EGC 2013
European Geothermal Congress
EGEC GEOTHERMAL
EUROPEAN IGA REGIONAL BRANCH
Unione Geotermica Italiana

Integrating Geological and Hydraulic Models of the Danube Basin – TRANSENERGY project cross-border pilot area

Jaromír Švasta[1], Radovan Černák[1], Ivan Baráth[1], Rudolf Berka[3], Klement Fordinál[1], Gregor Goetzl[3], Balázs Kronome[1], Juraj Maglay[1], Gyula Maros[2], Alexander Nagy[1]; Ágnes Rotár-Szalkai[2], Teodora Szőcs[2], György Tóth[2], András Uhrin[2]

[1] State Geological Institute of Dionýz Štúr, Mlynská dolina 1, 85107 Bratislava, Slovakia

[2] Geological and Geophysical Institute of Hungary, Stefánia út 14, Budapest 1143, Hungary

[3] Geological Survey of Austria, Neulinggasse 38, Wien 1030, Austria

jaromir.svasta@geology.sk

Keywords: 3D modeling, geology, hygrogeology, geothermal energy.

ABSTRACT

The project „TRANSENERGY“ – Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia”, aims to support the harmonized thermal water and geothermal energy utilization in the western part of the Pannonian Basin, focusing also on selected cross-border areas, where utilization schemes may cause future conflicts due to missing harmonized management strategies between the neighbouring countries. The Danube Basin is one of the selected pilot areas, which also forms part of delineated transboundary groundwater bodies within the Danube River Basin and as such is in the focus of ICPDR. The 3D geological model of the area is based on 146 Slovak, 189 Hungarian and 74 Austrian boreholes, 21 Slovak and 57 Hungarian seismic profiles and numerous published works. The model is the first 3D visualization of selected geological horizons covering the whole Danube basin in all three countries using unified stratigraphic scheme and fault patterns, which gives opinion on the surface geometry of pre-Tertiary basement, Badenian, Sarmatian, Lower Pannonian, Upper Pannonian and Quaternary horizons. Important fault systems and faults that cause the drop of more than 500 m are incorporated in 3D geological model. The model shows features that were not shown earlier – pre-Tertiary relief in the western part of the Danube basin and buried Lower Badenian volcanic structures.

The 3D hydraulic and geothermal model is based on modelled geological horizons, lithological content (with assigned hydraulic properties), known and presumed hydraulic and geothermic boundary conditions. Main outputs of the modelling include computed shallow groundwater table, confined cold and thermal water heads in the intergranular porosity aquifers, computed flow lines, groundwater mean transit time distribution in 3D. As a result of thermal groundwater energy calculation, the model allows for an approximative assessment of geothermal potential and reserves too.

1. INTRODUCTION

This article 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 m3/year and on Slovak side 87 631 m3/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.

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 (Fig. 1).

