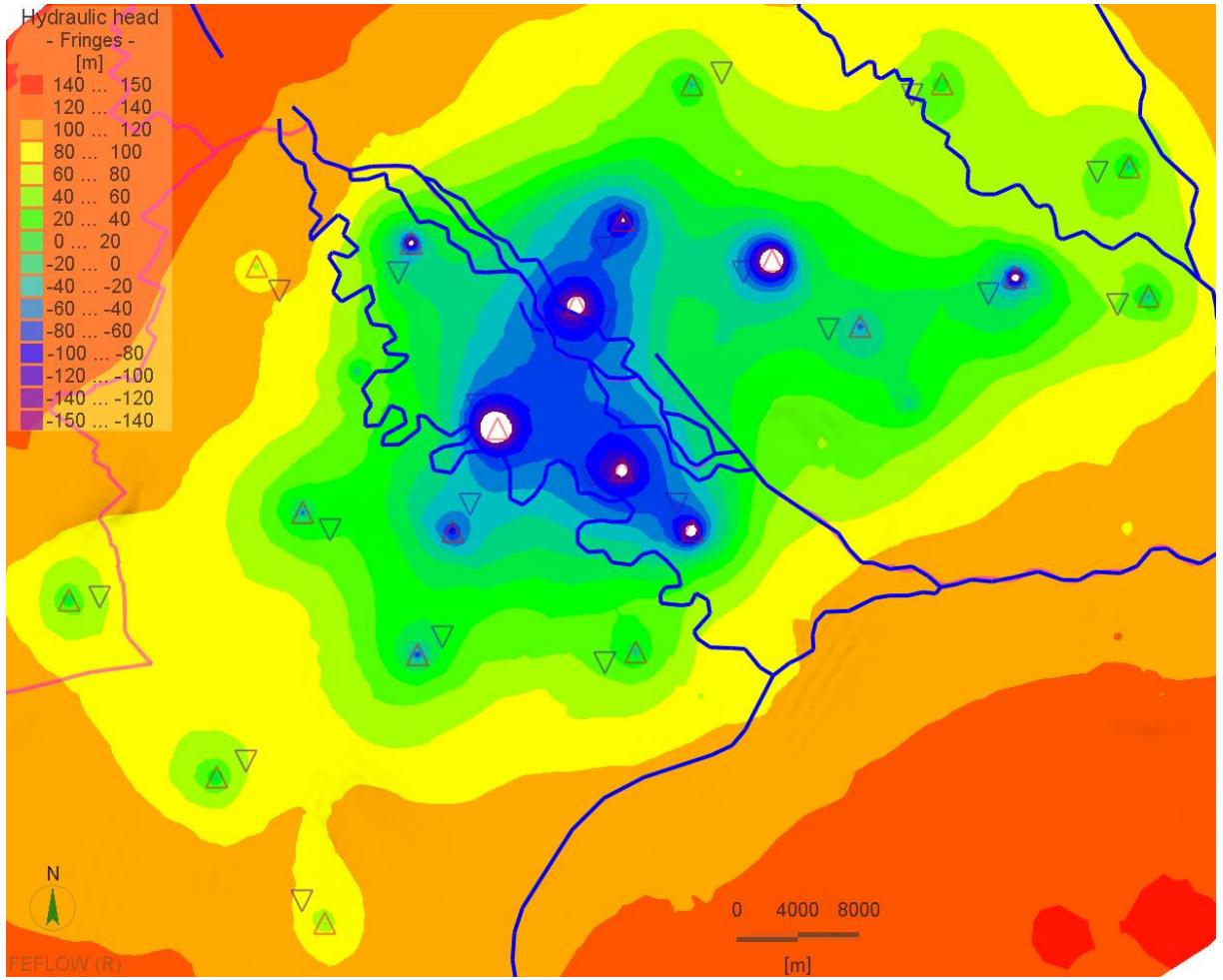


Figure 7: Hydraulic heads field in upper Pannonian geothermal aquifer, pumpig wells scenario.

3.4.1 Energetic balance

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.

4 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. 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 (Figure 1). 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 9.

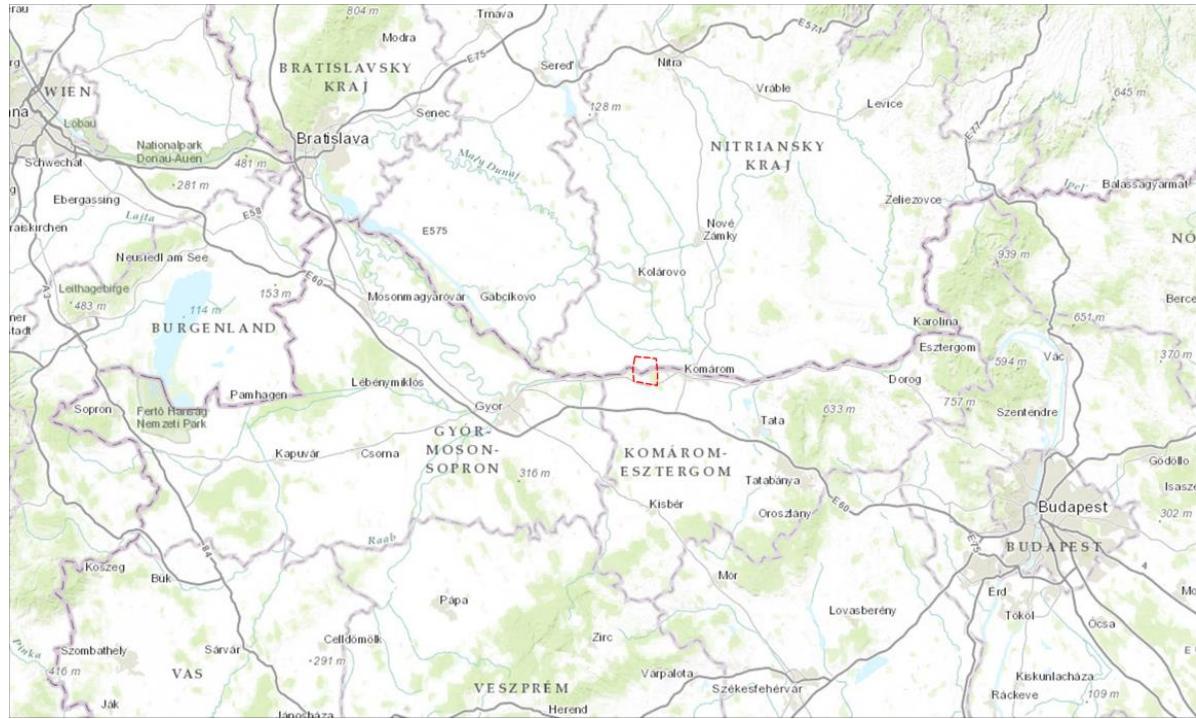


Figure 8: Localization of the investigated area.

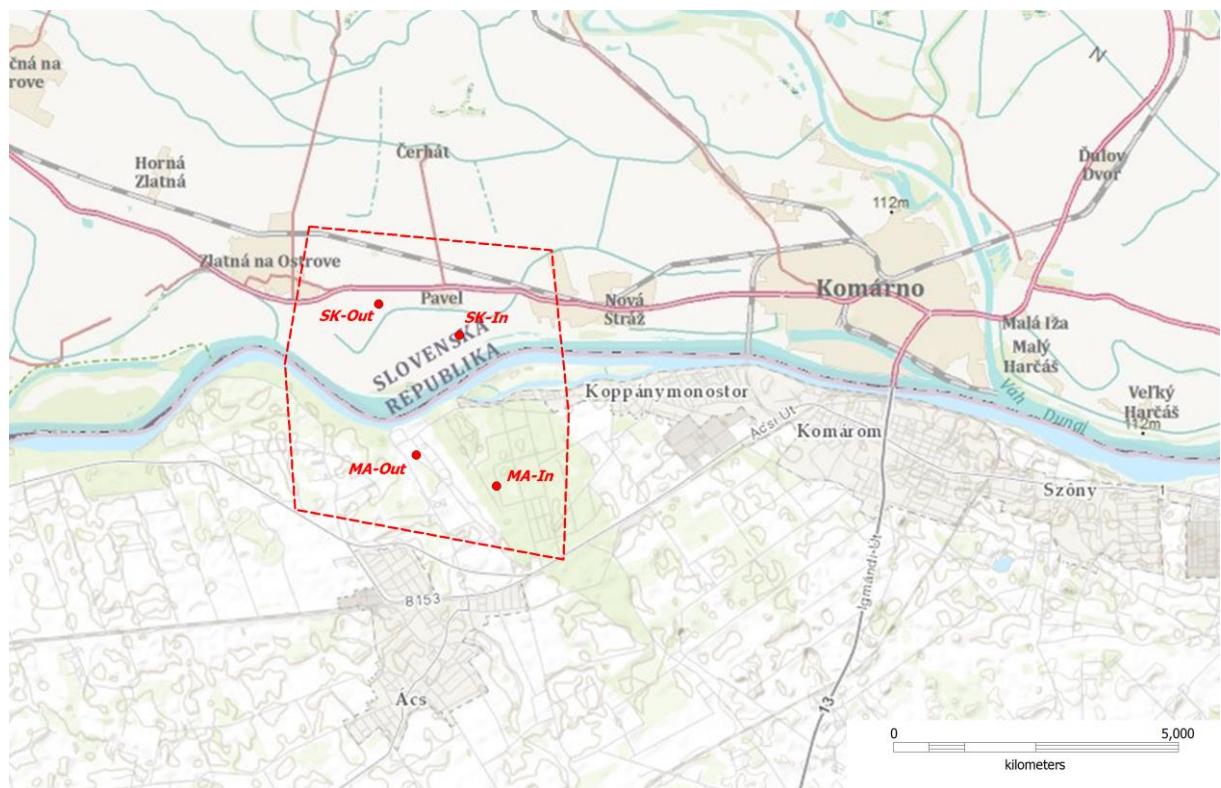


Figure 9: Model area and design of the doublet cluster.

