This project is implemented through the CENTRAL EUROPE Programme co-financed by the ERDF.
http://transenergy-eu.geologie.ac.at

Report on the Danube basin pilot area model

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

Date 31-MARCH-2013

Status final

Type Text

Description The report presents the results of the modeling in the Danube basin pilot area of the TRANSENERGY project. The modeling 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 modeling

5.2.5 Detailed geothermal modeling

Table of contents

List of Figures

List of Tables

1 INTRODUCTION

The report presents the results of the steady state modelling of the Danube basin pilot area of the Transenergy project with the focus on Upper Pannonian aquifer, partly on adjacent thermal karst aquifers.

The utilization of the geothermal water is spread throughout the whole pilot area on Slovak and Hungarian side and partly on Austrian side. The utilization of geothermal water is performed by pumping and natural overflow form wells. The average yield of utilized geothermal water on Hungarian side of the Danube basin pilot area is 51 349 m^3/year and on Slovak side 87 631 m^3/year (as reported for the purposes of Work Package 3 of this project). No utilization on delineated Danube basin area is present on Austrian side.

The goal of modeling that comprises 3D groundwater flow and heat transport simulations was to provide information for better understanding of the hydrogeological and geothermal conditions in the pilot area. It is a first step in modeling process and basis for scenario analysis for sustainable utilization of the geothermal resources. The modeling simulations were calculated for of steady state conditions – steady flow and steady heat transport. Two scenarios are compared in the model – pre-utilization reflecting “natural conditions” with no pumping assumption and assumption considering influence of the production wells based on accessible data about the geothermal water extractions.

Presented approach is first attempt of conceptual and numerical presentation of studied geothermal system of the Danube basin on Slovak, Austrian and Hungarian parts of the structure. It is based on current state of knowledge and data, which all have certain limitations. To the account of uncertainty, related to estimation of parameters of hydrogeological model. The information used for model set up, verification and optimalization is based on database of geological and hydraulic parameters, database about the utilization characteristics, both compiled for the project purposes. Helpful sources of the data and interpretations were Atlas of Geothermal energy of Slovakia (Franko et al., 1995) Geothermal Atlas of Europe (Hurter and Haenel, 2002) and previous studies performed in Slovakia, Austria and Hungary.

1.1 Geographical setting

The pilot area of Danube basin evaluated in TRANSENERGY project is situated in Slovakia, Hungary and partly at Austria. The Danube basin pilot area covers around 12 170 km^2 (Figure **1.**).

The Danube Basin is geographically represented by the Danube Lowland in Slovakia and by the Little Hungarian Plain in Hungary. On the west it is bordered by the Eastern Alps, Leitha Mts. and Male Karpaty Mts. On the north the basin has finger like extensions which penetrate among the core mountains of Male Karpaty, Povazsky Inovec and Tribec. On the northeast it is bounded by the Middle Slovakian Neovolcanics and the Burda volcanics. On the southeast, there are emerging units of the Transdanubian Central Range.

1.2 Climate and hydrology

Climate and hydrology

The upper regions in the west and north show influence from the Atlantic climate with higher precipitation partly affected by continental climate with lower precipitation and typical cold winters. In the area on the south, influences from the Mediterranean climate, can also be detected. The heterogeneity of the relief (in wider vicinity of the pilot area), the differences in the extent of exposure to the predominantly westerly winds and the differences in altitude diversify this general climate pattern. This leads to distinct landscape regions showing differences in climatic conditions. The mean annual air temperature is in interval 10 - 12°C. The precipitation ranges from < 500 mm to > 700 mm (in nearby mountains) based on differences in the regions. The mean annual potential evapotranspiration is in range 750 – 800 mm. The mean annual actual evapotranspiration is < 450 mm (Atlas krajiny Slovenskej republiky, 2002).

The Danube river in the studied area has discharge (input Slovakia – output Hungary) approximately in interval 2500 – 3000 m3/s (based on data in 1994-1997) Main rivers that are tributaries to the Danube River on studied area are: Morava/March - 119 m3/s (average discharge 1961-1999), Raab/Rába – 88 m3/s (average discharge 1901-2000), Vah 161 m3/s (average discharge 1931-1980), Hron 55 m3/s (average discharge 1931-1980), Ipel/Ipoly 22 m3/s (average discharge 1931-1980) (ICPDR, 2005).

Important lakes in the Danube Basin area

Neusiedler See / Ferto˝ -tó – West edge of the Danube basin pilot area. Neusiedler See / Ferto˝-tó is located in the east of Austria and shared with Hungary - total surface area of 315 km2 (at a defined water level). Has an average natural depth of 1.1 m, its maximal water depth is 1.8 m. In its history it has dried out completely several times. Since 1965 the water level is stabilised by the outlet sluice based on an agreement of the Hungarian-Austrian Water Commission in 1965 (water level in April-August: 115.80 m a.s.l., October-February: 115.70 m a.s.l., transition periods March and September: 115.75 m a.s.l.). The main surface water input is through precipitation on the lake surface, secondly by smaller tributaries. Inflow due to groundwater is close to negligible. The lake water is characterised by a high salt concentration.

Major wetlands in the Danube Basin area

The wetlands in the Alps and Carpathians also represent valuable drinking water reserves for millions of people. The current extent of wetlands in the DRB is only a remnant of the former wetland systems.

The Donauauen National Park (Austria) with approximately 11,000 ha of floodplain forests, riparian habitats and side-arms between Vienna and Hainburg represents the last intact floodplain of the upper Danube. (out of the studied area). Together with the *Floodplains of the Lower Morava and Dyje* (Austria, Czech Republic and Slovak Republic) it forms a transboundary “wetland of international importance” and was declared as a trilateral Ramsar Site.

The Neusiedlersee and Fertó-Hanság (Austria and Hungary), a transboundary National Park since 1993, and World Heritage Site since 2003, is a 30,000 ha shallow steppe lake area with a huge reed belt, adjacent small soda lakes.
Szigetköz and Žitný Ostrov Floodplain Complex (Hungary and Slovak Republic), an extended meander zone around the low water bed of the Danube are protected landscape area, includng small nature reserves.

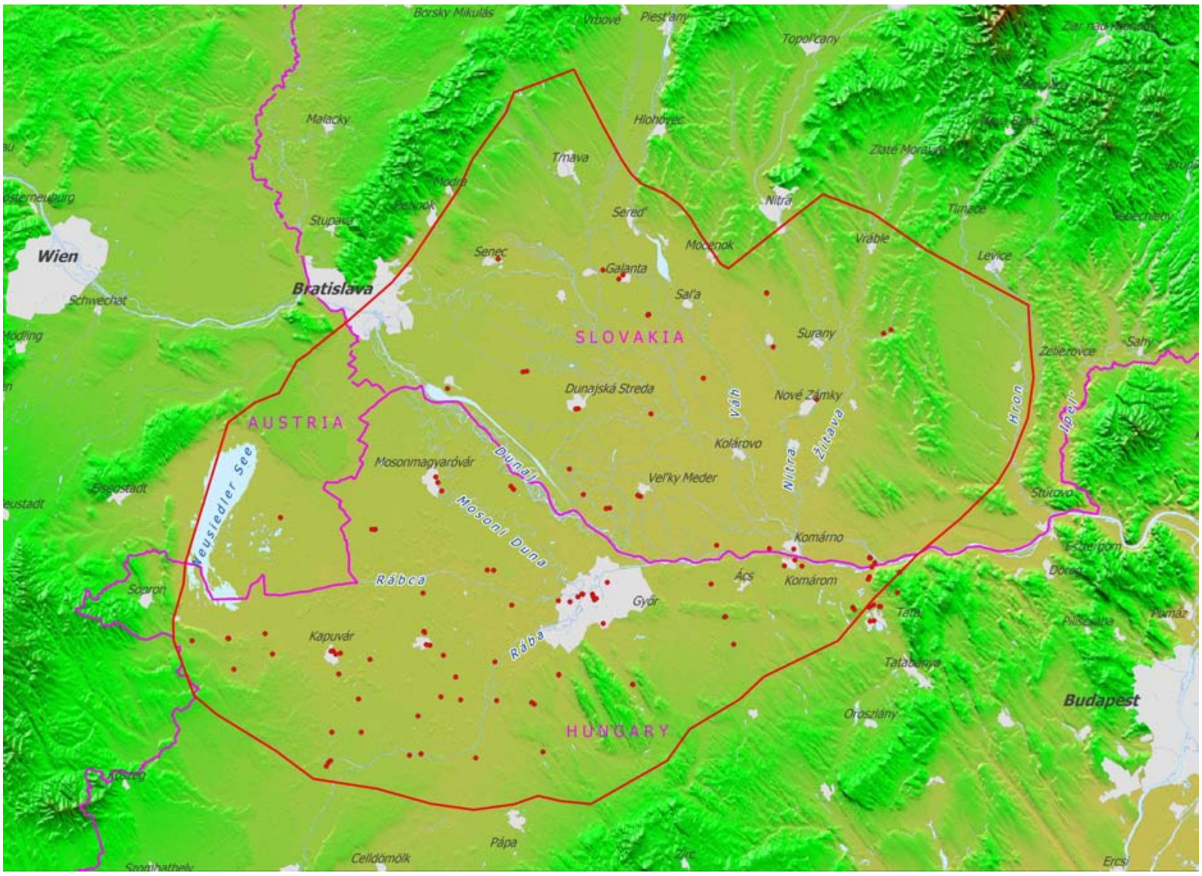


Figure 1. Delineation of pilot model area with the production wells.

1.3 Geological setting

The Pre-Tertiary basement of the basin at the western and northern boundary is built up of several units of the Central Eastern Alps and Central Western Carpathians, while in the southeastern part of the basement units of the Transdanubian Central Range are also present. In the Slovakian part the basement is built up of crystalline and mainly late Paleozoic and Mesozoic cover sequences of the Tatric and Veporic units and nappe systems of Fatricum and Hronicum composed mainly of Mesozoic (dominantly Triassic – Jurassic) sedimentary seqences. The Tatric and Veporic units continue into Hungarian and Austrian territories as their equivalents in the Lower Austroalpine nappe systems. The Transdanubian Central Range forming the basement in the southern part of the area is built up of a sequence of Paleozoic rocks, massive Triassic and Jurassic strata dominantly forming in platform or open-sea environment. Cretaceous sediments of terrestric or shallow-water environment are terminating the Mesozoic part of this succession.

Tertiary rocks of the so-called Buda-type Paleogene in the area are known only from the Transdanubian unit on the southern rim of the area. This type of succession is characterized by shallow-water to terrestric sedimentation and is represented by shallow-water limestones, sandstones, marls and clays as well as coal or bauxite occurrences.

Lower Miocene deposits occur in two separate areas: in the NE part of the area in Slovakia and in the Transdanubian area at the SW, mainly in Hungary.

The oldest Neogene deposits in the Slovakian part of the Danube Basin are of Eggenburgian age. The Eggenburgian marine depositional area was paleogeographically connected to those, in the northern part of the Vienna Basin. In the Ottnangian the depositional environment started to be brackish. The Karpatian marine deposits of the Laksary Formation and alluvial-deltaic Jablonica Formation are present in the northern part of the Blatne depression and in the Dobra Voda depression.

Lower Miocene deposits in the Transdanubian part represent a stratigraphical continuation from the underlying Buda-type Paleogene and are built up of fluvial – lacustrine or brackish-water gravels, sands and clays sometimes with coal layers.

Due to the Miocene tectonic evolution of the area the Badenian is the first horizon with similar sedimentary developement in the whole area. Since our model contains a single horizon for the whole Badenian, we discuss the different Badenian sub-phases together.

The Early Badenian developed separately in the NE and the SW parts of the basin: the mostly deep-marine deposits The Middle Badenian open marine deposits cover practically the entire area of the Danube Basin. The Late Badenian are represented by shallow marine deposits, covering whole the area of the basin.

In the central part of the basin large stratovolcanic bodies of Early Badenian age belonging to the Šurany (or Burda) Formation can be observed, being covered by younger sediments. Other smaller occurrences are known in the vicinity of Bratislava and in the Csapod Trench in Hungary.

The Sarmatian deposits of the were formed in a shallow brackish sea and are facially variable in the area of the entire basin.

The division and correlation of the Pannonian sediments and their boundary with the Quaternary is probably the biggest stratigraphic problem of the area. In the geological model that served as a background for hydraulic model the Lower Pannonian horizon (as Ivanka Formation in Slovakia) was defined which is correlated with numerous dominantly marly beds in Hungary (Peremarton, Endrőd, Zsámbék, Csákvár Marl Fm.). All these formations formed from shallow water to lacustrine environment, the Ivanka Fm. also contains prograding deltaic lobes. We joined the Upper Pannonian and Pliocene sediments due to their lithological similarities and unclear definition of the boundary between them into one horizon. In the central parts of the Danube Basin their thickness exceeds sometimes 2500 m. They developed in continuing and further shallowing lacustrine environment changing upward into deltaic and fluvial facies. The built up of clays, marls, sands and are ranged into the Beladice, Volkovce, Kolárovo, Zagyva, Újfalu

Formations. In the younger parts of the Upper Pannonian also basaltic intra-plate volcanism is known (Tapolca and Podrečany Basalt Fm. and Pula Alginite Fm.).