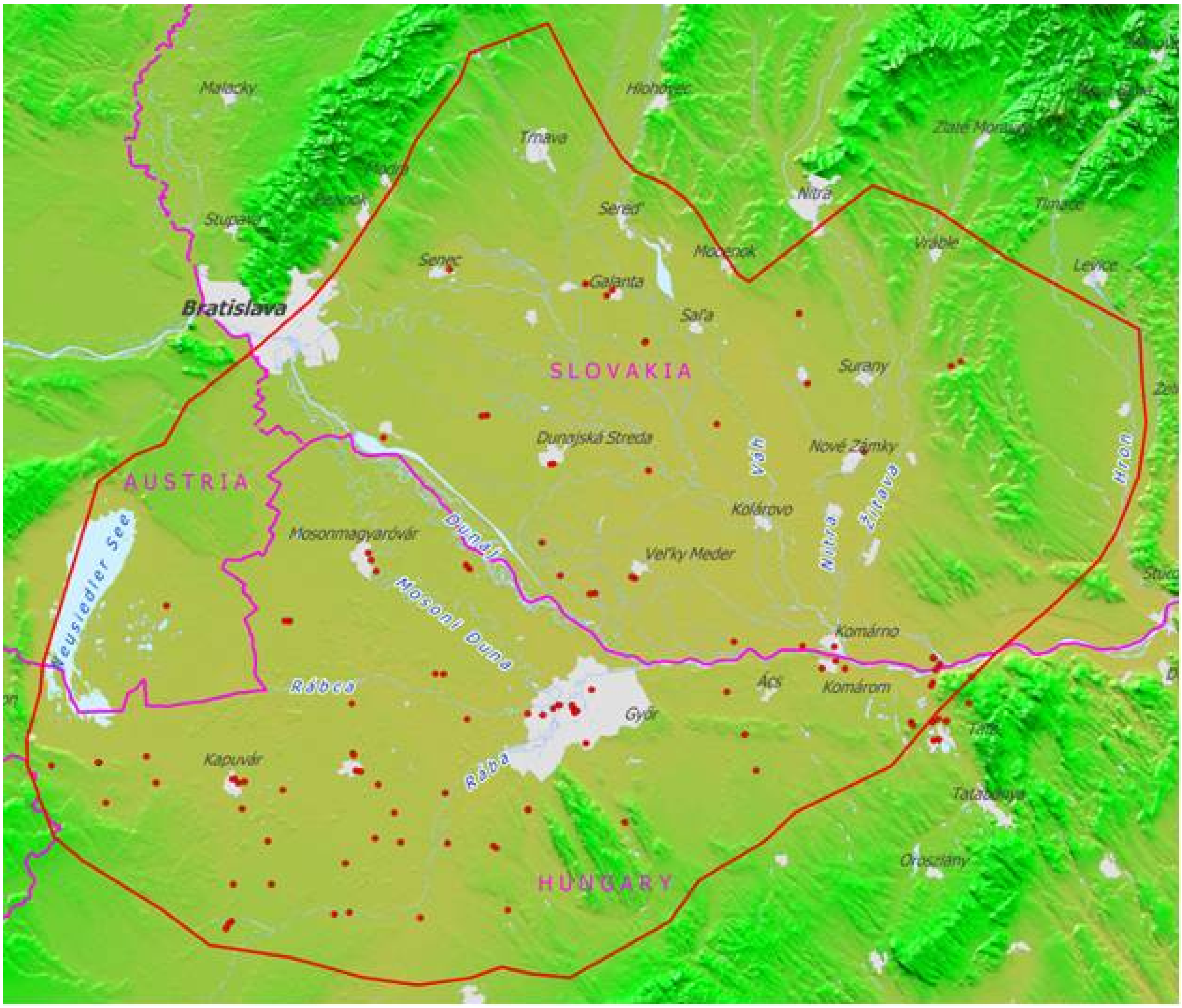

Figure 1: Delineation of pilot model area and production wells.

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.

2. GROUNDWATER FLOW AND HEAT TRANSPORT 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 the 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 made for 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.

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.

2.1 Model geometry

From top the model is limited by the topographical surface, adopted from the digital elevation model SRTM (USGS 2000). To the depth the model extends 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. Thus the generated mesh, consisting of triangular prisms, ended up counting 31,114 nodes per slice (in total 373,368), forming 61,602 elements per layer (total 677,622).

The model adopted the 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 and Journel 1998, Fig. 2).