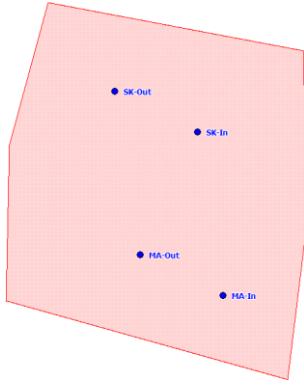


Figure 10: Scheme of the doublet cluster.

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 10). 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. The following text describes the model definition, its setting and evaluates the impact of the geothermal water use at different scenarios. For the modelling of flow and heat transport simulation program FEFLOW version 6.0 was utilized.

4.1 Geometry of modelled area

Coordinates of the evaluated area were imported into FEFLOW. Based on these data, we created two-dimensional mesh of computing nodes for modelling (Figure 11). This mesh was adjusted by linear gradation of nodes in places of wells. Density of mesh nodes in the direction to the edge of model decreases. The character was designed in relation to sufficient conversion of simulated modelling scenarios.

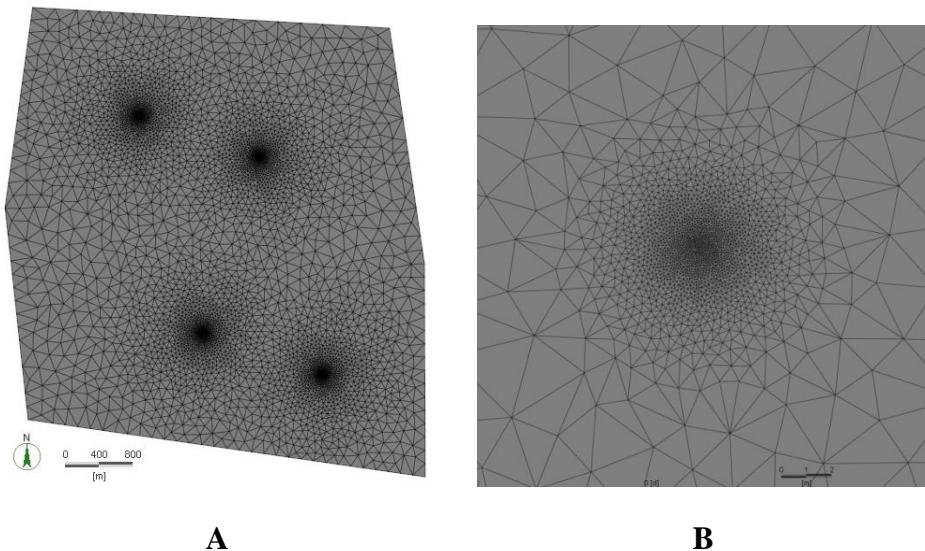


Figure 11: Horizontal definition of computing model mesh (A – general overview of the model; B – detail of nodes refinement in the place of well).

The basic layout of the model in the vertical direction is shown in Figure 12. From the geological point of view in vertical direction the model is divided into four geological layers. The first stratum from the surface is formed by Quaternary sediments. The second layer consists of group of Tertiary sediments, which form hydrogeological isolator in this model. Then following Mesozoic rocks (limestone and dolomite), which form modelled collector of geothermal waters. Underneath follow Crystalline rocks, forming hydrogeological isolator.

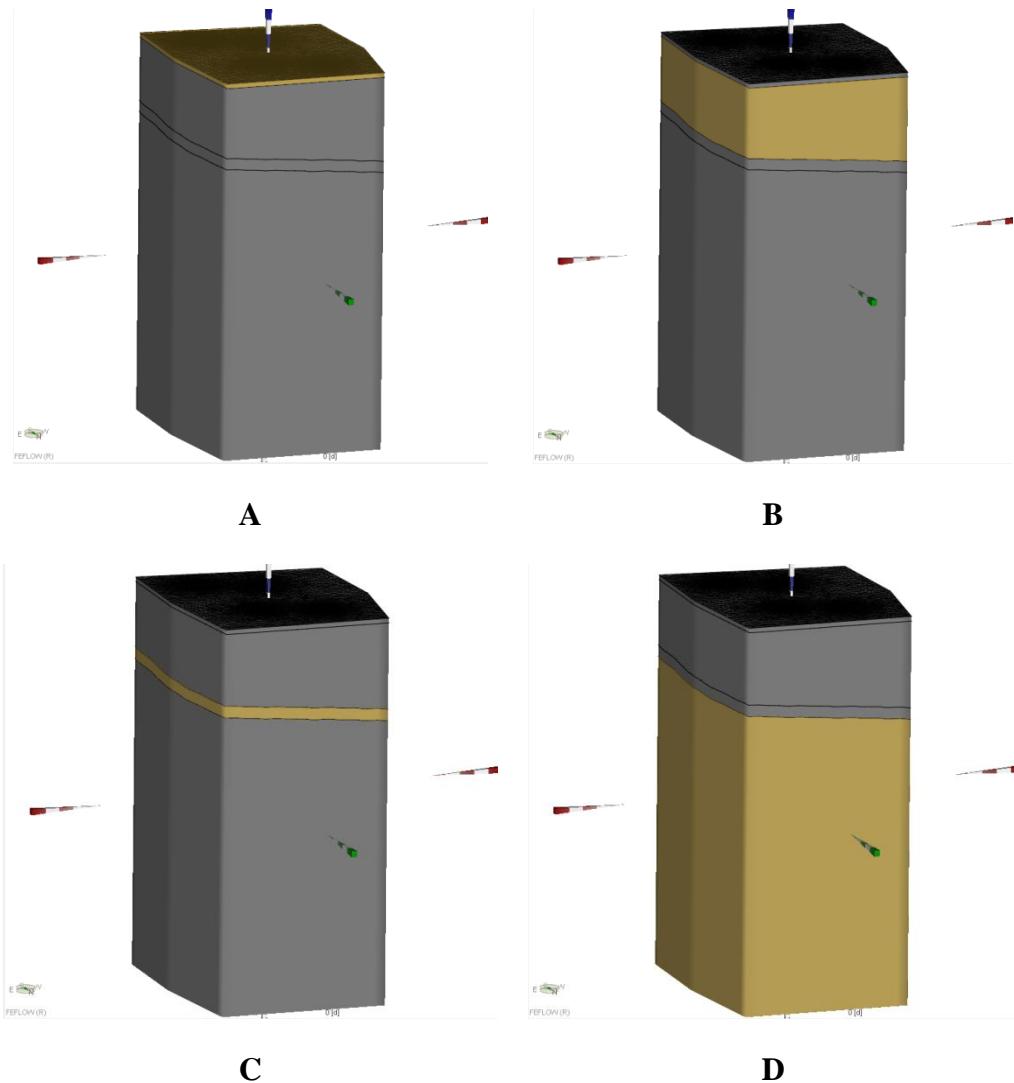
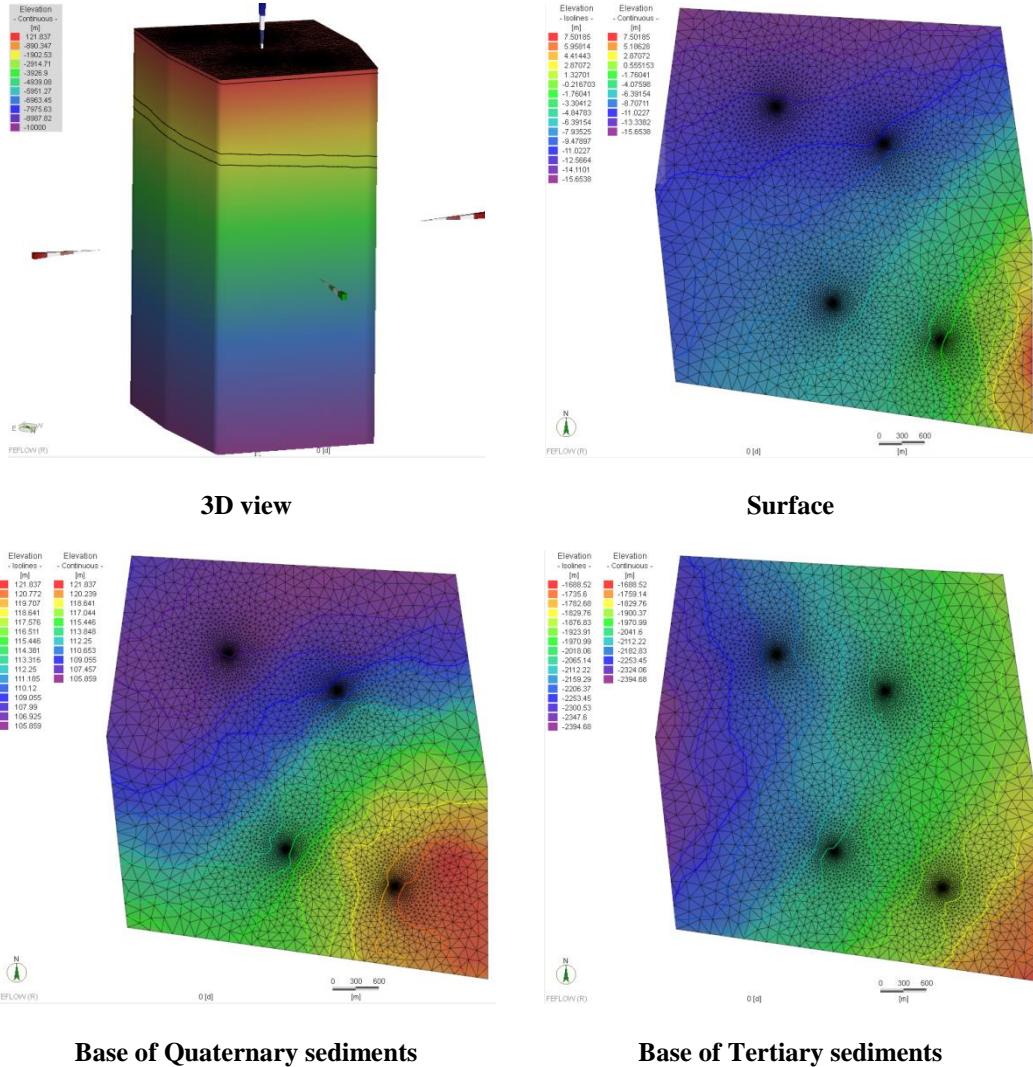