The Quaternary deposits have an erosive base and accumulated in depressions. However in the Gabcikovo depression the deposition was continuous from the older sediments. Fluvial deposits are dominant, but an important amount of loess is typical for the basin areas as well (Maros, G., et al., 2012).

1.4 Hydrogeological setting

The crystalline basement has no significant influence on the groundwater flow system. They have fissure-type permeability. They differ in stratigraphy, but the main features are the same. Usually they can be characterize with intensive heterogenity, 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 it has 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 *Komarno 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 Komarno 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 3 000 m near Hurbanovo fault. The pre-Tertiary substratum of the Komarno block consists largely of Triassic dolomites and limestones up to 1 000 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 Komarno 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 (Remsik - Franko, et al. 1979; Franko, et. al. 1984; Remsik, et al. 1992). 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 3 000 m). The Komarno 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 $1{,}28.10^{-3}$ $m^2 \cdot s^{-1}$. T in the marginal block ranges from $5{,}07.10^{-5}$ to $2{,}21.10^{-4}$ $m^2 \cdot s^{-1}$.

The representative *block of Graz Palaeozoicum* (part of the Upper Austroalpine nappes) *in Bük-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 Bük is separated from the reservoir of Rábasömjén at northwest along tectonical zones. It is supposed that the Bük 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 meter 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, calcareus sandstones, or organogenic limestones.

The covering Quaternary layers represented by gravel and sands. The maximum thickness (520-600 meters) occurs in the region of Gabcikovo and Baka.

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 content 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 aquicludes. 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.

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 Gabcikovo 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 represents a great amount of good quality water. The dynamic discharge in some places exceeds 8 m^3/sec of water. It has great potential for the future drinking water resources.

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

2 NUMERICAL MODELING

The aim of the numerical modeling was to simulate the hydrogeological and geothermal conditions in the in the geothermal water body of pre-Neogene and Neogene fill of the Danube basin. The goal of modeling that comprises 3D groundwater flow and heat transport simulations was to provide information for better understanding of the hydrogeological and geothermal conditions in the pilot area. The modeling simulations were calculated for of steady state conditions – steady flow and steady heat transport. Two scenarios are compared in the model – pre-utilization reflecting “natural conditions” with no pumping assumption and assumption considering influence of the production wells based on accessible data about the geothermal water extractions

Modeling software

The character of the problem requires a tight approximation of complex faulted geology with discrete line and point features, such as rivers and point water abstractions, where steep pressure and temperature gradients are unavoidable. Therefore a finite element model was chosen as the most appropriate. FEFLOW (Diersch, 2006) is capable of solving coupled groundwater flow, mass transfer and heat transfer problems in three dimensional porous domains. Its powerful mesh generators enable to construct good quality triangular meshes with inclusion of discrete finite elements representing wells, faults, etc. 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.

2.1 Pilot model

2.1.1 Horizontal extent

The model area is outlined in accordance with the TE project pilot area (Figure 1).

2.1.2 Vertical extent

From top the model is limited by the topographical surface, adopted from the digital elevation model SRTM. To the depth the model extends down to -10,000 m a.s.l.

2.1.3 Horizontal resolution

Due to expected elevated hydraulic and thermal gradients around fault zones, rivers and wells, the computing mesh needed to be locally refined around these features. Thus the generated mesh, consisting of triangular prisms, ended up counting up to 31114 nodes per slice (in total 373368), forming 61602 elements per layer (total 677622).

2.1.4 Vertical resolution

The model adopted a geological model consisting of 8 hydrostratigraphic units:

1. Quaternary - phreatic
2. Upper Pannonian
3. Lower Pannonian
4. Sarmatian
5. Badenian
6. Badenian volcanites
7. Cenozoic
8. Mesozoic, Paleozoic and Crystalline basement

Upper Pannonian was further subdivided into two formations: delta plain and delta front. For this purpose a sequential indicator kriging was performed upon borehole data using GSLIB (Deutsch & Journel, 1998, Figure 2).

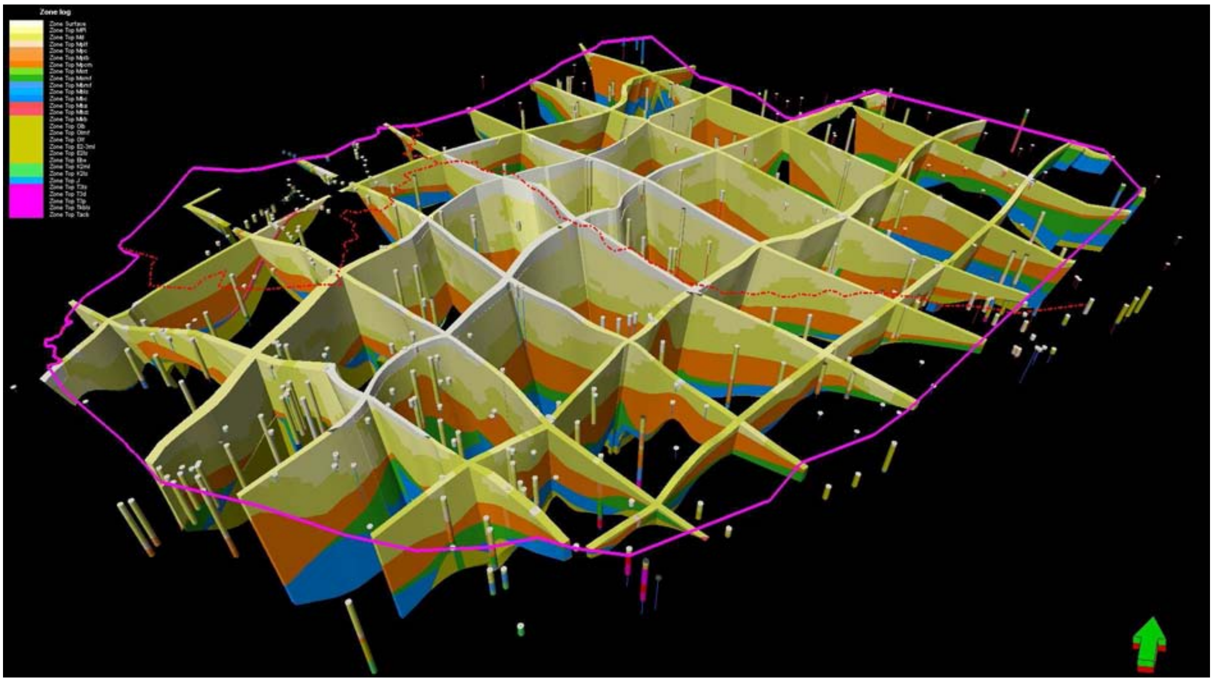


Figure 2. Fence diagram of geological model.

Due to large thickness of the basement layer, it was divided into 2 numerical sub-layers and a separate, 10 m thick weathered zone at the top was created.

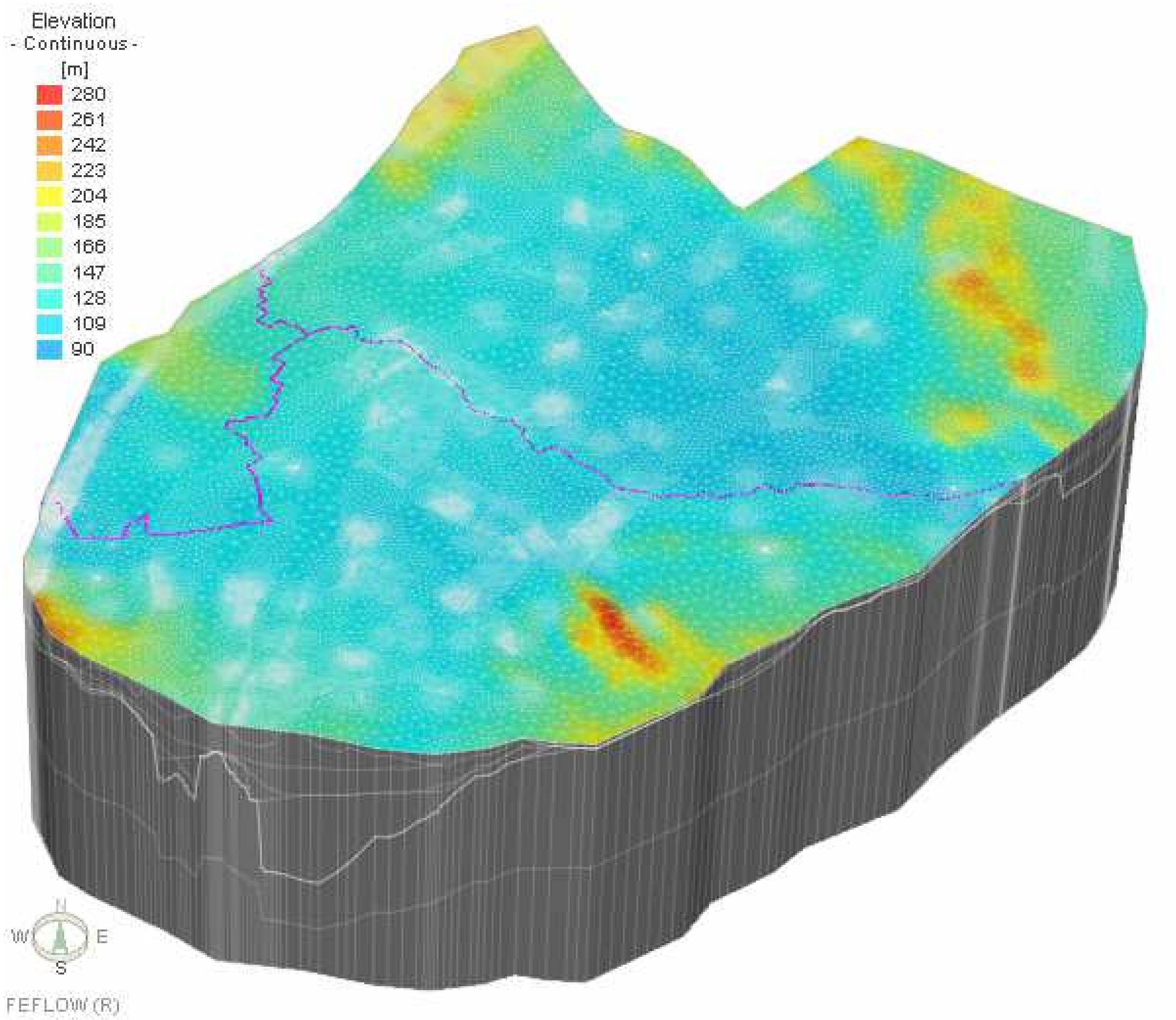


Figure 3. Geometry of the pilot area model. Vertical exaggeration 5x.

Due to unknown hydraulic function of regional faults, it was unnecessary to explicitly define faults in the model. They manifest themselves only in morphology of individual model layers.

2.1.5 Boundary conditions

Flow boundary conditions

The outer limit of the model was chosen to follow natural hydrogeological boundaries, defined either by extend of thermal water bearing horizons or by groundwater divides. Thus setting it as a no-flow boundary was justifiable.

All across the top surface a Dirichlet boundary condition (constant groundwater head) was set (Figure 4). The purpose of it was to prescribe realistic groundwater potential of cold water Quaternary aquifers laying on top of thermal aquifers. The groundwater heads were adopted from the calibrated supra-regional groundwater model (Tóth et al, 2012).

For the utilization variant of the model a second order (Neumann) boundary condition was applied at screen intervals of all active pumping wells also. Average reported well yields from years 2007 – 2010 were assigned as pumping rates. FEFLOW internally sets a special 1D linear finite element along well screens, to better approximate flow within a borehole.