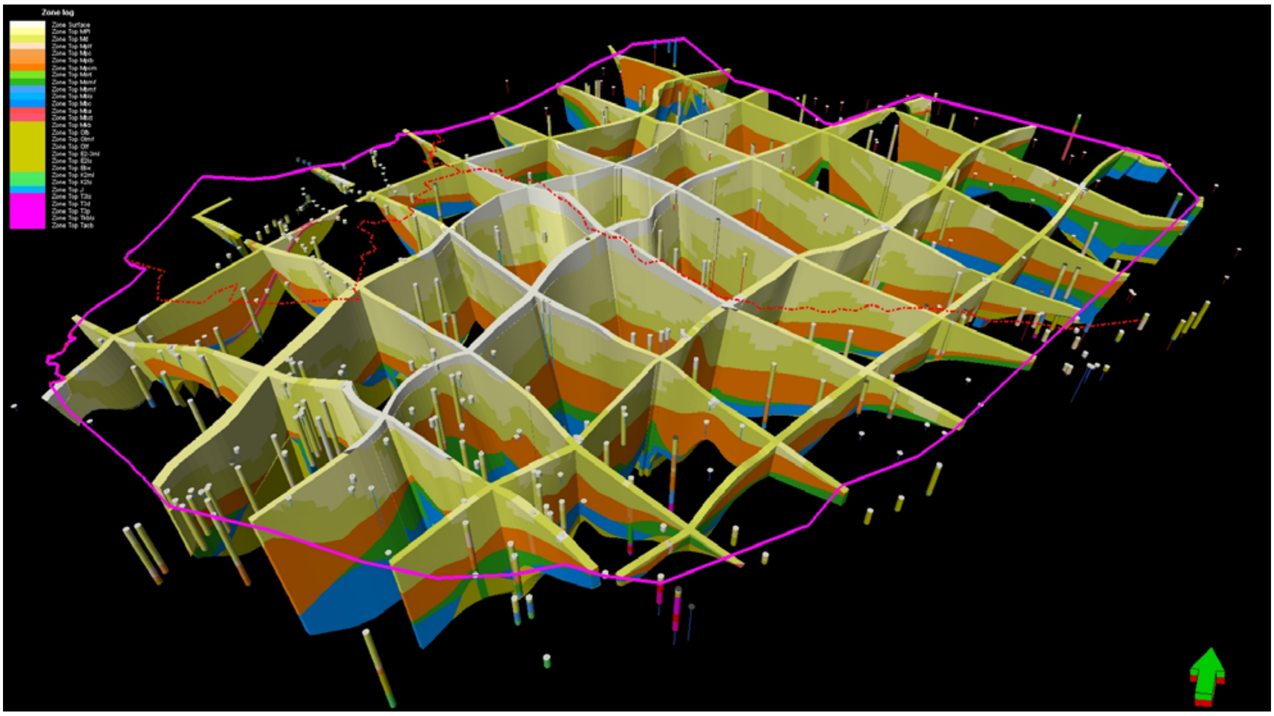

Figure 2: Fence diagram of the geological model.

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. 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.

2.2 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. 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.

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. 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.

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.

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.

2.3 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.

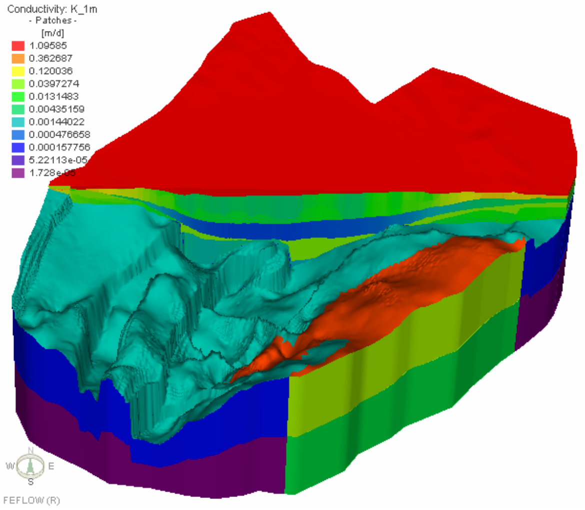

Figure 3: Horizontal conductivity distribution in the sedimentary basin (partial cut-out) and basement rocks. Higher values in the bedrock are Mesozoic carbonates.

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.

2.4 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. Simulated pressures are fitted with measured ones with RMSE 117.4 Pa, which is favourable.

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).