Figure 12: Vertikálna stratifikácia modelu (A - kvartérne sedimenty; B – terciérne sedimenty; C – geotermálny kolektor pozostávajúci z vápencov a dolomitov; D – nepriepustné podložie – kryštalinikum)

Based on this division of geological units were created individual layers of the model. Vertical discretization of the layers we transpose from the previous results of the TRANSENERGY project. Visualization of these values, imported into the model, is shown in Figure 13. Overall, it is possible to determine the layers are inclined in the direction SE-NW. The altitude values for surface and base of Quaternary and Tertiary sediments we had from previous geological interpretations. However, it is questionable the thickness of Mesozoic

carbonates formation. In evaluated area was not determined by drilling exploration, but experts estimate it at 300 m. This thickness was used in model as a constant value for the whole model. The thickness of the last layer was set to a depth of – 10 km, for which we have the values of heat flux parameter.

This division formed the basis of vertical network definition of the model. Due to better conversion and accuracy of results, these layers were divided into next sub-layers with the same parameters. As a result, the model was divided in vertical direction into 10 layers.



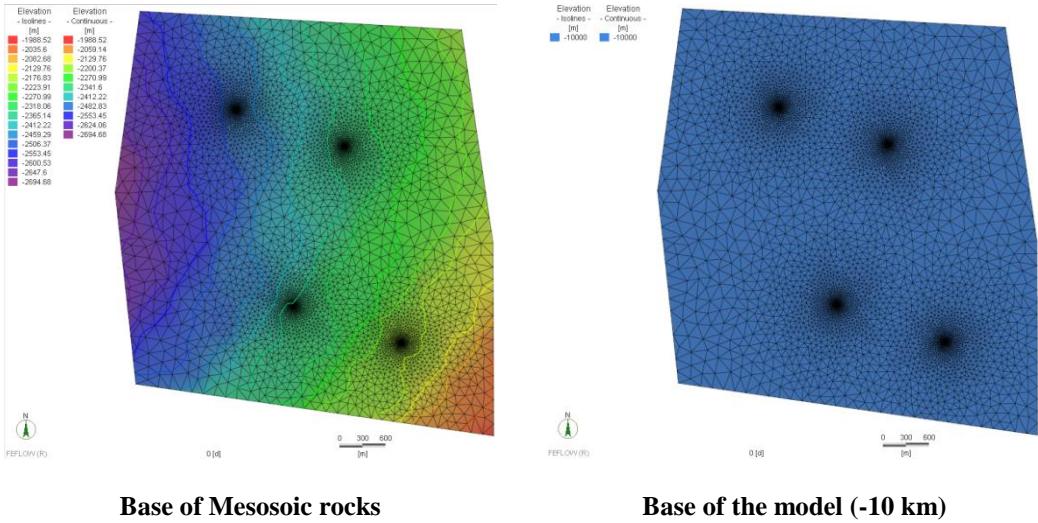


Figure 13: Vertical definition of model (altitude values of individual layers).

4.2 Material properties

Properties of the rock environment are the determining parameter of groundwater flow and heat transport options. This sub-section deals with setting the material properties of the model environment. These properties are schematically shown in Figure 14 and 15.

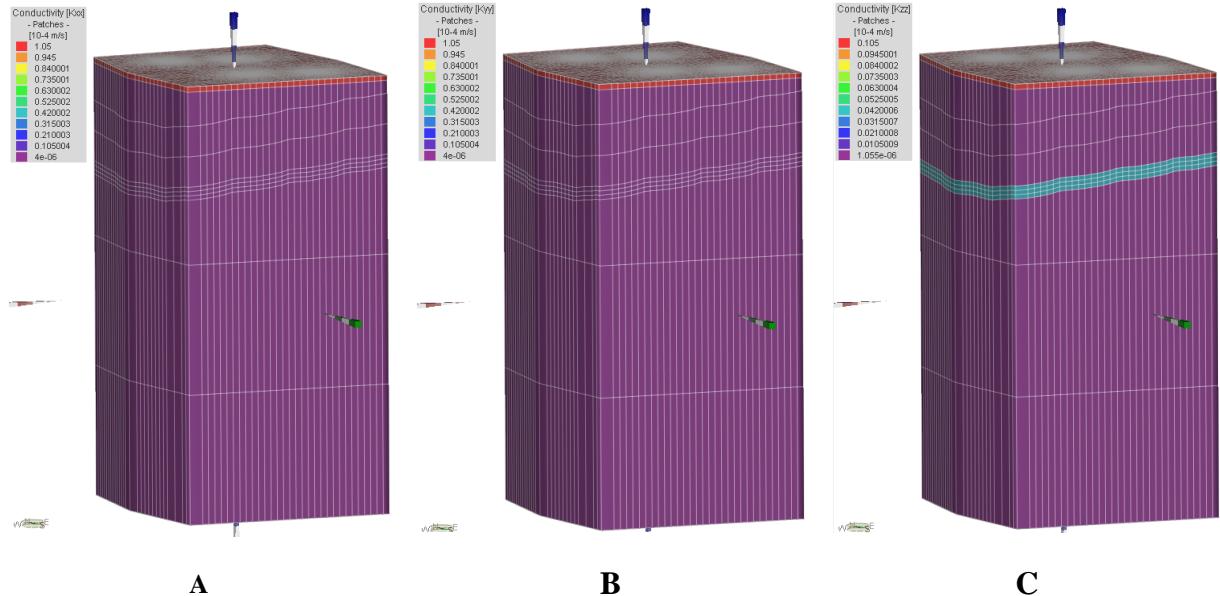


Figure 14: Values of conductivity in X (A), Y (B) and Z (C) direction.

For groundwater flow the conductivity is a decisive parameter. The FEFLOW modelling program set this parameter in the three-dimensional space by axes X, Y and Z. An example of this setup is in Figure 14 and values for individual layers displays Table 1.

Table 1: Hydraulic parameters of rock in model

Layer	Conductivity (ms^{-1})		
	X	Y	Z
Quaternary sediments	$1.05*10^{-4}$	$1.05*10^{-4}$	$1.05*10^{-5}$
Tertiary sediments	$4.00*10^{-6}$	$4.00*10^{-6}$	$4.00*10^{-9}$
Mesozoic rocks	$4.00*10^{-7}$	$4.00*10^{-7}$	$4.00*10^{-6}$
Crystalline rocks	$1.055*10^{-9}$	$1.055*10^{-9}$	$1.055*10^{-10}$

Setting of individual values was based on multiple sources and studies. In the first three formations Quaternary and Tertiary sediments, Mesozoic rocks) are based on previous surveys and research in studied locality or in the surrounding area. In the case of pre-Mesozoic rocks, we have set the value so that the environment meets the condition of hydrogeological isolator.