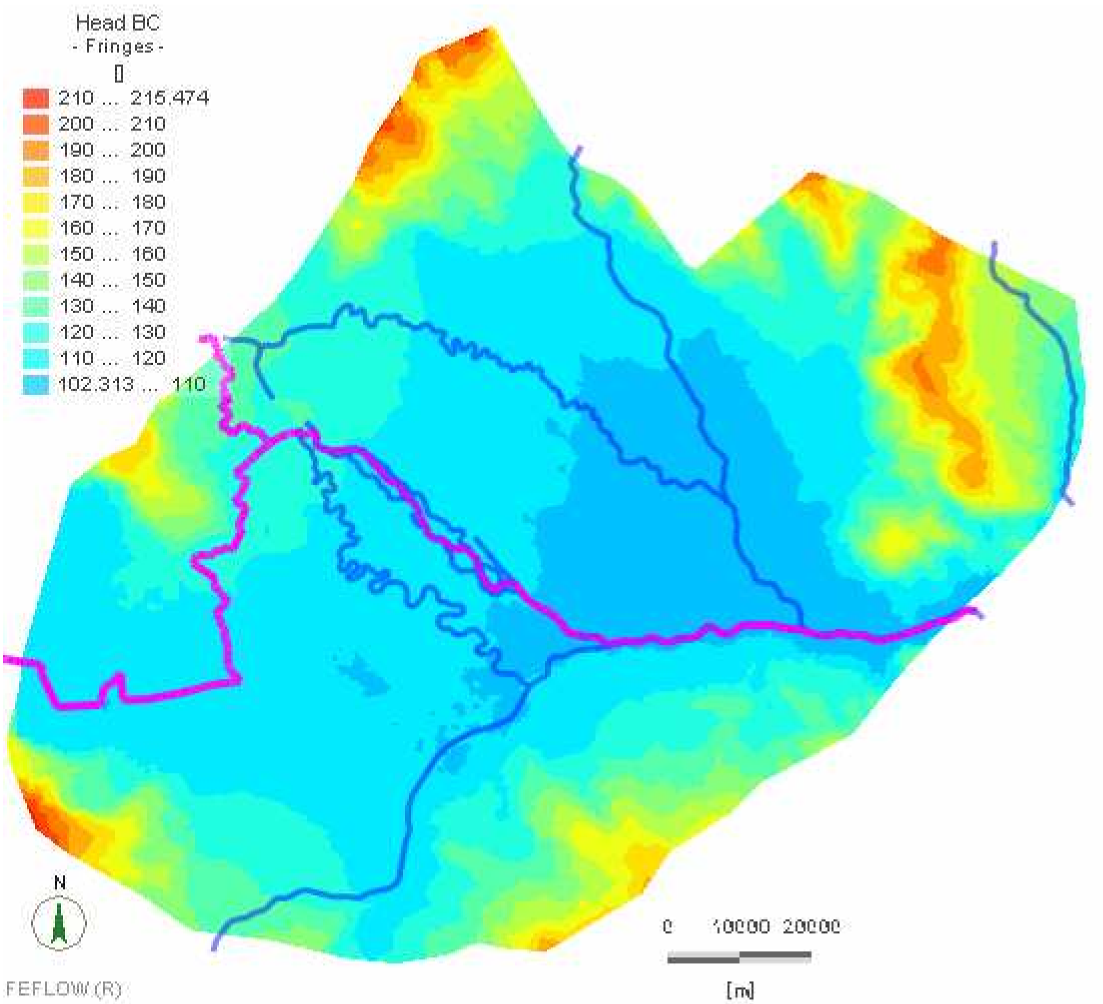


Figure 4. Constant hydraulic head boundary condition (m a.s.l.) in the Quaternary aquifer.

Heat boundary conditions

At the base of the model a Neumann (constant heat flux) boundary condition was set. The values of basal heat flux were taken from the supra-regional conductive thermal model of Lenkey et al 2012 (Figure 5). At the ground surface a Dirichlet boundary condition with uniform temperature 10 °C was set, which corresponds to annual mean air temperature in the model area.

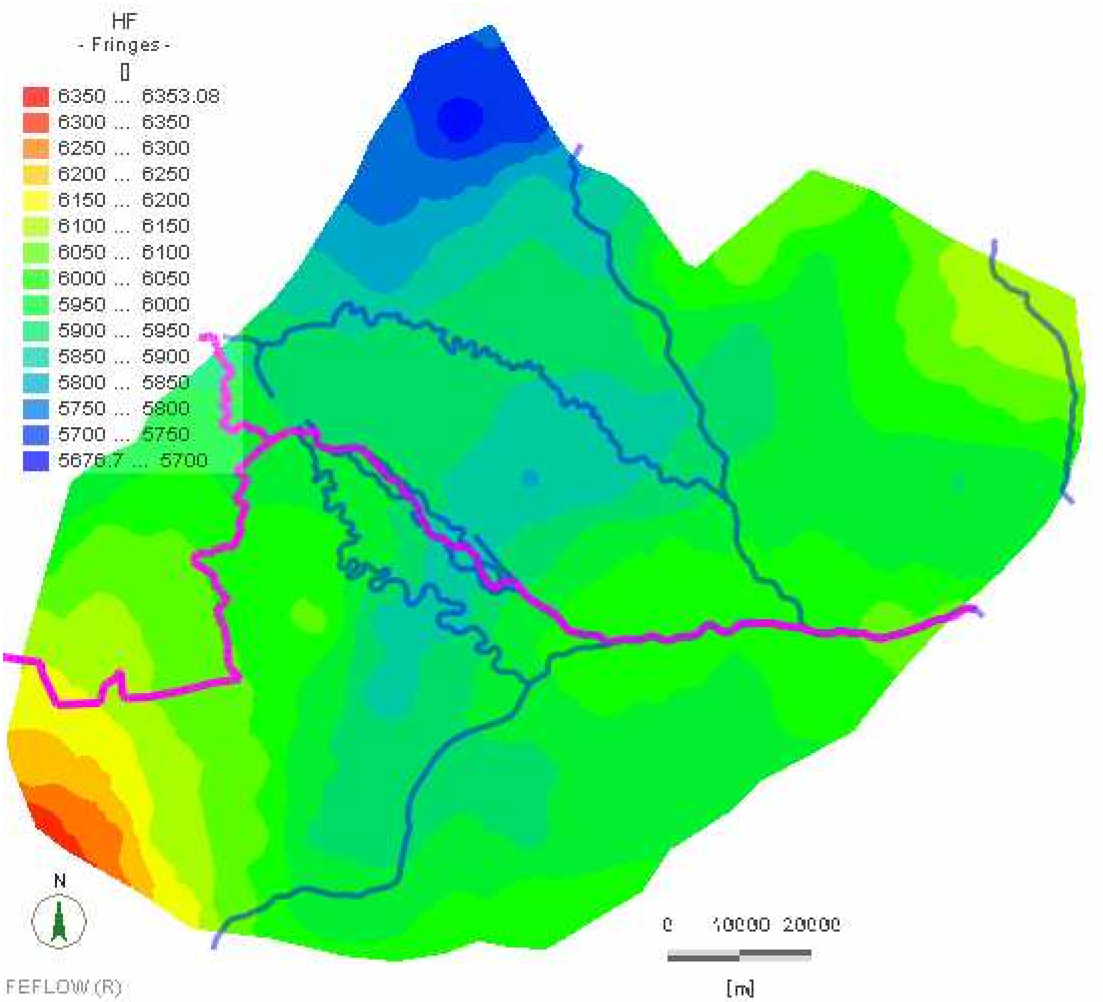


Figure 5. Constant basal heat flux (J/m^2/day) boundary condition at depth -10,000 m a.s.l. (from Lenkey et al 2012).

Radiogenic heat production in rocks is subtle, but not negligible source of total heat in present in geothermal systems. In FEFLOW it can be added as a material property (internal source), although it, in fact, acts as a boundary condition of second order. Because exact concentrations of uranium, thorium and potassium are not available to allow calculation of produced radiogenic heat, estimates based on published data were used instead.

2.1.6 Recharge and discharge

Because of prescribed head boundary condition at the top of the model, all groundwater recharge is handled at this boundary. Generally, water is infiltrated into the model at areas with higher head elevations and discharged at lower. The quantity of recharged and discharged groundwater is not constrained by any means, making it possible that at some locations within Quaternary aquifer groundwater fluxes and flow velocities can be unrealistically high. But as Quaternary aquifer with relatively cold water is not in the centre of our research, and acts solely as a pressure load on lower, thermal aquifers, this poses no restrictions to deep geothermal waters evaluation.

2.1.7 Material properties

Hydraulic conductivity is a very sensitive parameter, determining groundwater flow and heat transport in a model. At the same time, it is also very difficult to be assessed, especially in deeper parts of the model out of reach testing boreholes. Furthermore, data acquired from boreholes represent only the screened horizons, usually selected as the best permeable zones and thus overestimating the hydraulic conductivity. Another problem is high spatial heterogeneity of permeability, owing to frequent interchanging of very contrasting rocks within short horizontal and especially vertical distance. All this lead us to adopt an approach, in which hydraulic conductivities of individual model layers, corresponding to hydrostratigraphic units, were estimated based on borehole tests or data found in literature, regionalized and further adjusted in calibration process.

Quaternary sediments had been best investigated by well tests, therefore in the topmost model layer hydraulic conductivities correspond to measured values very closely. In deeper, Neogene sediments hydraulic conductivities are estimated. In this environment, typical by strong interchanging of impervious clayey aquitards with permeable sandy local aquifers, the enhanced flow along strata is mimicked by a high degree of anisotropy in direction perpendicular to bedding direction, up to three orders of magnitude. Also decrease of permeability and porosity with depth was accounted for.

Igneous, metamorphic and carbonate bedrock has a very low isotropic permeability and effective porosity, also decreasing with depth. Exception is the few meters thick upper part, which, prior to covering by younger sediments, undergo weathering and sometimes karstification, leaving behind higher porosity and permeability.

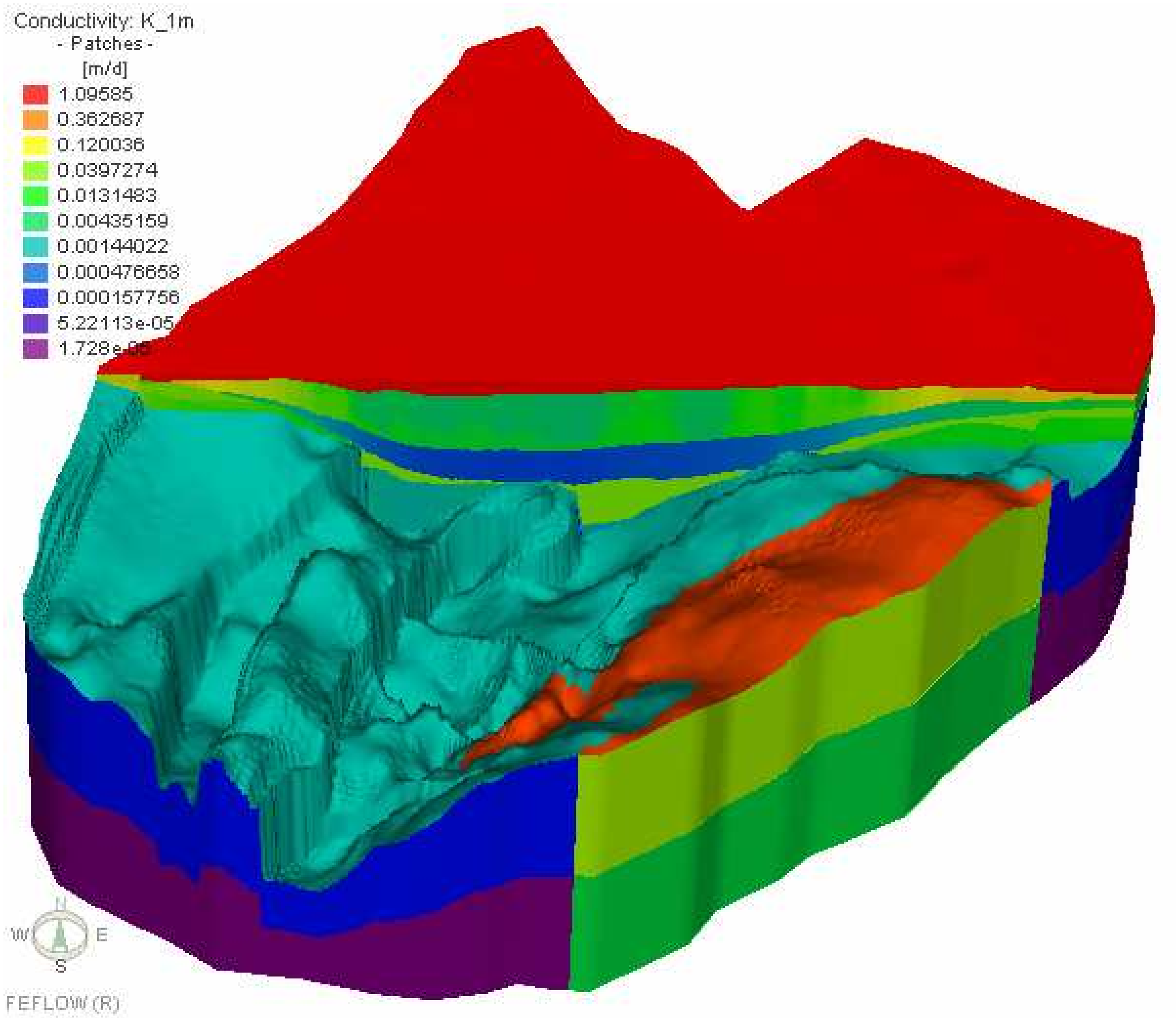


Figure 6. Horizontal conductivity distribution in the sedimentary basin (partial cut-out) and basement rocks. Higher values in the bedrock are Mesozoic carbonates.

Main heat transport parameters comprise volumetric heat capacity and thermal conductivity of rock and water, longitudinal and transversal thermal dispersivity, porosity. Fortunatelly, good database of these values exists for Neogene sediments and Mesozoic carbonates too. Values for the rest of the rock types present in the model were adopted from other published data.