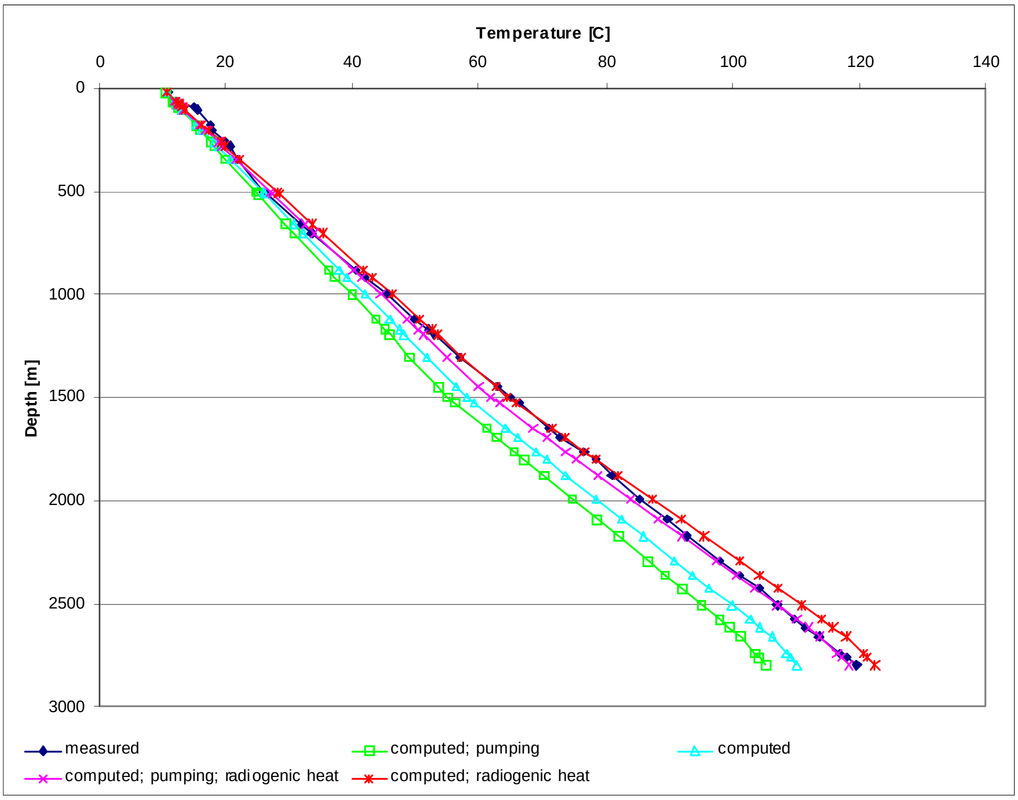

Figure 4: Comparison of different model set ups on goodness of fit between computed and measured temperatures, example from the monitoring well GPB 1. Best match was achieved for both scenarios, natural pre-utilization state and steady pumping, with inclusion of radiogenic heat production.