Similarly, we proceed even in the definition of parameters determining the heat transport in model. These values are shown in Figure 15 and in Table 2. In this case, values were also based on previous studies and from the results of the steady flow/ steady heat transport model calibration. The description of this modelling step is in chapter 3.4.

Table 2: Material parameters of rocks for heat transport modelling.

Layer	Porosity	Volumetric heat capacity of solid ($\text{Jm}^{-3}\text{K}^{-1}$)	Heat conductivity of solid ($\text{Jm}^{-1}\text{s}^{-1}\text{K}^{-1}$)
Quaternary sediments	0.275	$3.42*10^6$	1.0
Tertiary sediments	0.05 – 0.11	$2.80*10^6$	1.0
Mesozoic rocks	0.1 – 0.03	$2.60*10^6$	2.5
Crystalline rocks	0.01 – 0.003	$2.4*10^6$	3.0

The values of porosity in the direction from the surface gradually decrease from values 0.275 to 0.003. Like the porosity, values of the volumetric heat capacity of solid also decrease. Overall, for the model was set values from $3.42*10^6$ to $2.4*10^6 \text{ Jm}^{-3}\text{K}^{-1}$. The opposite character of values has the parameter of heat conductivity of solid, which ranges from 1.0 in the Quaternary sediments to $3.0 \text{ Jm}^{-1}\text{s}^{-1}\text{K}^{-1}$ in Crystalline rocks.

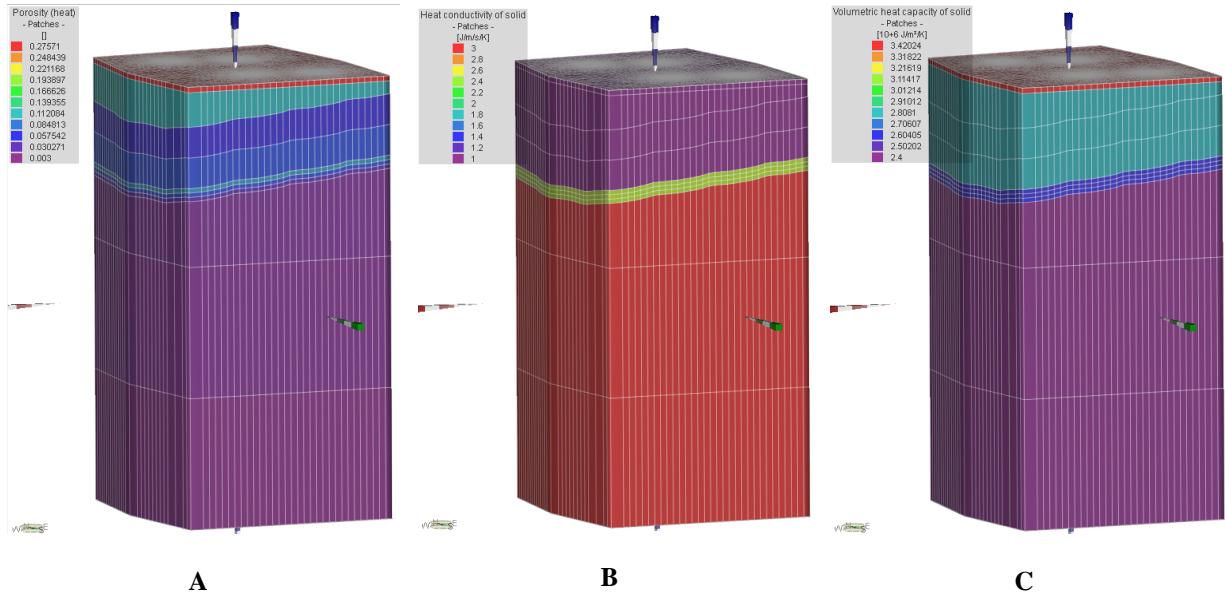


Figure 15: Parameters for heat transport modelling (A – Porosity; B – Volumetric heat capacity of solid; C – Heat conductivity of solid).

Thus set values of material properties entered as a basis to individual model scenarios.

4.3 Boundary conditions

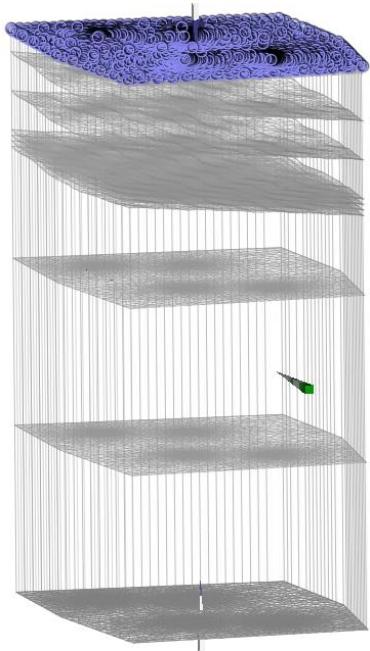


Figure 16: Position of defined flow boundary conditions.

Another important parameter of flow and heat transport model is boundary conditions, which determine the processes occurring at the edges of the modelled area.

In modelling the steady flow of groundwater was set static groundwater level. As background data of this boundary condition were used the results of previous regional modelling.

Due to the fact this boundary condition does not affect the results significantly, for the final model was in relation to conversion acceleration determined constant value for the entire model. Thus set constant groundwater head in space and time was then used in individual model scenarios.

In a similar manner were also set boundary conditions for heat transport. The position of these boundary conditions is shown in Figure 17.

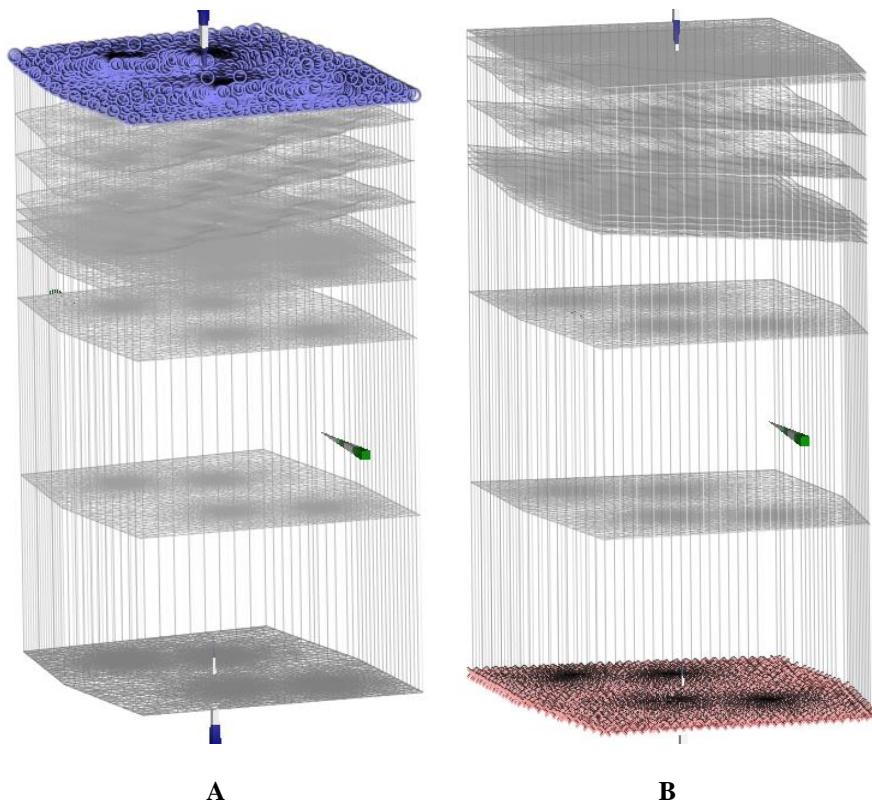


Figure 17: Heat transport boundary condition (A – temperature boundary condition; B – Heat-flux boundary condition).

On the surface of model was as a boundary condition set a constant temperature, which is based on the long-term mean annual air temperature, which for the modelled area reaches 10°C. At the bottom of the model at a depth of -10 km from the surface was set heat-flux type of boundary condition. Values that have been imported into the model are based on previous result of Transenergy project. On average, this parameter reached in model nodes value around $0,06 \text{ Wm}^{-2}$. Previous text of sub-chapter describes how boundary conditions were set. These were used to model a steady state conditions in the geothermal structure. The results of this modelling are the content of following chapter.

4.4 Steady flow and heat transport modelling

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.