2.1.8 Calibration and validation of the model

Initial values of hydraulic parameters were stepwise adjusted during multiple simulation runs to achieve best match between measured and computed hydraulic pressures at 149 measured points in the whole area. Resulting simulated pressures are compared with measured in figures 7 and 8.

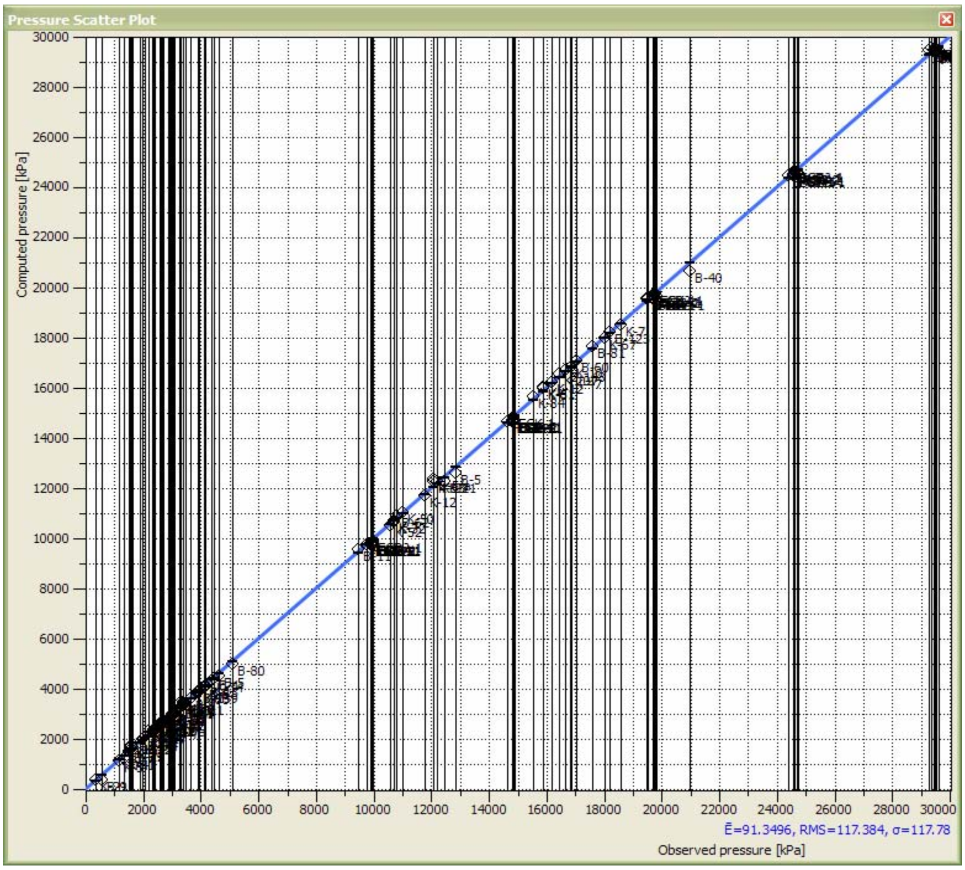


Figure 7. Goodness of fit between computed and measured pressures in boreholes, natural pre-utilization state.

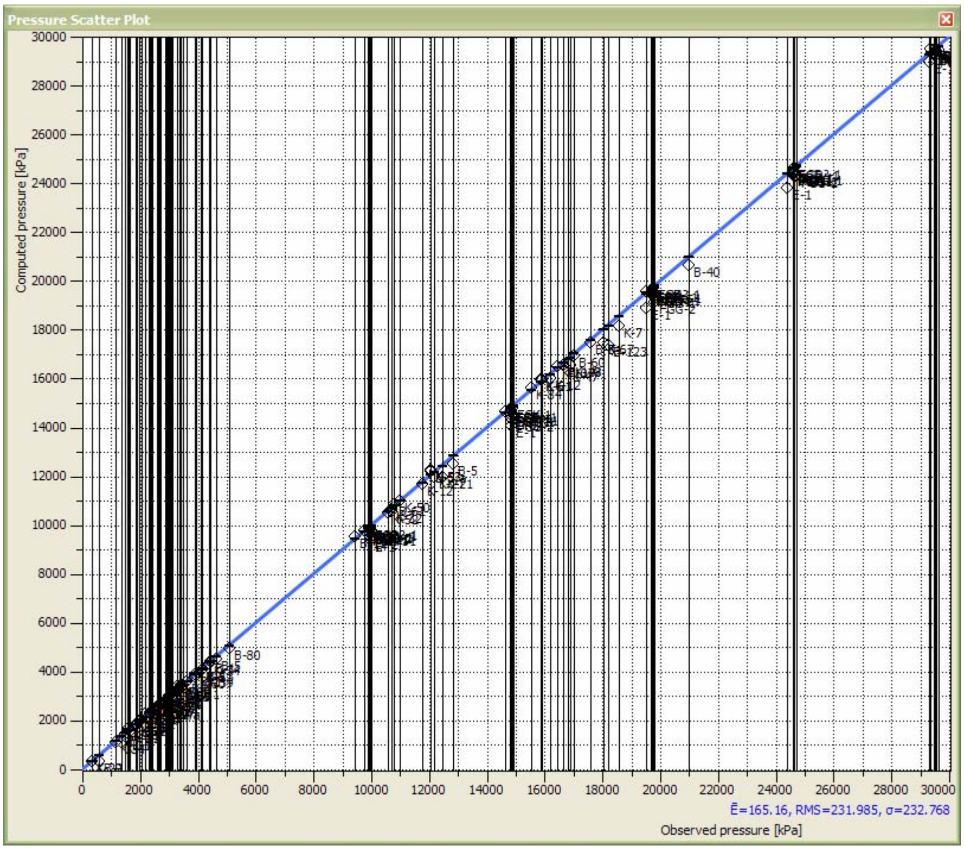


Figure 8. Goodness of fit between computed and measured pressures in boreholes, steady pumping scenario.

Since environmental groundwater heads measured at boreholes reflect density of water, influenced by temperature and dissolved salts content, it had to be converted into freshwater equivalent heads for use in numerical simulations. For this purpose groundwater heads in all boreholes with known temperature distribution and TDS were reevaluated. This involved calculation of average thermal gradient, from which average temperature in whole water column was calculated. Together with weighted average of TDS, an average water density in a borehole was obtained. Freshwater equivalent heads at reference temperature 10 °C, TDS=0 mg/l and density of pure water 999.7281 kg/m^3 were then calculated using equation of McCutcheon et al 1993.

Calibration of geothermal parameters was based on 67 downhole temperature measurements. Great effort was made to select data from measurements on closed, non operated boreholes only. However, due to missing information and disturbances of pressure and temperature field caused by drilling, this could not be guaranteed in many cases, which adds some extra error into the calibration results (Figure 9).

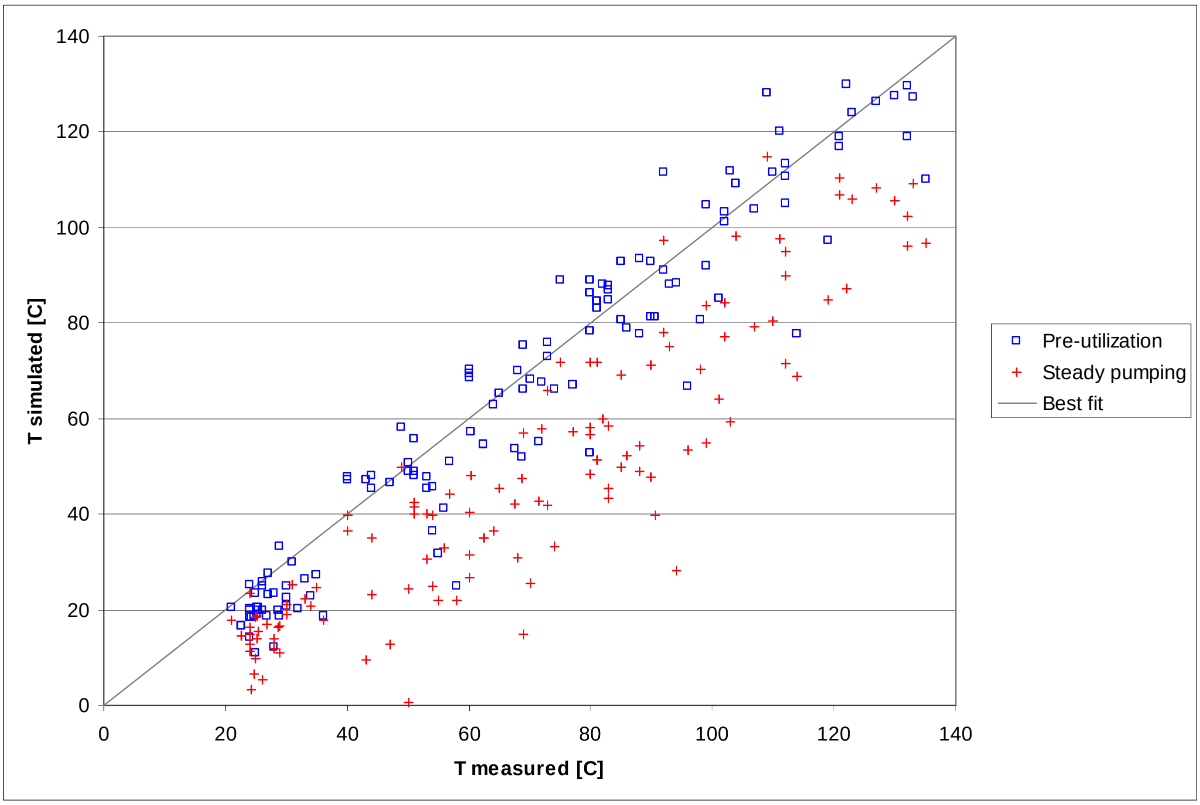


Figure 9. Comparison of temperature evolution in boreholes for two model scenarios: pre-utilization and steady pumping. Obvious is systematical temperature decrease when pumping is functional, resulting from enhanced circulation of cold Quaternary waters into deeper thermal aguifers causing shortening of travel times. Root mean square error (RMSE) for first scenario is 9.32 and 13.31 for the latter.

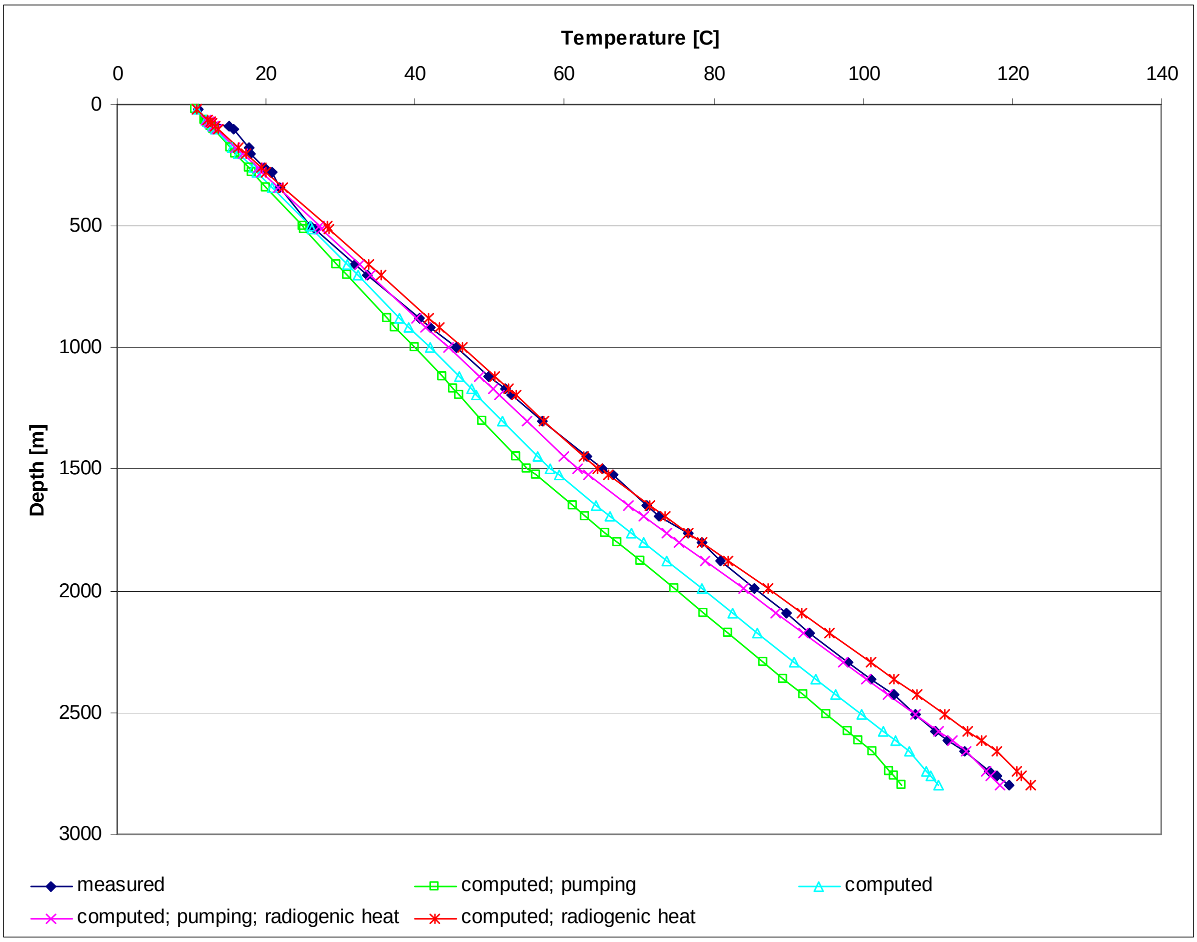


Figure 10. Comparison of different model set ups on goodness of fit between computed and measured temperatures, example from the monitoring well GPB-1 Boheľov. Best match was achieved for both scenarios, natural pre-utilization state and steady pumping, with inclusion of radiogenic heat production.