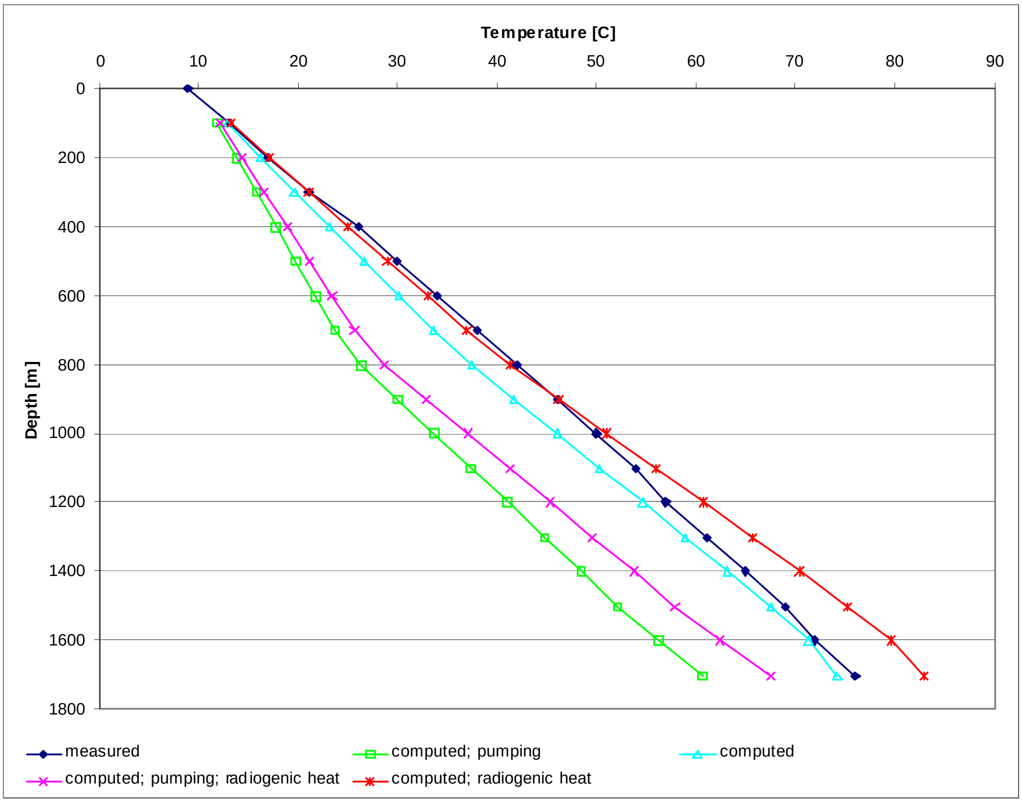

Figure 5: Comparison of different model set-ups on goodness of fit between computed and measured temperatures, example from the monitoring well Di 1. Steady pumping scenario exhibits significant deviation from measured temperatures in upper 800 meters. It can be attributed to cooling by increased infiltration of cold Quaternary water induced by pumping.

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.

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.

Distribution of hydraulic heads in the model depends primarily on boundary conditions and spatial distribution of hydraulic conductivities (Fig. 3). 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.

3.1 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.

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.

3.2 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. Intensive recharge of precipitation is causing a considerable cooling of the whole carbonate massive.

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 (Figs. 6 - 9, mind the different colour scales).

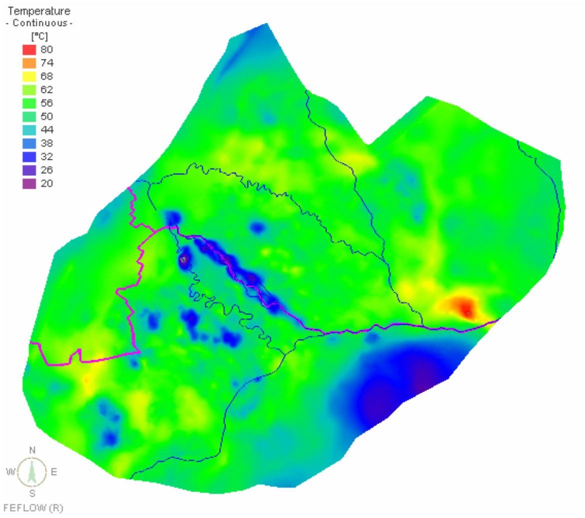

Figure 6: Temperature at depth -1000 m a.s.l.

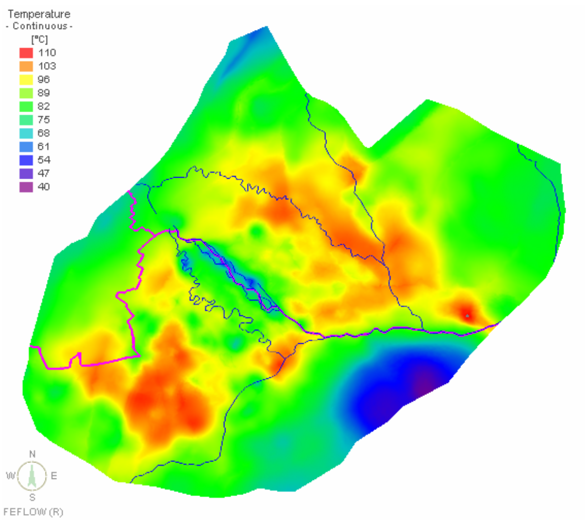

Figure 7: Temperature at depth -2000 m a.s.l.