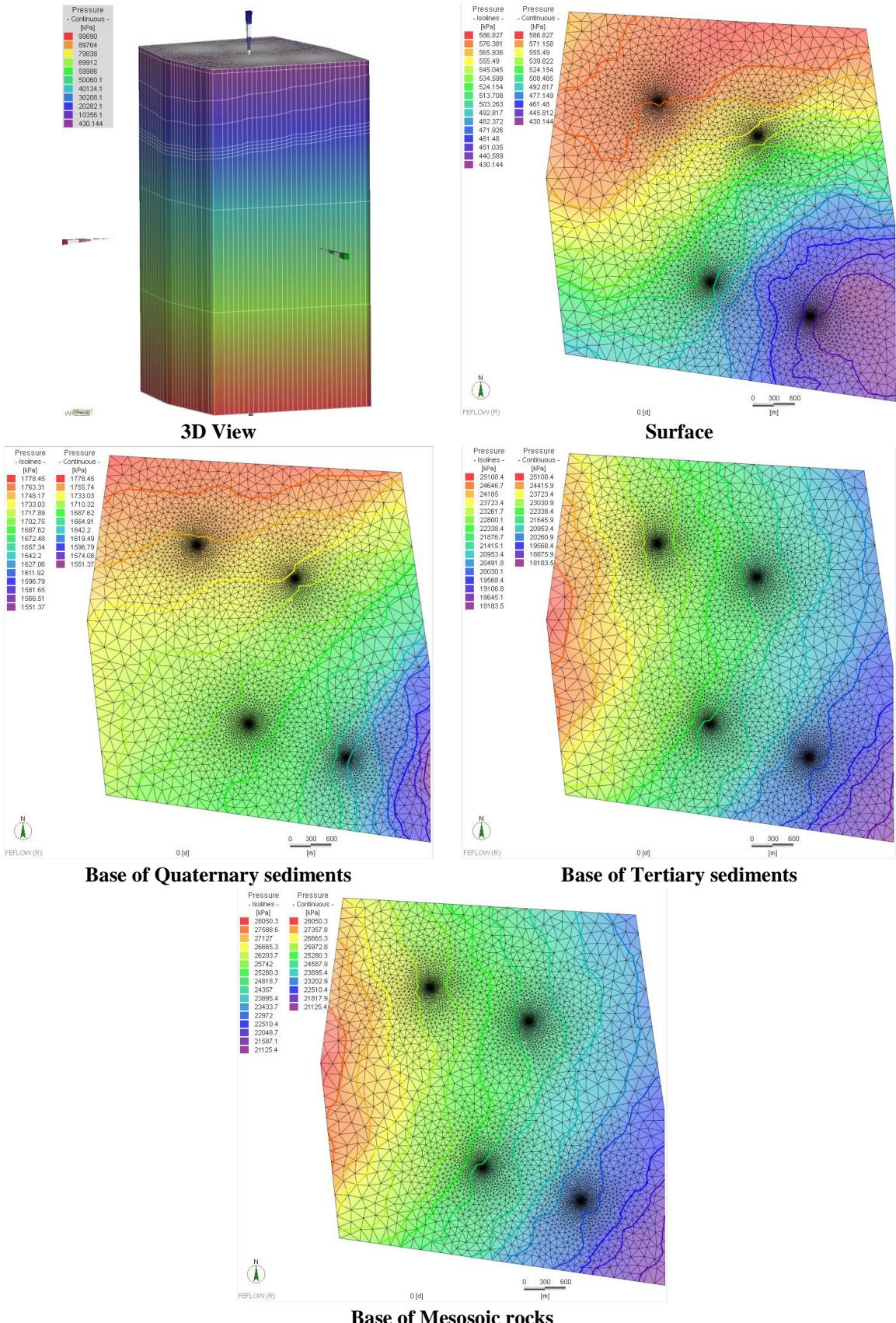


Figure 18: Water pressure values from steady state model of flow and heat transport modelling.

The purpose of this model was to determine the long-term steady temperature – pressure conditions in the geothermal structure, which will initially define the conditions before modelling the use of geothermal water. As input data were used parameters and settings, described in the previous subsections. Individual material properties of model were in this step calibrated according to measured values of water temperature in existing geothermal wells from evaluated area. The simulation results of groundwater temperature and pressure are shown in Figure 18 and 19.

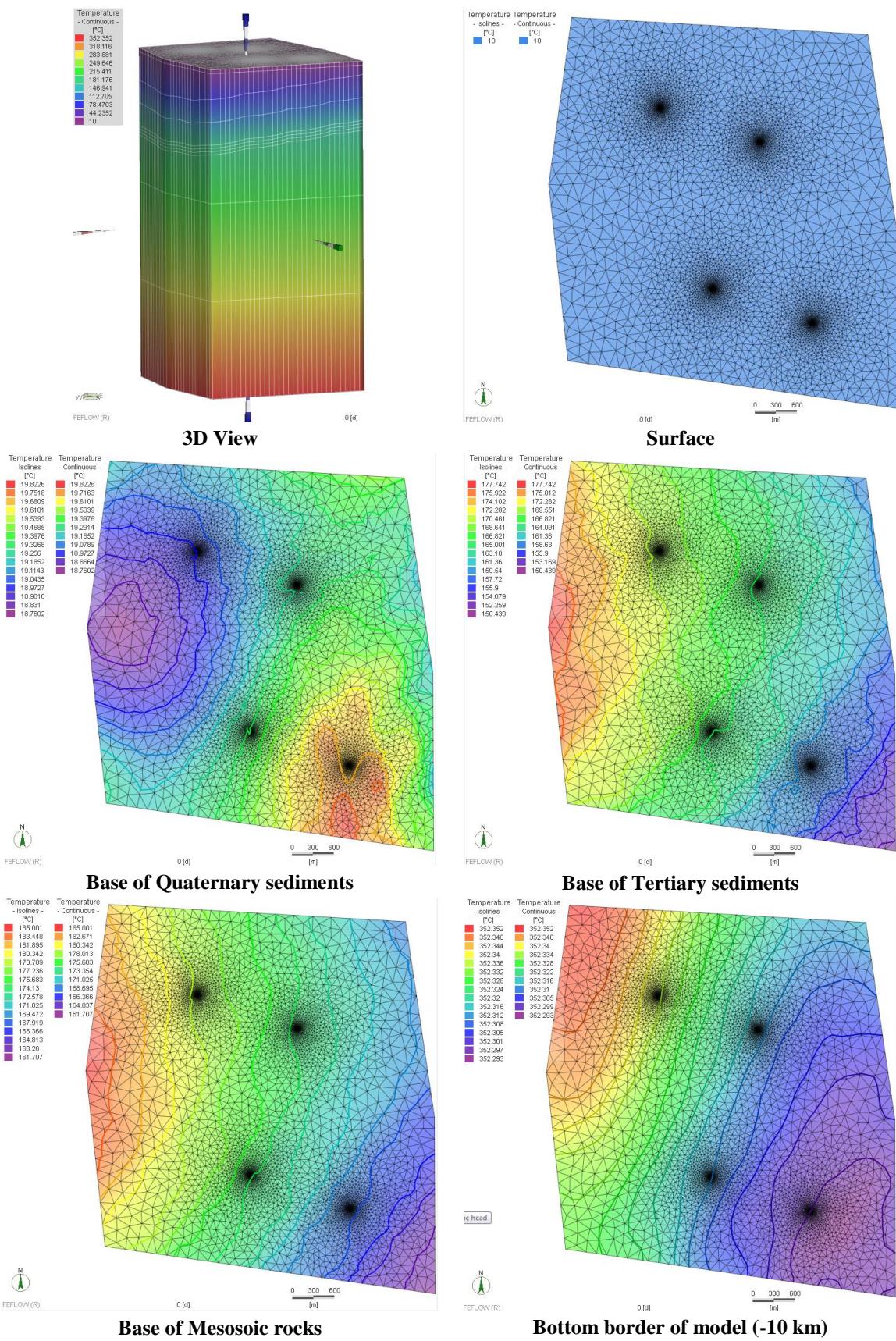


Figure 19: Water temperature values from steady state model of flow and heat transport modelling.

In this way calibrated properties and values of water temperature and pressure in the next modelling scenarios steps were used.

4.5 Transient heat modelling

In the next step we advanced to the transient-type modelling of heat transport. For this purpose, we have modified the model boundary conditions. Their definition is shown in Figure 20.