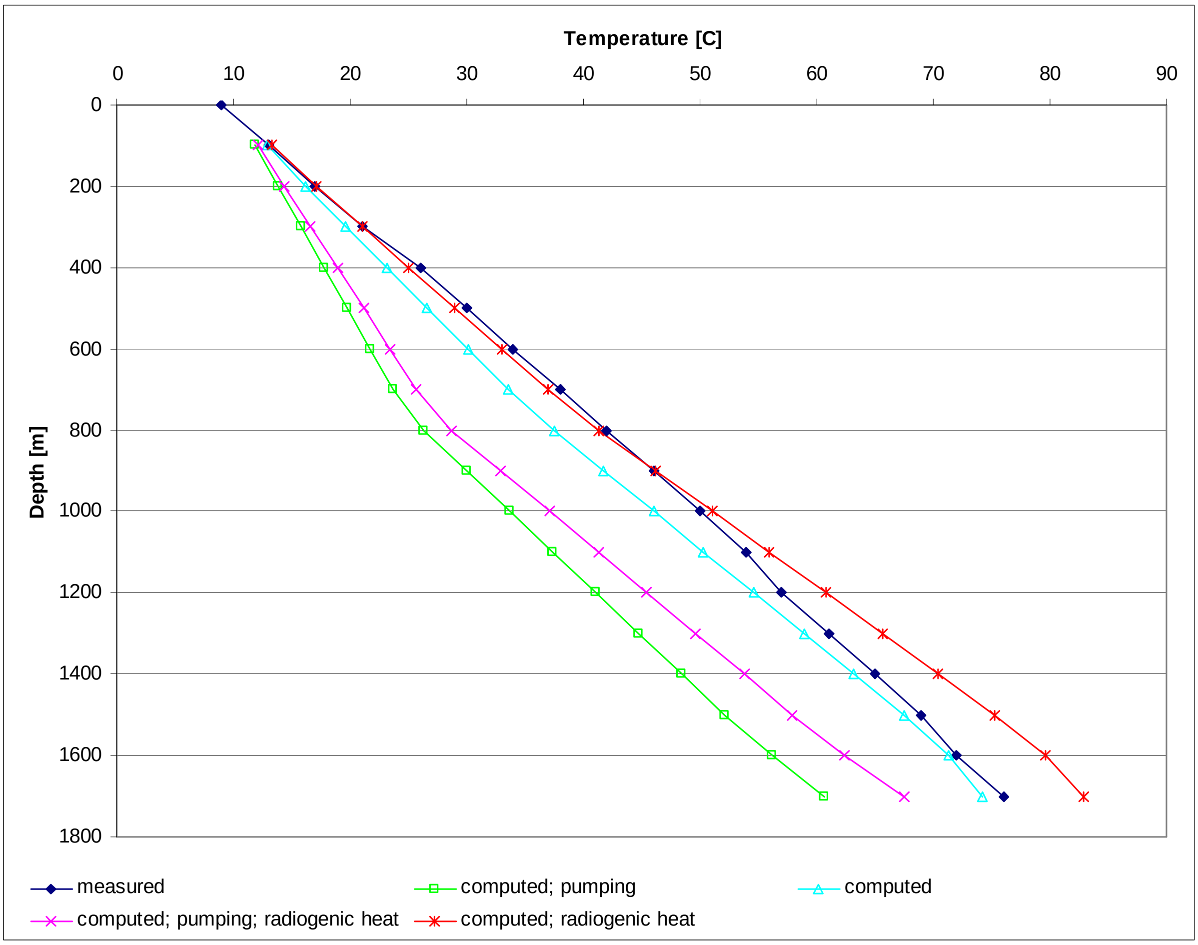


Figure 11. Comparison of different model set-ups on goodness of fit between computed and measured temperatures, example from the monitoring well Di-1 Diakovce. Steady pumping scenario exhibits significant deviation from measured temperatures in upper 800 meters. It can be attributed to cooling by increased infiltration of cold Quaternary water induced by pumping.

Table 1 contains values of parameters, used in the pilot area model.

Table 1. Parameters used in the pilot area model.

Model Layer	Horizontal hydraulic conductivity [m/s]	Vertical hydraulic anisotropy [-]	Porosity	Specific storage [1/m]*	Radiogenic heat production [μW/m^3]	Heat conductivity of solid [W/mK]	Heat conductivity of fluid [W/mK]	Expansion coefficient [1/K]*	Volumetric heat capacity of solid [JK/m^3]	Volumetric heat capacity of fluid [JK/m^3]	Longitudinal dispersivity [m]	Transverse dispersivity [m]*	Anisotropy of solid heat conductivity [W/mK]*
Quaternary	1.268×10^{-5}	0.1	0.276	1×10^{-4}	0.8	1.974	0.6	0	3.420×10^{6}	4.186×10^{6}	50	5	1
Upper Pannonian - delta front	3.228×10^{-8} - 3.526×10^{-6}	0.082 - 0.01	0.111	1×10^{-4}	1.3	2.219	0.6	0	2.737×10^{6}	4.186×10^{6}	50	5	1
Upper Pannonian - delta plain	6.080×10^{-8} - 1.0883×10^{-5}	0.01	0.181	1×10^{-4}	1.3	1.769	0.6	0	2.750×10^{6}	4.186×10^{6}	50	5	1
Lower Pannonian	3.327×10^{-9} - 9.159×10^{-7}	0.01	0.083	1×10^{-4}	1.3	2.406	0.6	0	2.999×10^{6}	4.186×10^{6}	50	5	1
Sarmatian	4.922×10^{-7}	0.002 - 0.007	0.111	1×10^{-4}	1	2.42	0.6	0	2.737×10^{6}	4.186×10^{6}	50	5	1
Badenian	1.277×10^{-8} - 4.642×10^{-6}	0.002 - 0.009	0.113	1×10^{-4}	1.2	2.754	0.6	0	2.496×10^{6}	4.186×10^{6}	50	5	1
Badenian volcanites	5.688×10^{-6}	0.001 - 0.005	0.1	1×10^{-4}	0.2	2.24	0.6	0	2.700×10^{6}	4.186×10^{6}	50	5	1
Cenozoic	1.047×10^{-8} - 4.445×10^{-6}	0.001 - 0.005	0.08	1×10^{-4}	0.7	2.554	0.6	0	2.598×10^{6}	4.186×10^{6}	50	5	1
Weathered basement: Mesozoic	6.960×10^{-6}	0.001	0.1	1×10^{-4}	1.1	2.7	0.6	0	2.584×10^{6}	4.186×10^{6}	50	5	1
Weathered basement: Paleozoic and Crystalline	2.000×10^{-8}	0.01	0.1	1×10^{-4}	1.1	3.11	0.6	0	2.584×10^{6}	4.186×10^{6}	50	5	1
Upper non-weathered basement: Mesozoic	6.960×10^{-7}	0.01	0.03	1×10^{-4}	1.1	2.7	0.6	0	2.600×10^{6}	4.186×10^{6}	50	5	1
Upper non-weathered basement: Paleozoic and Crystalline	2.000×10^{-9}	0.1	0.03	1×10^{-4}	1.1	3.11	0.6	0	2.600×10^{6}	4.186×10^{6}	50	5	1
Lower non-weathered basement: Mesozoic	6.960×10^{-8}	0.1	0.01	1×10^{-4}	1.1	2.7	0.6	0	2.600×10^{6}	4.186×10^{6}	50	5	1
Lower non-weathered basement: Paleozoic and Crystalline	2.000×10^{-10}	1	0.01	1×10^{-4}	1.1	3.11	0.6	0	2.600×10^{6}	4.186×10^{6}	50	5	1

* Default values in FEFLOW

3 RESULTS

Constructed regional model is simplified numerical representation of hydrological and geothermal characteristics of the pilot area and enable simulation of basic features of the geothermal system.

3.1.1 Hydraulic head distribution

Distribution of hydraulic heads in the model depends primarily on boundary conditions and spatial distribution of hydraulic conductivities (Figure 12). In upper parts hydraulic potentials are reflecting hydraulic heads set as constants in Quaternary, in deeper horizons hydraulic pressures are equilibrated, resulting in lower head differences.

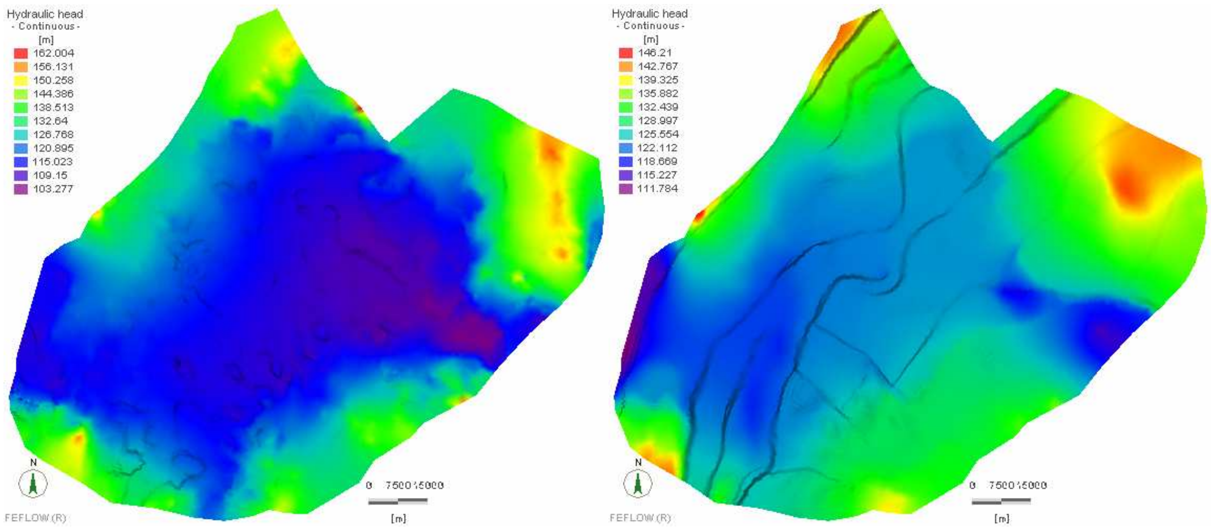


Figure 12. Distribution of computed hydraulic heads at the base of Upper Pannonian (left) and base of Cenozoic (right), pre-utilization state. Remember, that pictures show values on whole model layer, while respective hydrostratigraphic units cover only central part of the area. The same principle applies for all similar maps in this report.

3.1.2 Evaluating effects of thermal wells utilization

Simulation of theoretical infinite pumping of all existing operating geothermal wells was performed to predict future evolution of pressure and thermal field in the area and to help identifying potential adverse impacts of extensive and unsustainable thermal water over-utilization. It also serves as a base for calculation of transboundary induced flows and energy transfer. The simulations were performed as steady flow and steady heat transport, practically meaning that results show a hypothetical situation in infinite future, if current amounts of water would be extracted. This, off course is unrealistic, but results can highlight potentially problematic places. For instance, areas with very high pressure drop can indicate closed geothermal structures. Similarly, boreholes where a high temperature decrease is predicted should turn attention towards possible future risk of cold front arrival and thus shortening the production life of the site.