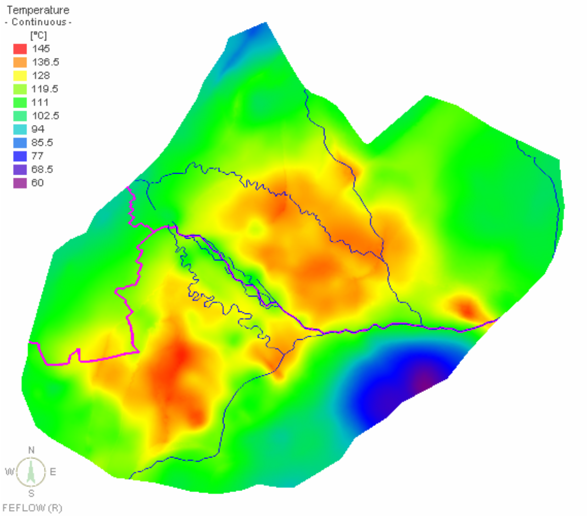

Figure 8: Temperature at depth -3000 m a.s.l.

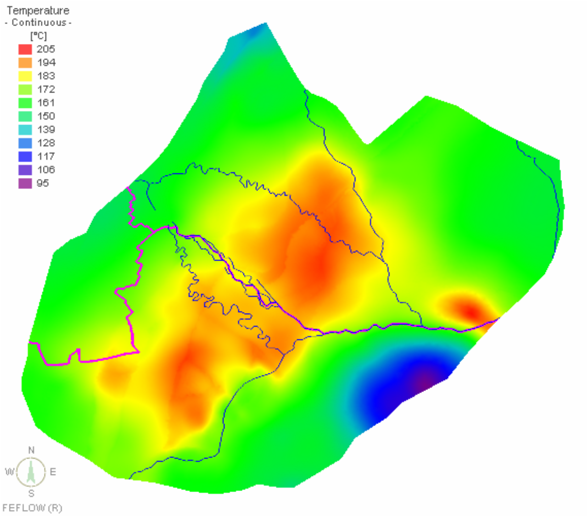

Figure 9: Temperature at depth -5000 m a.s.l.

3.3 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. Amounts of groundwater flowing across national boundaries were quantified by calculating flow budget for different model domains. Results are summarized in Fig. 10.

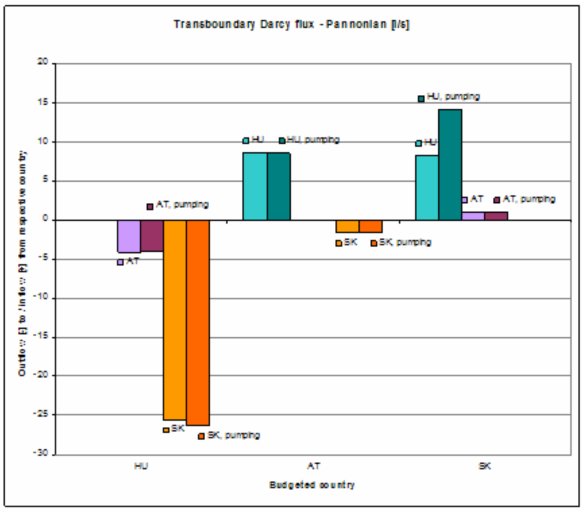

Figure 10: Transboundary flow within Upper Pannonian sediments between Hungary, Slovakia and Austria quantified for two model scenarios.

The Fig. 11 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.