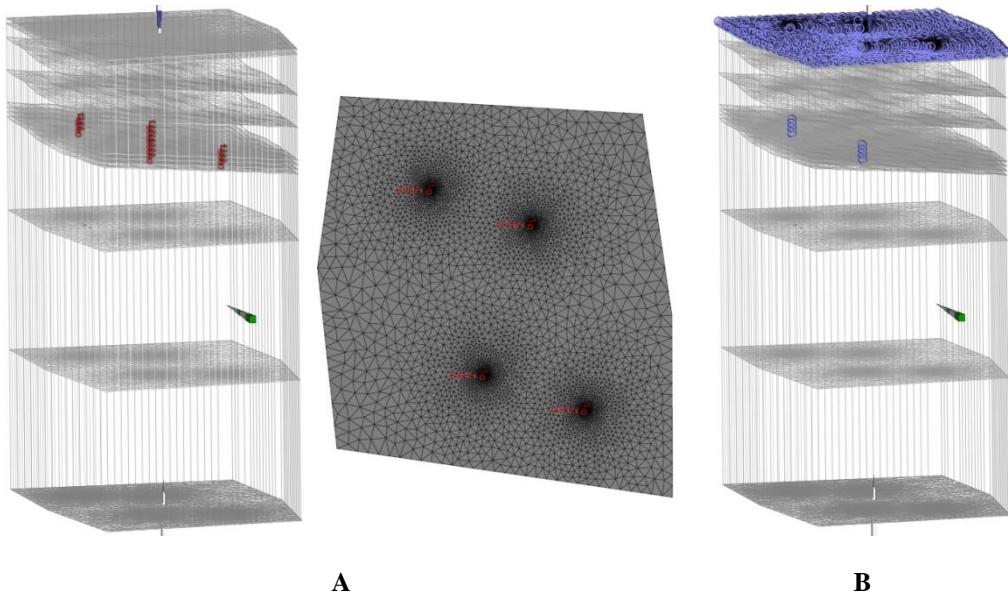


Figure 20: Boundary conditions for transient heat transport modelling (A – well boundary condition; B – temperature boundary conditions)

For the flow groundwater modelling the Well BC boundary condition was added into model. For the purpose of re-injection four wells were added to the model: two for pumping and two for re-injection. Within the two countries (SK/HU) is one separate system. These well for modelling were designed to interfering with the filter entire collector of geothermal waters in carbonate rocks. Under these boundary conditions were set pumped and re-injected amounts of water. These quantities are varies and we analyze the impact of using geothermal water. For the heat transport modelling we set the temperature of the injected water. The temperature was constant in all cases. For modelling, we assumed that the technology allows pumped water to cool down to 15°C. Finally we set the simulation time and we observe the transport of cooled water in geothermal collector in the direction from the injection wells to pumping wells.

The first visualization is shown in Figure 21. This visualization shows the streamlines in the Slovak part of the geothermal water use system. The top part shows the streamlines form the long-term point of view in direction from injection well to pumping well. Bottom

visualization displays the range of flow pathlines after 35 years, what is the expected lifetime of system for geothermal water use. From this visualization it is clear that during the system lifetime the cooled water does not reach the pumping system.

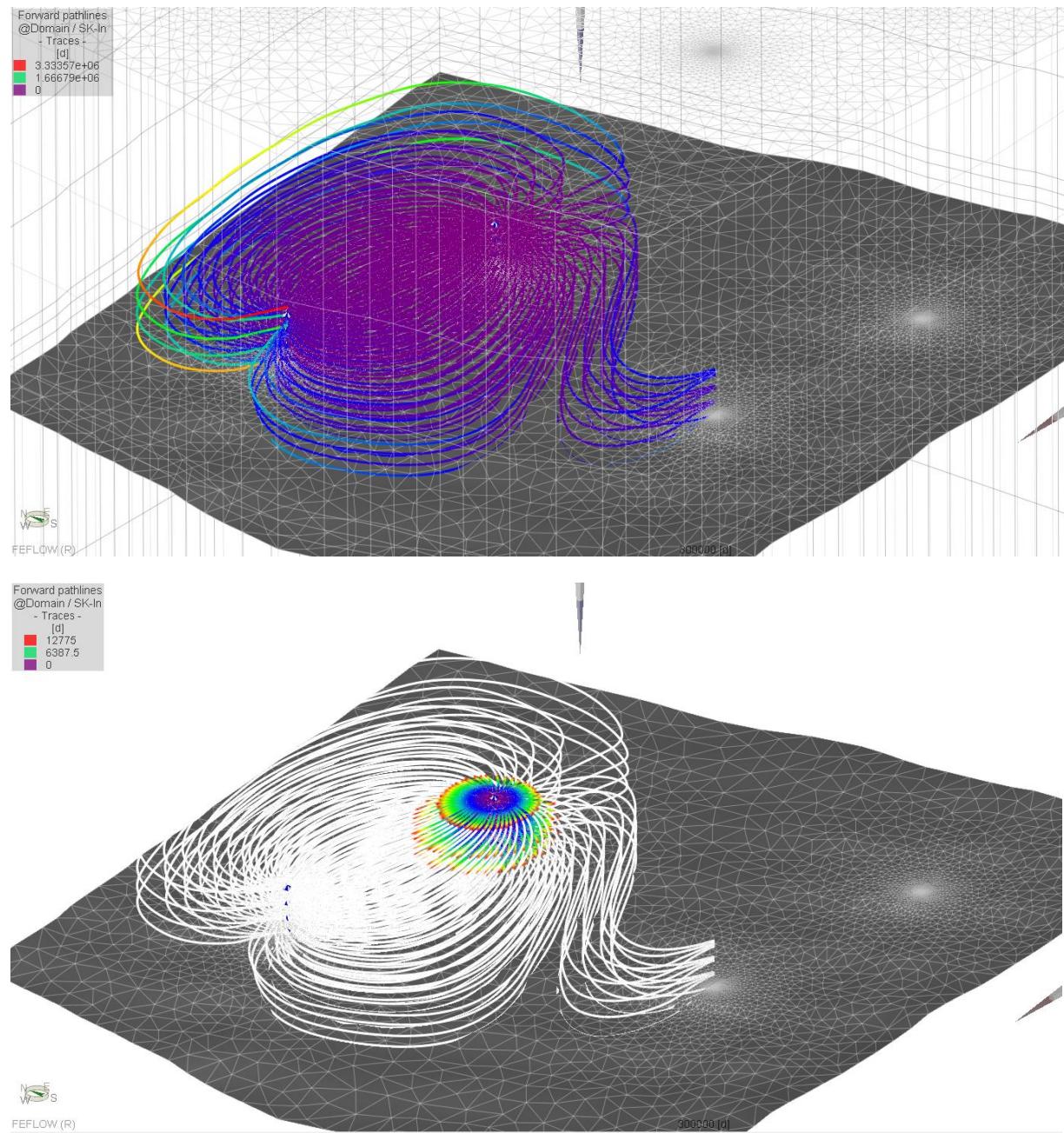


Figure 21: Visualization of flow pathlines of water (Top – long-term pathlines of water from Slovak-side injection well to pumping well; Bottom – flow pathlines radius – colored – after 35 years).