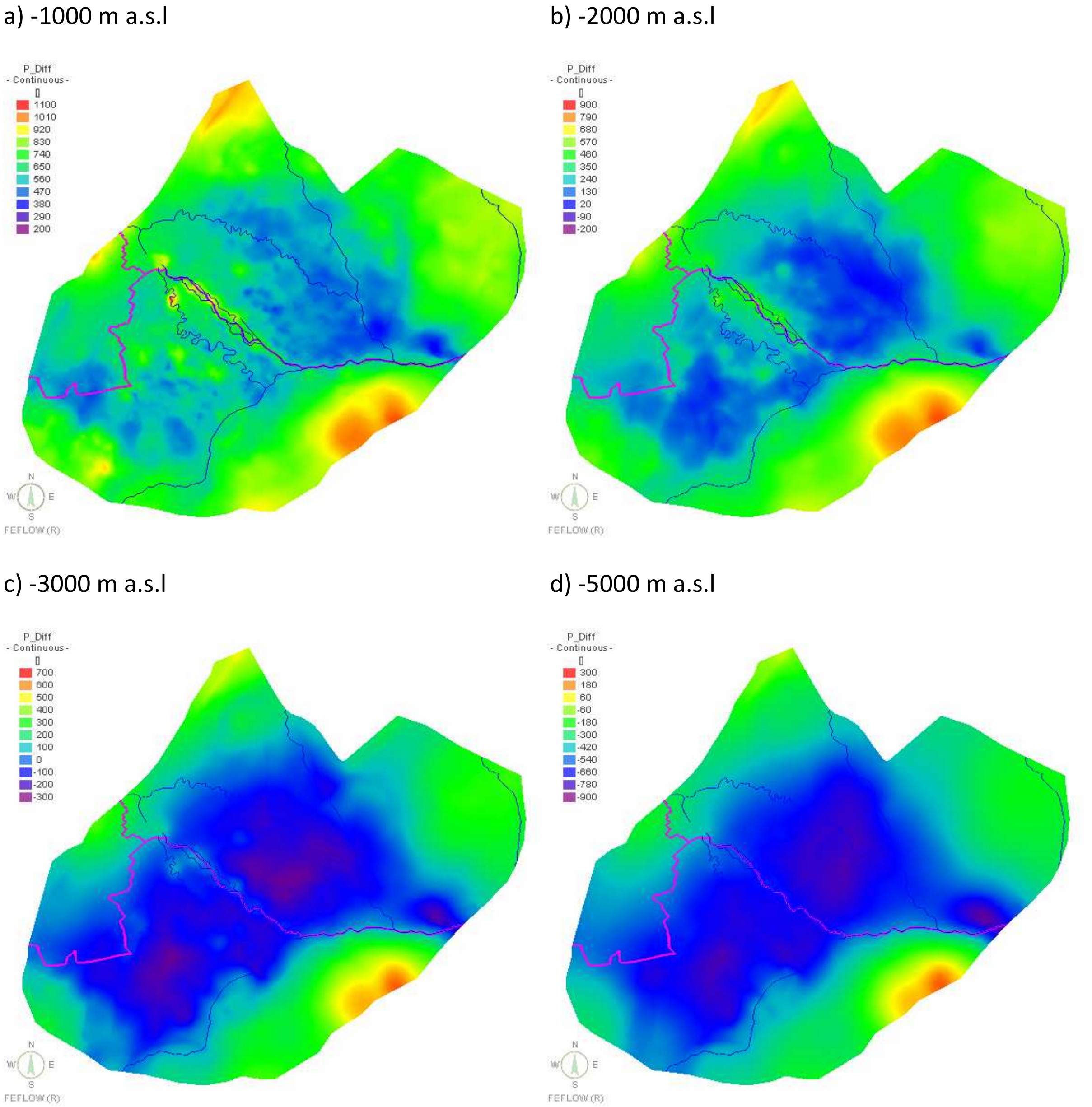


Figure 13. Pressure differences (Pa) caused by steady pumping at different depth levels.

Pumping thermal water from utilized wells in the area is causing a decrease in hydraulic pressure in penetrated geothermal aquifers, as well as adjacent aquitards and basement rocks. Moreover, due to induced general decrease of temperatures caused by enhanced circulation (see next chapter), colder water with higher density is promoting pressure increase in deeper parts of the central depression, because groundwater head at the top is maintained at constant level by recharge. These changes are visualized on Figures 13 a – d.

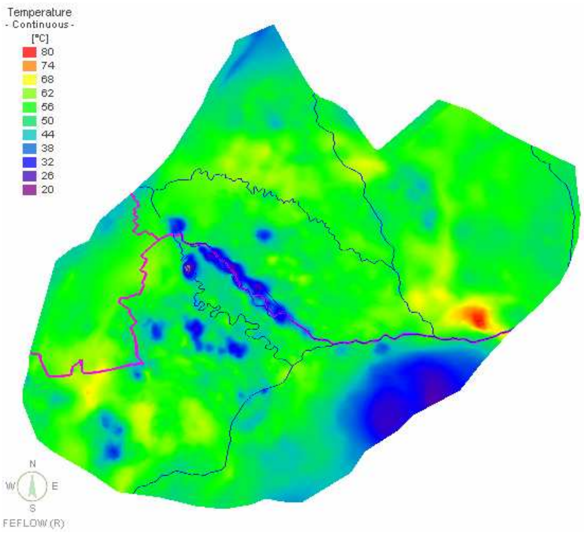
3.1.3 Temperature distribution

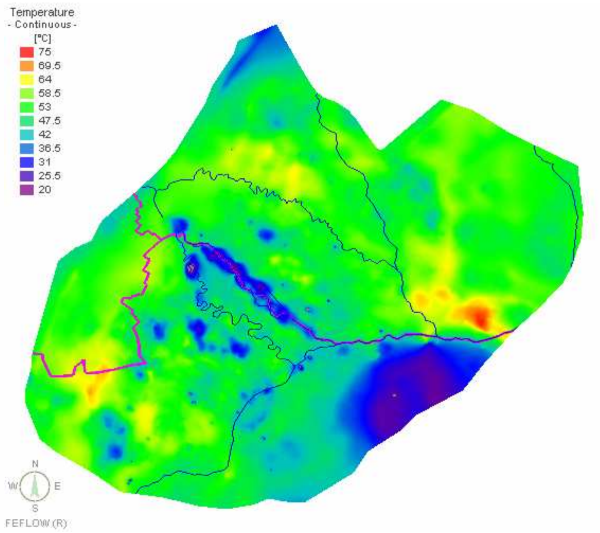
In Pre-Quaternary rock formations conduction is the main mechanism for heat transport. Due to relatively intensive water interchange between recharge and discharge zones in Quaternary sediments, convection is of high importance. Convection driven heat transport is also dominating in karstified Mesozoic carbonate formations in Gerecse and Pilis Mts. and

Komárno elevated block. Recharge of precipitation is causing a considerable cooling of the whole carbonate massive in Komarno elevated block in the south-eastern part of the model (Figure 13).

Pre-utilization **Steady pumping**

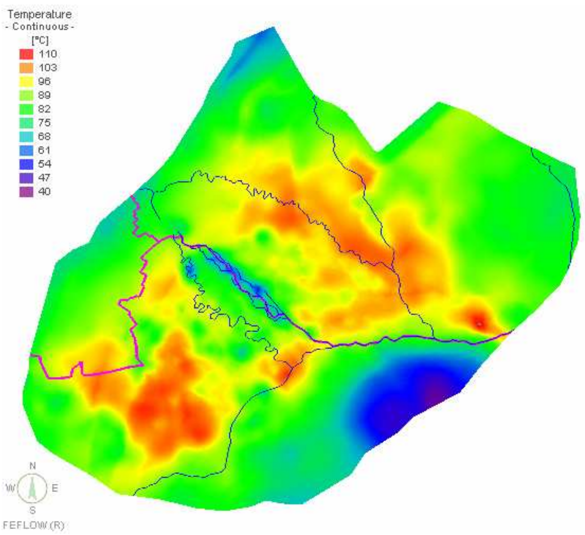
a) -1000 m a.s.l

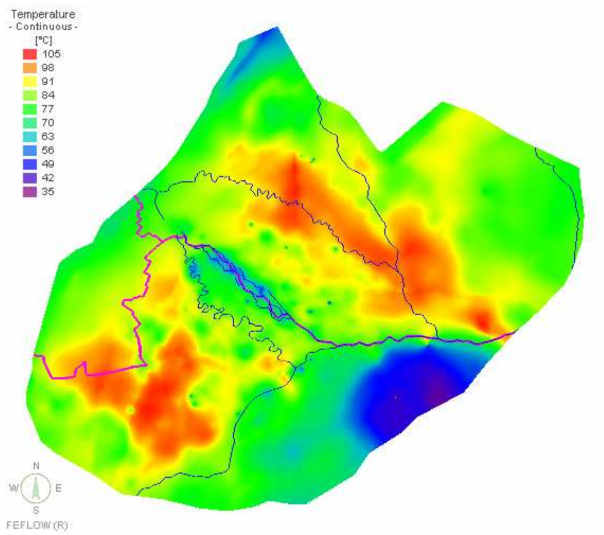




Pre-utilization **Steady pumping**

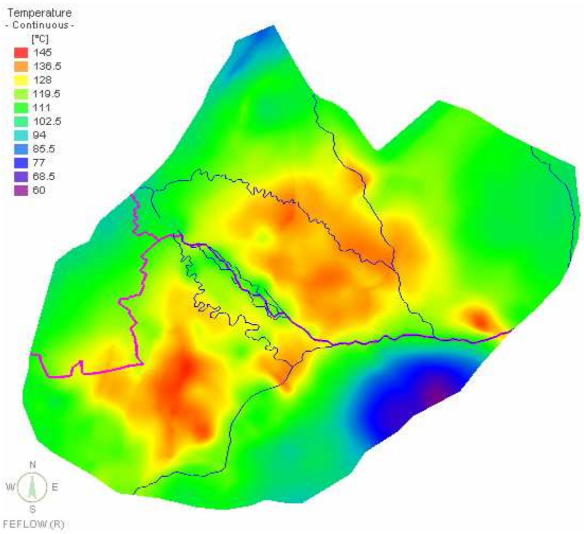
b) -2000 m a.s.l

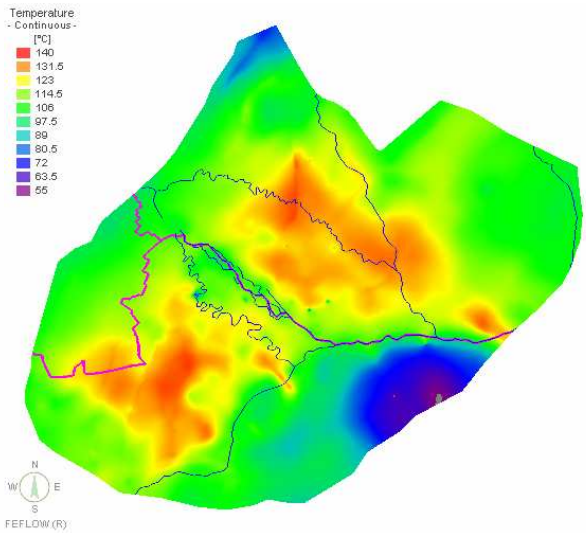




Pre-utilization **Steady pumping**

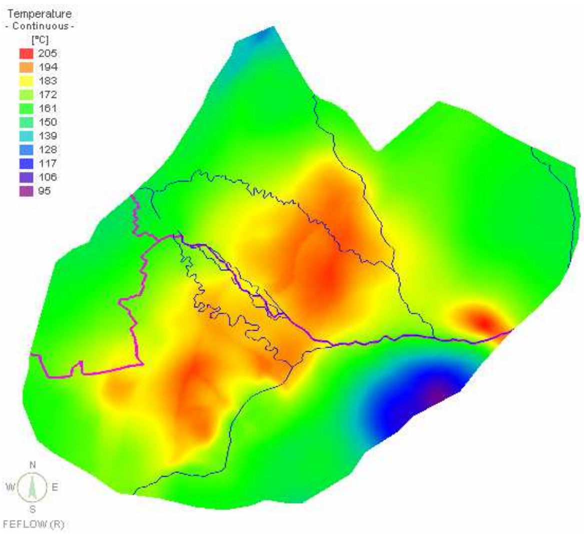
c) -3000 m a.s.l





Pre-utilization **Steady pumping**

d) -5000 m a.s.l



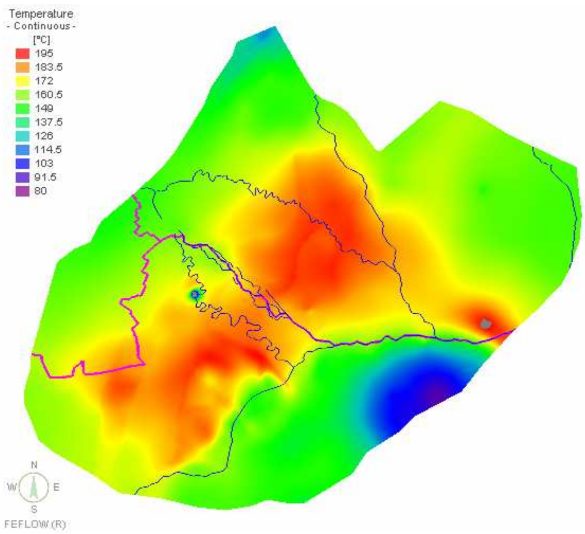
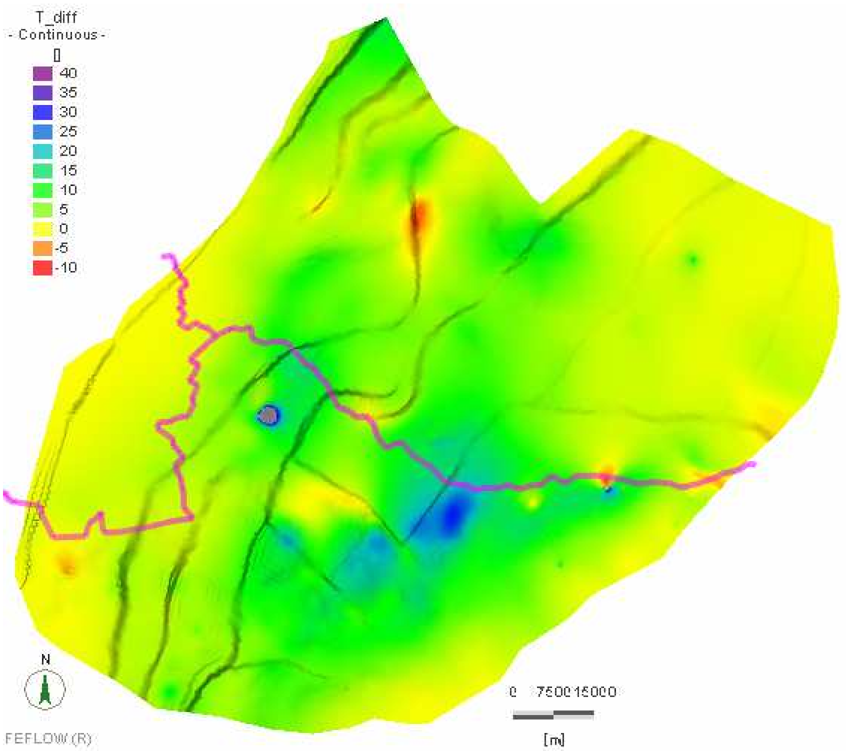


Figure 14.Temperature distribution at different depth levels. Compared are both state scenarios: pre-utilization and steady pumping.. Mind the different color scales.