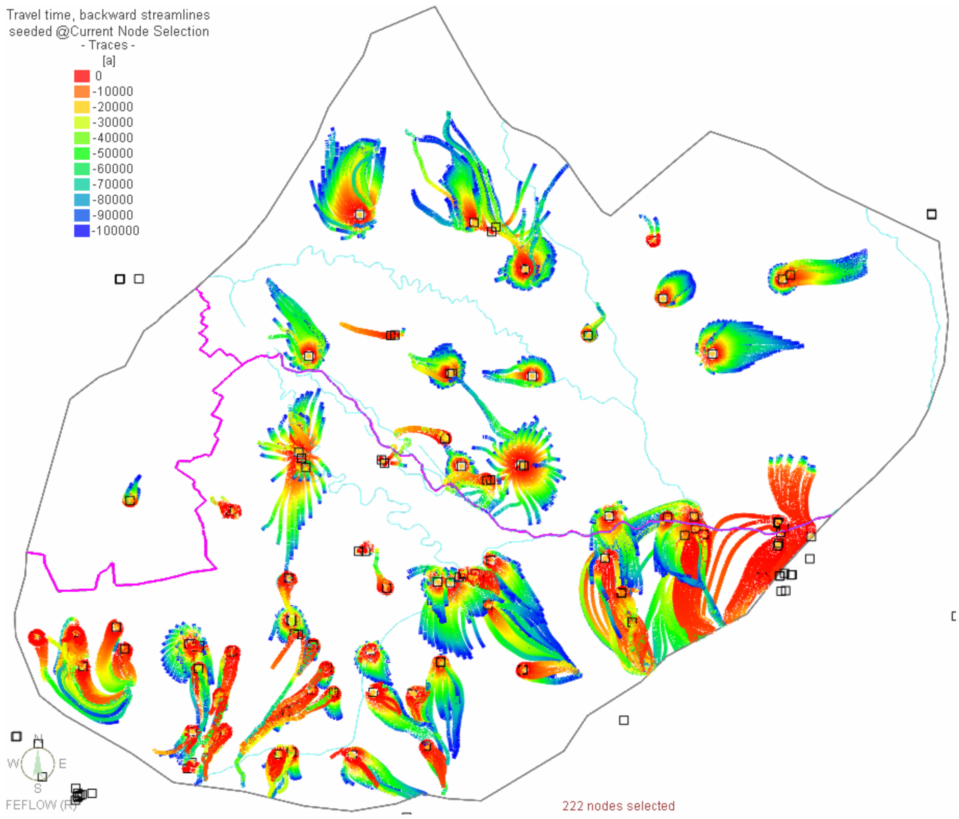

Figure 11: Vertical projection of 3D flow paths towards thermal wells with travel time [years].

3.4 Energy balance and identified 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 (MWt) for all 3 involved countries (Fig. 12).

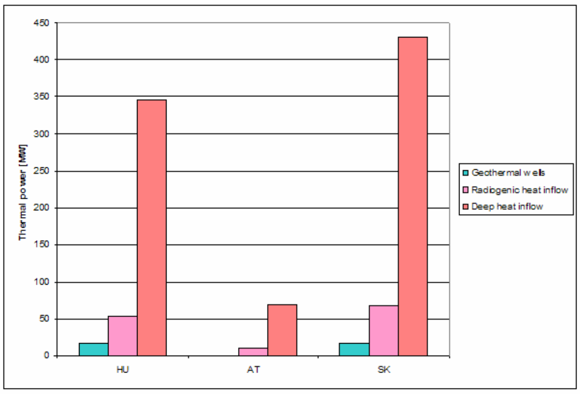

Figure 12: Thermal power of wells, radiogenic heat generation and basal heat inflow for Hungarian, Slovakian and Austrian parts of the project area.

Results of the numerical modeling allow for calculation of geothermal energy available in individual aquifers. After Muffler and Cataldi 1978, heat stored in a geothermal reservoir, q_R, is given by:

$$q_R = V\overline{\rho c}\left(T_R - T_r\right) \qquad [1]$$

where T_r - reference (or rejection) temperature, T_R - average reservoir temperature, V - reservoir volume and $\overline{\rho c}$ - volumetric heat capacity of fluid-saturated rock. Since only a part of the stored heat can be recovered at the well head, a geothermal recovery factor R_0 must be applied to calculate identified resources q_1:

$$q_1 = R_0 q_R \qquad [2]$$

For a case of single doublet, Hurter and Haenel (2002) suggest the following formula [3] for recovery factor calculation:

$$R_0 = 0.33\frac{T_R - T_{inj}}{T_R - T_r} \qquad [3]$$

where T_{inj} is the temperature of the reinjected water. In this manner, identified resources of the main geothermal aquifer in the area, Upper Pannonian sediments, were calculated (Fig. 13).