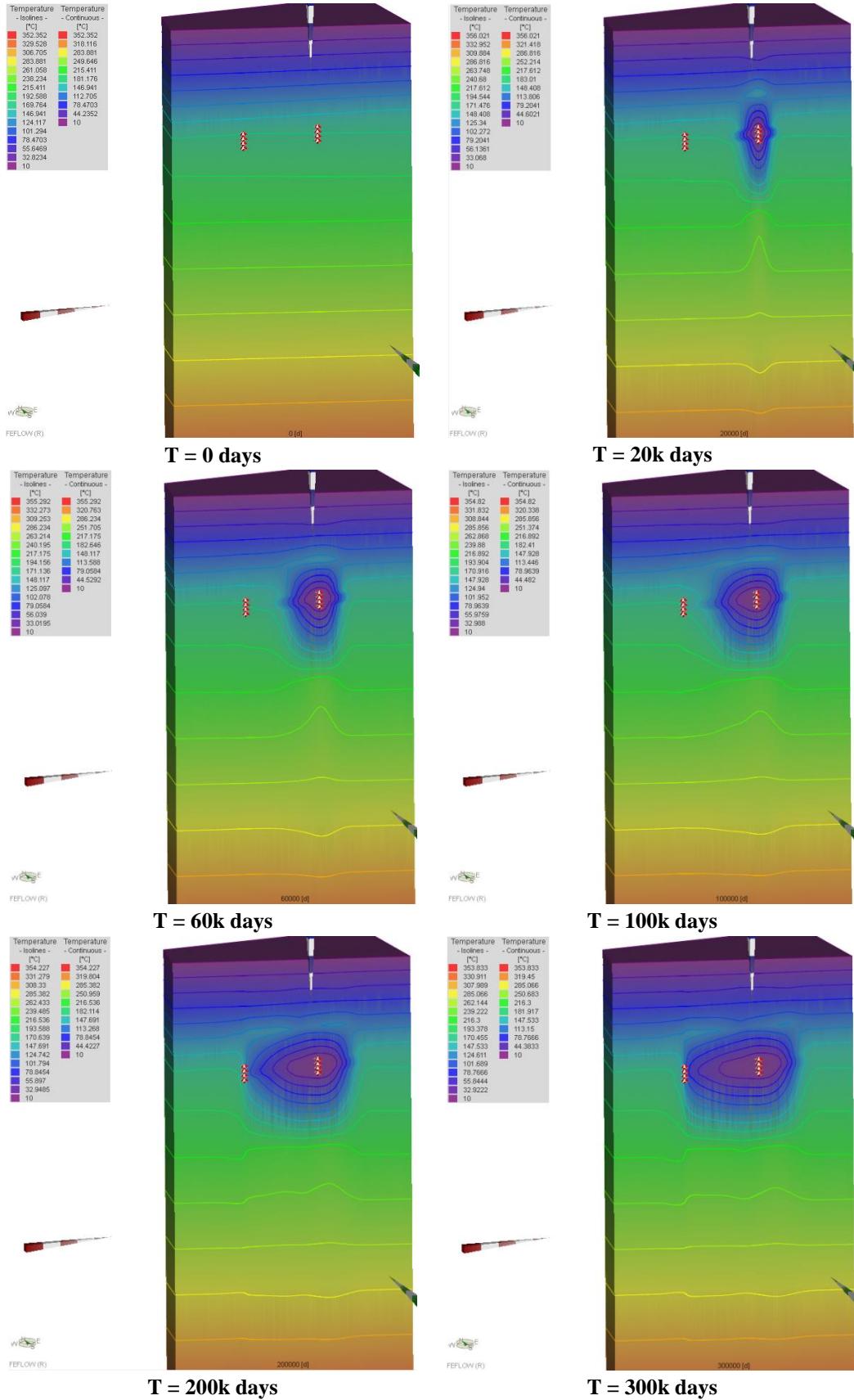
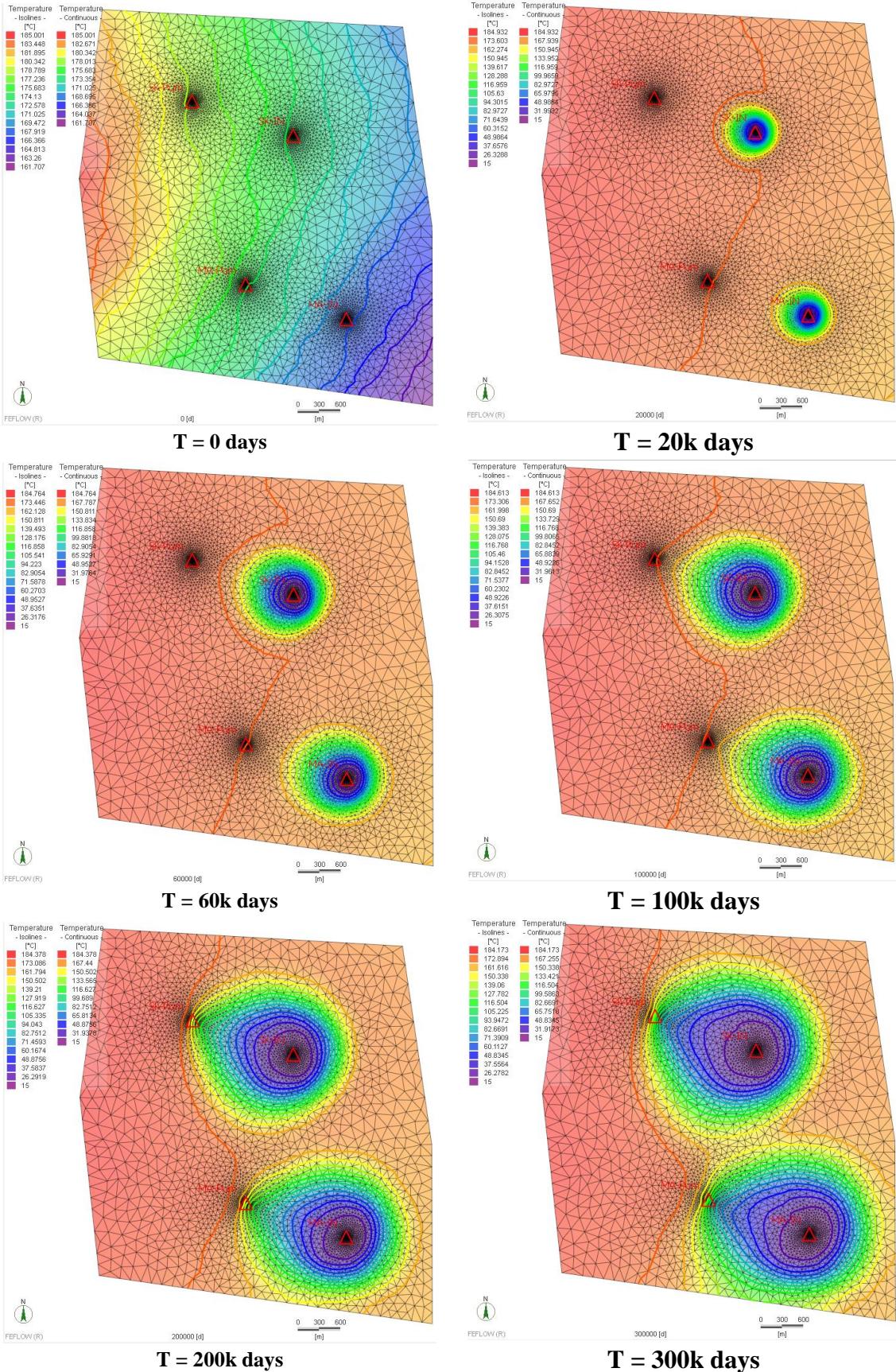


Figure 22: Visualization of the water heat transport within the Slovak part of the system at pumping and injecting 50 l/s of water.

Spatial view of the cooled water injection impact is shown in Figure 22. Picture

shows a Slovak section of the system. Individual images show the effect of cooled water injection into the geothermal structure at time steps 0, 20k, 60k, 100k and 200k days of pumping and injection of 50 l/s water from individual wells. In this picture you can see the progress of cooled water transport between wells.

Similarly, this progress showing Figure 23, which 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.



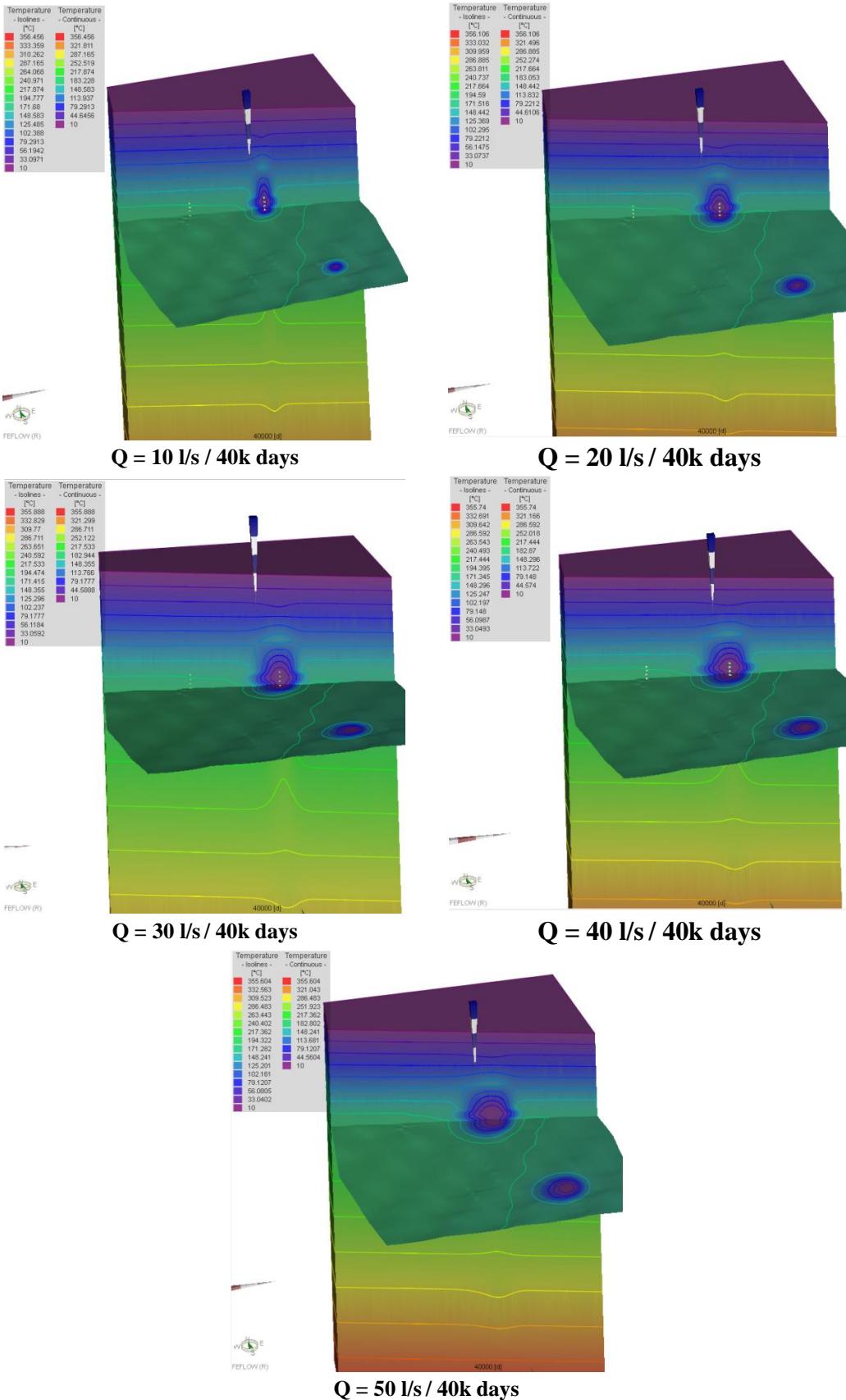


Figure 24: Water cooling impact in geothermal aquifer at different levels of geothermal system utilization.