The influence of the cooled water intrusion into the geothermal aquifer is visible in both modeling scenarios and in all visualized levels. Though the temperatures in geothermal aquifer, proven by drilling especially on Slovak part, show (north part adjacent to Sturovo) much further influence of the cooled water front. This might be caused by excluding the infiltration area in Gerecse and Pilis Mts. that would add higher recharge rate and thus have stronger effect on cooling further northern parts of the structure. Adding to that the numerical noise of the computation and incomplete convergence can cause the disturbance of the model on this part.

Notable is also cooling effect of thick quaternary gravels and sands along the central part of Danube river. Owing to large depth (up to 713 m) and high permeability of these sediments, rapid circulation of 10˚C cold groundwaters across the whole thickness, coming from almost infinite source – river Danube, excavates heat from underlying Neogene sediments. This cooling propagates to large depths over 3 km (Figure 14 a, b and c).

a)



b)

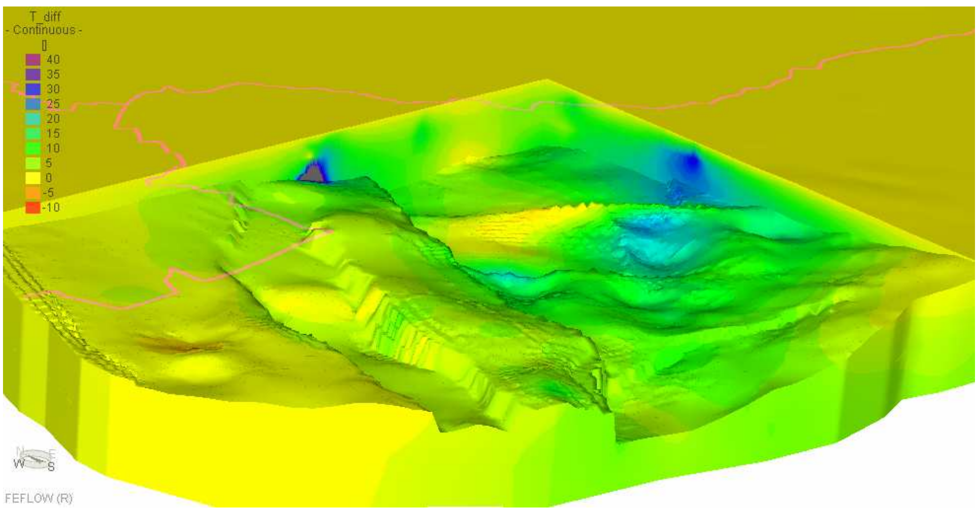


Figure 15.Difference in temperature between the pre-utilization state and the steady pumping scenario. a) Basement of Upper Pannonian; b) Example of temperature decrease around production wells in Hungary.

3.1.4 Transboundary aspects evaluation

One of the major goals of the TRANSENERGY project is to have a closer look at transboundary aquifers. In the Danube basin pilot model three countries meet: Hungary, Slovakia and Austria, sharing important geothermal aquifers.

Naturally, national borders do not prohibit movement of groundwater mass and heat. It is also the case of the pilot model area. Quaternary, Neogene and also Mesozoic aquifers are developed on all sides of state borders. The hydraulic and geothermal models created show significant amounts of water and energy moving either naturally or by forced convection from state to state. This promotes international cooperation in managing geothermal resources.

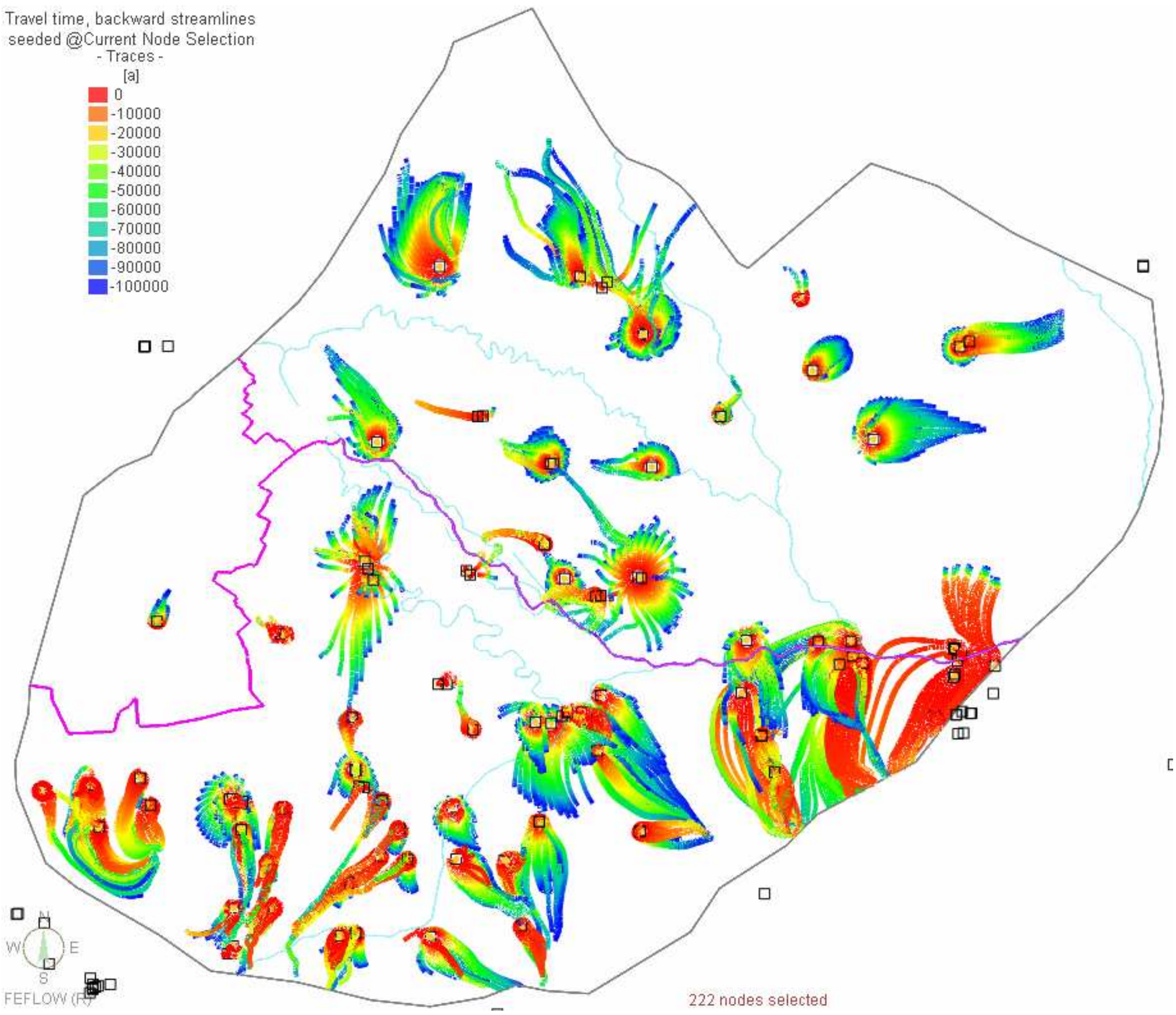


Figure 16. Vertical projection of 3D flow paths towards thermal wells with travel time [years].

The Figure 16 shows computed flow trajectories with travel times, induced by pumping in utilized thermal wells. The most intensive transboundary flow is in Komárno-Štúrovo area in central east. Here water that precipitated onto outcropping carbonates in Gerecse-Pilis Mts. percolates through partly karstified limestones and dolomites towards Danube river, where it seeps into the river or is partly captured by several wells. The lateral extend of well capture zones may be underestimated to some unpredictable level, because model assumes homogeneous aquifers, while in reality these are built up from interchanging permeable and impermeable layers of different thickness. Pumped amounts are withdrawn predominantly from more permeable layers that represent only a portion of total thickness. This is forcing water to flow at higher velocities in horizontal direction then would be predicted in homogeneous, albeit anisotropic media.

Amounts of groundwater flowing across national boundaries were quantified by calculating flow budget for different model domains. Results are summarized in Figures 17 and 18.

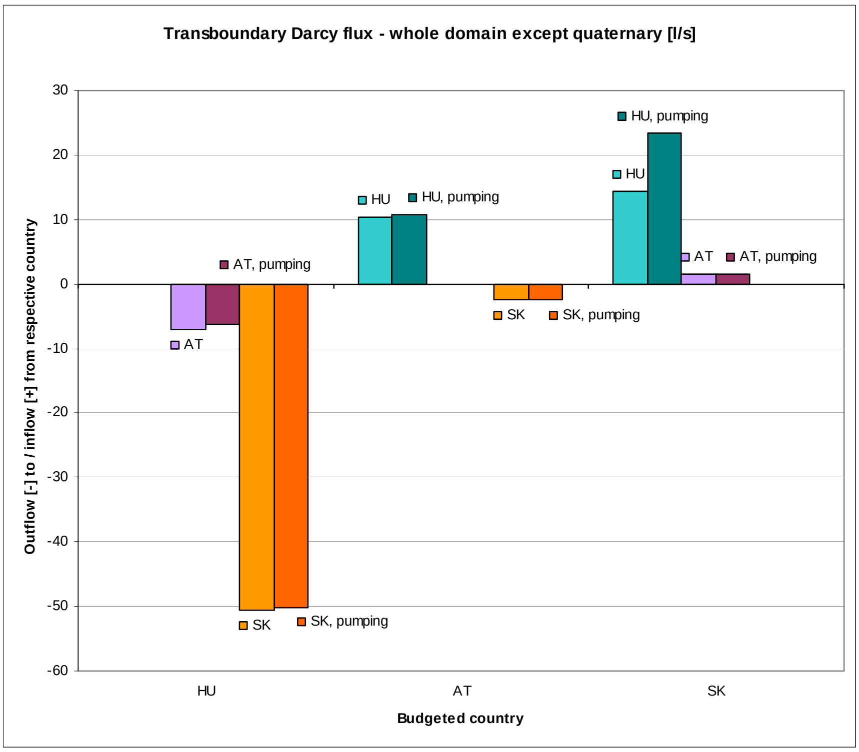


Figure 17. Transboundary flow within Pre-Quaternary rock formations between Hungary, Slovakia and Austria quantified for two model scenarios.