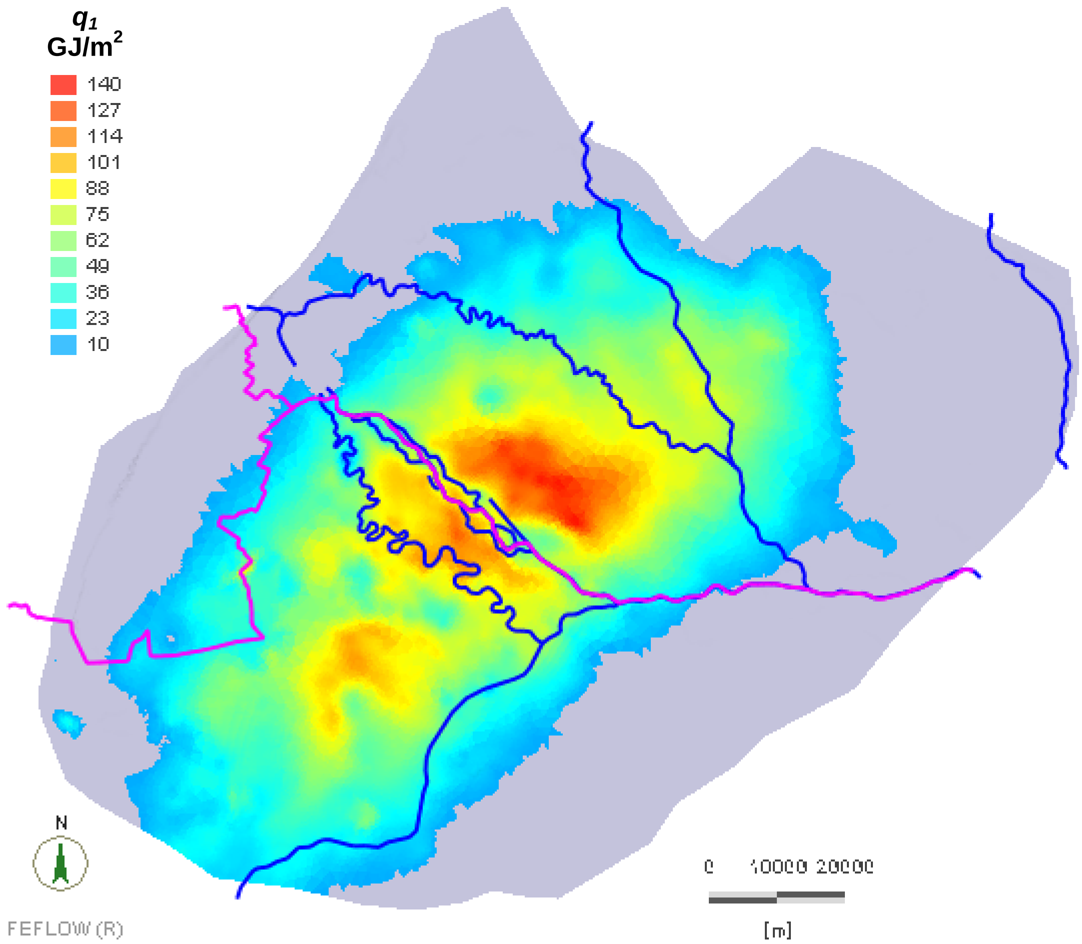

Figure 13: Specific identified resources [GJ/m^2] of Upper Pannonian reservoirs.

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.

REFERENCES

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

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

Franko, O., Fusan, O., Kral, M., Remšík, A., Fendek, m., Bodiš, D., Drozd, V., Vika, K.: Atlas of geothermal energy of Slovakia, *State Geological Institute of Dionýz Štúr*, Bratislava, (1995).

Hurter, S. and Haenel, R.: Atlas of Geothermal Resources in Europe, *Office for Official Publications of the European Communities,* Luxemburg, (2002), 93pp.

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

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

Muffler, P. and Cattaldi, R.: Methods for regional assessment of geothermal resources, *Geothermics*, 7, (1978), 53-89.

USGS: Shuttle Radar Topography Mission, 1 Arc Second scene, Unfilled Unfinished 2.0, Global Land Cover Facility, *University of Maryland*, College Park, Maryland, (2000).

Acknowledgement

Project TRANSENERGY is implemented throug the CENTRAL EUROPE Programme co-financed by the ERDF.