Figures 24 and 25 shows results of heat transport modelling at different amounts of pumped and injected water after 35 years.

In 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. From Figure 25 is clear that the injected water will begin impact the temperature in pumping wells after more than 100 years of use. This result shows that the evaluated structure is suitable for use of geothermal water by reinjection method.

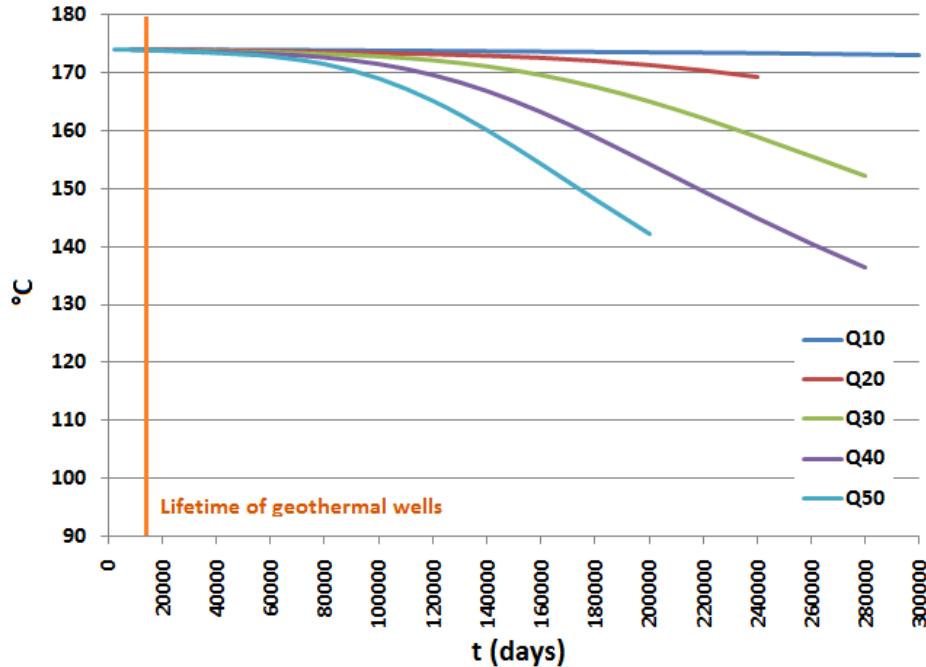


Figure 25: The course of changes in water temperature in the pumping well from the long-term point of view at different amounts of pumped/injected water.

4.6 Long-term impacts evaluation

Because defined numerical model is relatively easy to change the simulated scenarios, we add one more theoretical scenario to work. This scenario should answer the question, how long will it take until the water temperature in the geothermal structure returns to its original natural values. For this scenario, we modelled values of water temperature and pressure after 35 years of use the projected geothermal system, while the amount of pumped/re-injected water in this period was 35 l/s. From this state we started and we have cancelled boundary conditions defining wells. As the hydrogeological structure is closed, there is no percolation at the border and the only process that affects the water temperature is conduction.

The result is shown in a schematic figure 26. From this simulation we know that if on the restoring initial conditions attended only conduction process, the thermal values of the carbonate aquifer would be renewed for up to more than 2,500 years.

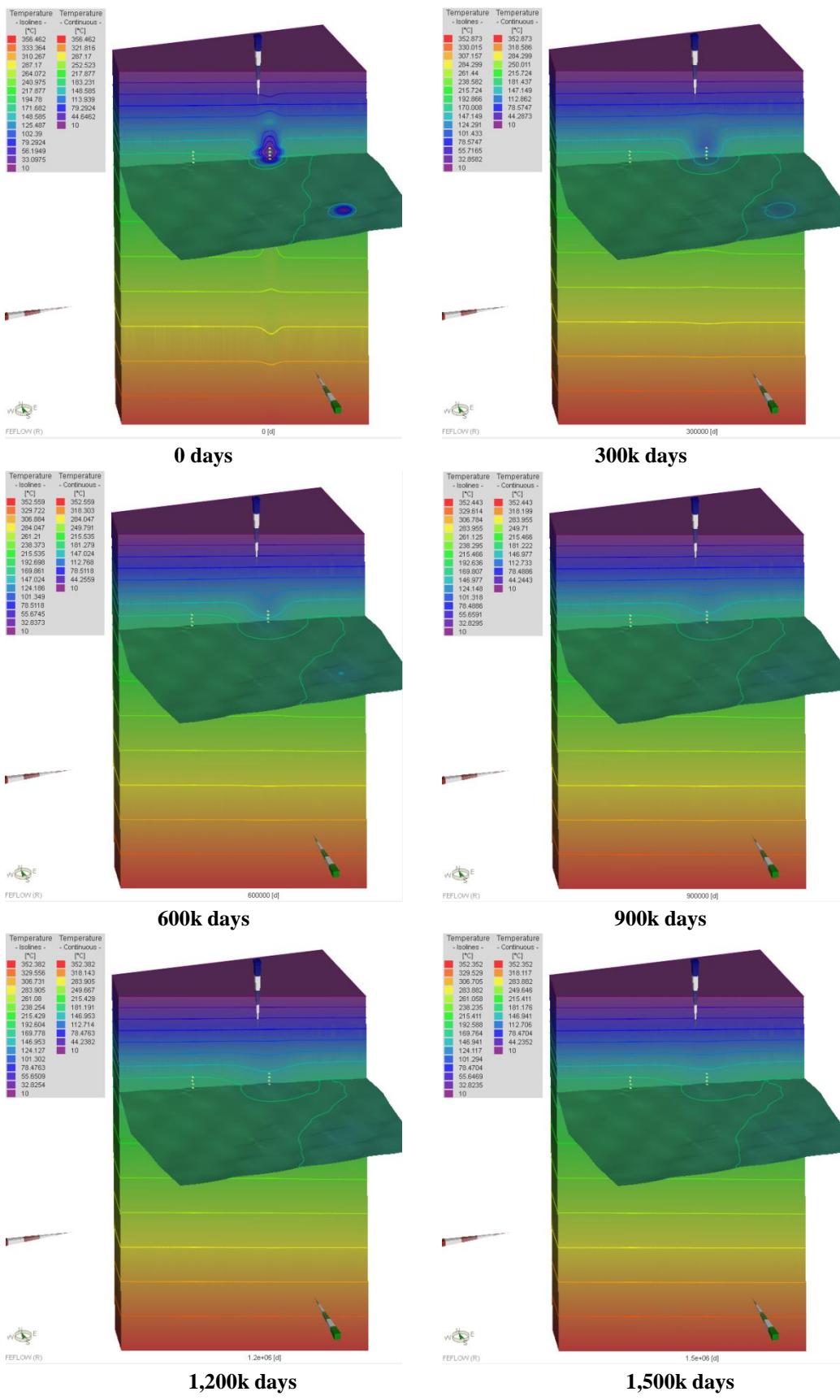


Figure 26: Simulation of conduction heating of geothermal waters in hydraulically closed aquifer after 35-year use i re-injection.

5 CONCLUSIONS

Two regional steady-state model scenarios 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:

- Modelled closed hydrogeological structure tied to the Mesozoic carbonates is suitable for use by re-injection.
- 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 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.

6 LITERATURE

Atlas krajiny Slovenskej republiky. 1. vyd. Bratislava: Ministerstvo životného prostredia SR; Banská Bystrica: Slovenská agentúra životného prostredia, 2002, 344 s.

Diersch H.J.G. (2006). FEFLOW Finite Element Subsurface Flow and Transport Simulation System. Reference Manual. WASY GmbH Institute for Water Resources Planning and Systems Research, Berlin.

Franko O., Fusan O., Kral M., Remsik A., Fendek m., Bodis D., Drozd V., Vika K. (1995): Atlas of geothermal energy of Slovakia. Geologicky ustav Dionyza Stura, Bratislava, 1995.

Hurter, S. & Haenel, R. (2002): Atlas of Geothermal Resources in Europe. - 93pp, 88 plates, ISBN 92-828-0999-4, CG-NA-17-811-EN-C; Luxemburg (Office for Official Publications of the European Communities)

ICPDR, 2005: The Danube River Basin District River basin characteristics, impact of human activities and economic analysis required under Article 5, Annex II and Annex III, and inventory of protected areas required under Article 6, Annex IV of the EU Water Framework Directive (2000/60/EC) Part A – Basin-wide overview The complete report consists of Part A: Basin-wide overview, and Part B: Detailed analysis of the Danube river basin countries, ICPDR Document IC/084, 18 March 2005

Lenkey, L., Rajver, D., Svasta, J. (2012): Summary Report „Geothermal Models at Supra-Regional Scale”. Project TRANSENERGY internal report.

Maros, G., et al., 2012: Summary report of geological models. Available on 30.1.2013 at:
<http://transenergy-eu.geologie.ac.at/>

Tóth, G., Rotár-Szalkai, Á., Kerékgyártó, T., Szőcs, T., Gáspár E. (2012): Summary report of the supra-regional hydrogeological model. Project TRANSENERGY internal report.