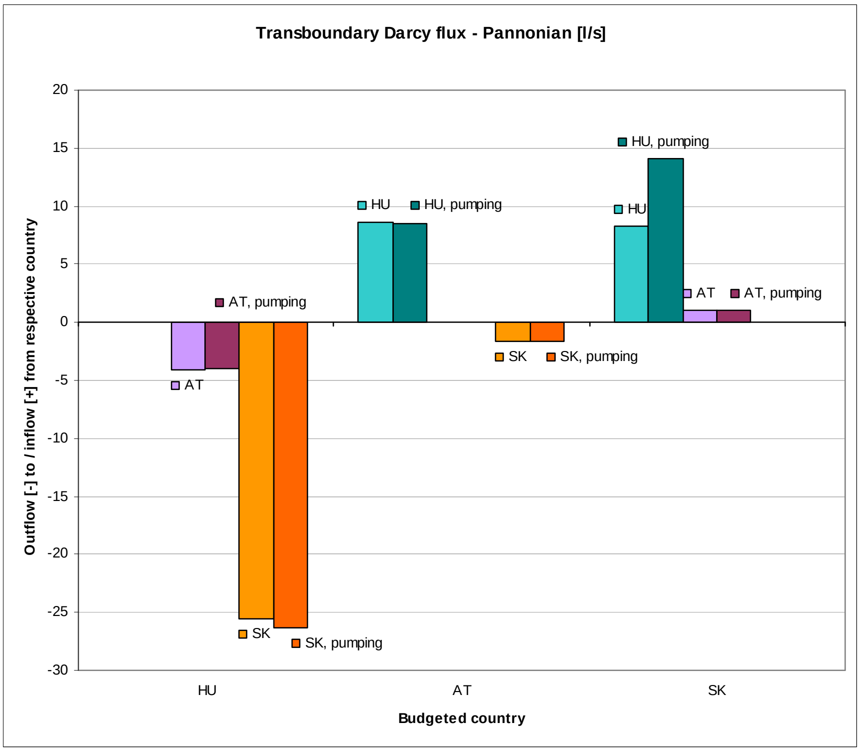


Figure 18. Transboundary flow within Upper Pannonian sediments between Hungary, Slovakia and Austria quantified for two model scenarios.

3.1.5 Energy balance

Geothermal modeling is a useful tool for calculating thermal energy associated with different parts of studied area. Separate calculations were made to evaluate thermal power (MWt) for all 3 involved countries (Figure 19).

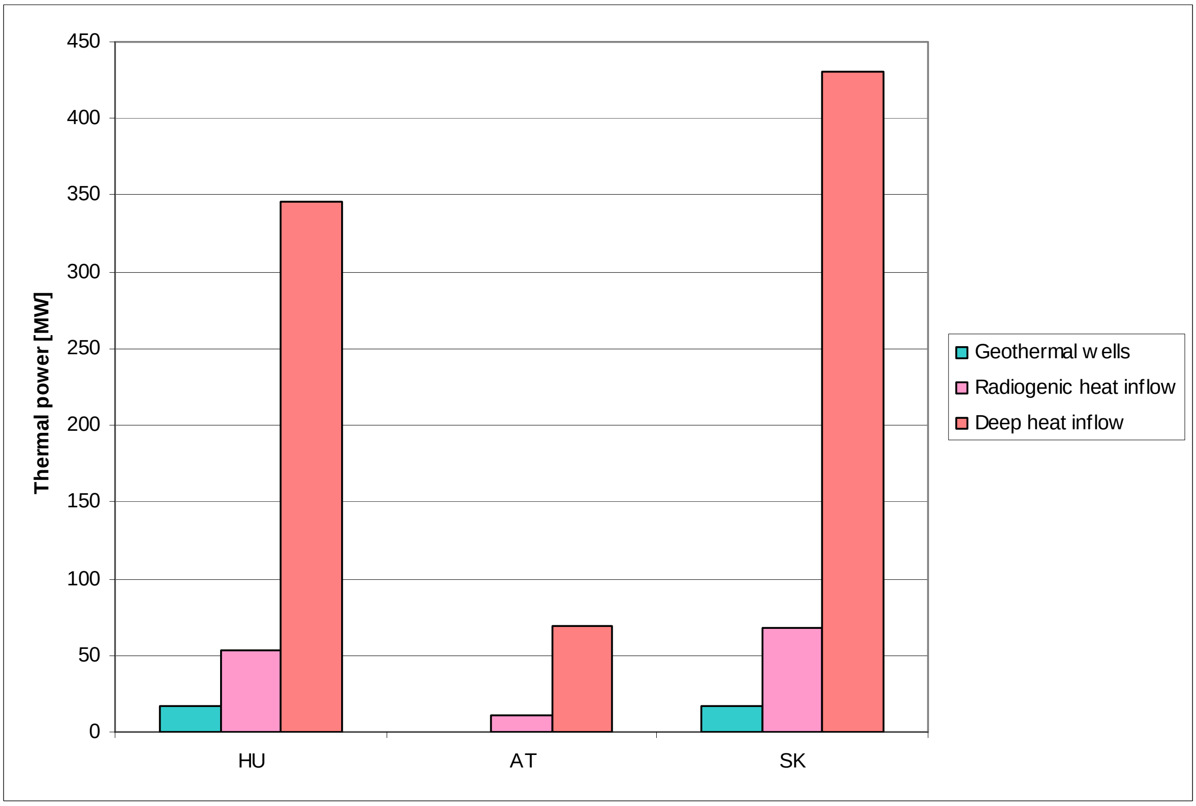


Figure 19. Thermal power of wells, radiogenic heat generation and basal heat inflow for Hungary, Slovakia and Austria.

4 CONCLUSIONS

The aim of the numerical modeling was to simulate the hydrogeological and geothermal conditions in the geothermal aquifer of the Danube basin. For the purpose of modeling a finite element model FEFLOW (Diersch, 2006) was chosen as the most appropriate. The vertical extent of the model is down to -10,000 m a.s.l. Due to expected elevated hydraulic and thermal gradients around fault zones, rivers and wells, the computing mesh needed to be locally refined around these features. The vertical resolution was based on geological model of the Danube basin consisting of 8 hydrostratigraphic units that were divided into 11 modeling layers. The coupled hydraulic and geothermal modeling of the Danube basin pilot area was focused on Upper Pannonian geothermal aquifers. The constructed models show simulations of natural hydrogeological and geothermal conditions, expected to exist before utilization of thermal waters by artificial pumping had started. This scenario is compared to hypothetical conditions of continuous pumping of geothermal waters, based on reported data form years 2007-2010, helping to identify possible tensions in sustainable thermal water use in the area.

Constructed regional model is simplified numerical representation of hydrological and geothermal characteristics of the pilot area and enable simulation of basic features of the geothermal system. The simulations were performed as steady flow and steady heat transport, practically meaning that results show a hypothetical situation in infinite future, if current amounts of water would be extracted. Simulation of theoretical infinite pumping of all existing operating geothermal wells was performed to predict future evolution of pressure and thermal field in the area and to help identifying potential adverse impacts of extensive and unsustainable thermal water over-utilization.

In Pre-Quaternary rock formations conduction is the main mechanism for heat transport. Due to relatively intensive water interchange between recharge and discharge zones in Quaternary sediments, convection is of high importance.

The hydraulic and geothermal models presented show significant amounts of water and energy moving either naturally or by forced convection from country to country across the border. This promotes international cooperation in managing geothermal resources.

Geothermal modeling is a useful tool for calculating thermal energy associated with different parts of studied area. Separate calculations were made to evaluate thermal power for all 3 involved countries

5 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.

Deutsch, C.V., Journel, A.G. (1998): GSLIB Geostatistical Software Library and User's Guide, 2nd Edition.

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/

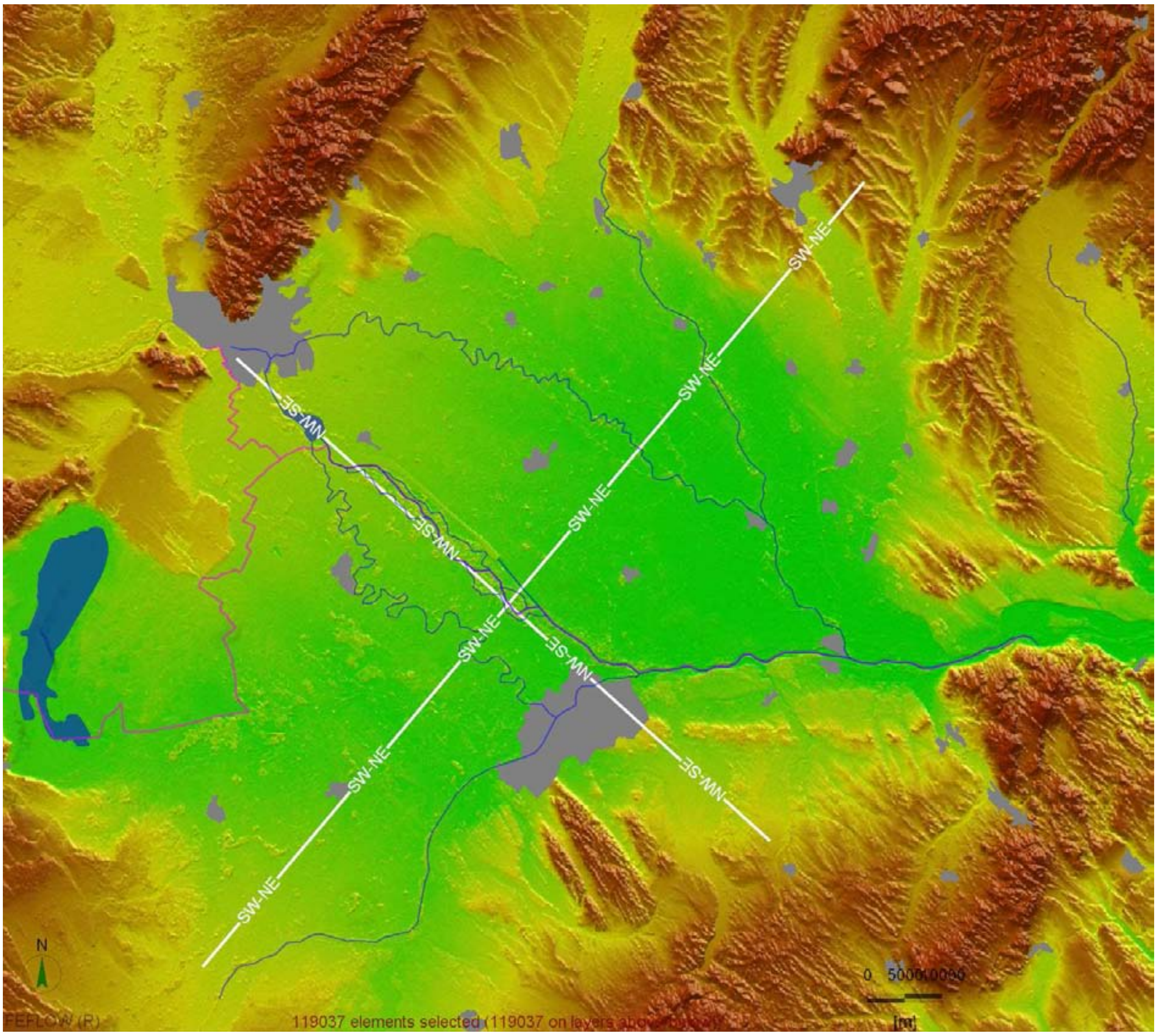
McCutcheon, S.C., Martin, J.L, Barnwell, T.O. Jr. (1993). Water Quality. In: Maidment, D.R. (Editor). Handbook of Hydrology, McGraw-Hill, New York, U.S.A. (p. 11.3).

György Tóth, Ágnes Rotár-Szalkai, Tamás Kerékgyártó, Teodóra Szőcs,

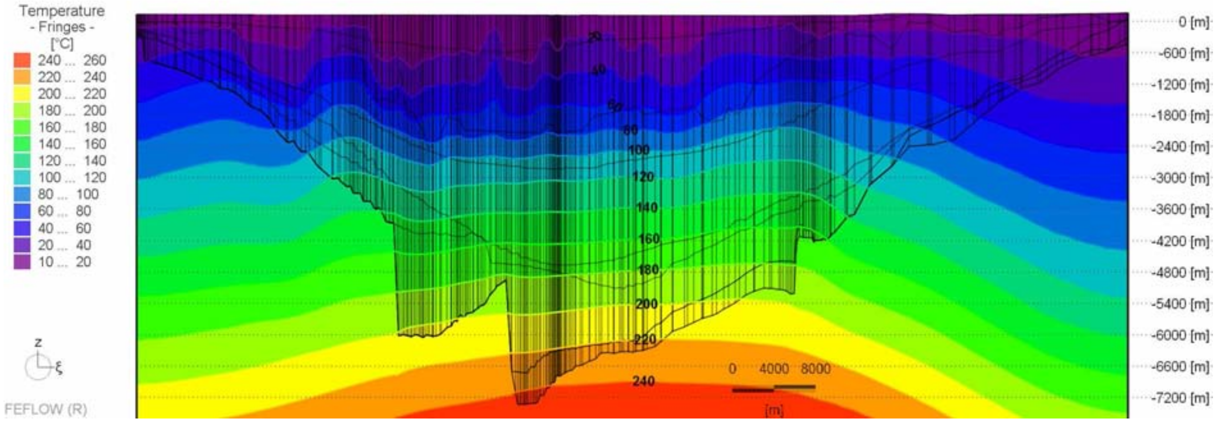
Tóth, G., Rotár-Szalkai, Á., Kerékgyártó, T., Szőcs, T, Gáspár E. (2012): Summary report of the supra-regional hydrogeological model. Project TRANSENERGY internal report.

Annex I

Position of geothermal cross-sections



Temperature distribution in the NW-SE cross-section



Temperature distribution in the SW-NE cross-section