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3. Assessing Thermal Groundwater Flow in the Danube Basin by Numerical Simulations

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Abstract. The article presents the results of the steadystate as well as transient modelling performed within the Danube Basin pilot area of the TRANSENERGY project with the focus on Late Pannonian aquifer and to less extent on adjacent thermal karst aquifers.

The research of geothermal potential of the Danube Basin was accomplished by utilizing fully three-dimensional coupled models of groundwater flow and heat transport at different temporal and geographical scales. Several scenarios of possible energy extraction from the most favourable geothermal aquifers of the area are compared in this study.

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, two principal scenarios of geothermal utilization were investigated: single wells and geothermal doublets. Furthermore, a detailed examination on possibilities of interstate geothermal energy exploitation was performed as well. The study investigates 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.

Keywords: geothermal modelling, heat flow, transboundary

3.1. Introduction

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 from wells. The average yield of utilized geothermal water on Hungarian side of the Danube Basin pilot area is 51,349 m^3 per year and on Slovak side 87,631 m^3 per year.

The goal of modelling 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 modelling process and basis for scenario analysis for sustainable utilization of the geothermal resources. The regional modelling simulations were calculated for steadystate conditions – steady flow and steady heat transport. Two scenarios of possible energy extraction from the distinguished geothermal aquifer of Danube Basin – Late Pannonian sedimentary unit 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.

Because sustainable use of thermal groundwater is promoted in all three countries within the pilot area, a scenario of additional heat utilization by means of geothermal doublets was tested. But due to technical limits of water reinjection in Late 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.

As an extension to the regional steadystate model, a separate modelling of a geothermal multiplet was performed, with intention to investigate thermal and hydraulic response of potential thermal water utilization at the Slovakia – Hungary state border.

This approach is the 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, originating from uncertainty related to estimation of parameters of hydrogeological model. The information used for model set-up, verification and optimization is based on database of geological and hydraulic parameters, database about the utilization characteristics, both compiled within the framework of the TRANSENERGY project. 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.

3.2. Natural conditions of the region

The Danube Basin pilot area covers around 12,170 km^2 (Fig. 3.1.) and 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 Malé Karpaty Mts. On the North the basin has finger-like extensions which penetrate among the core mountains of Malé Karpaty, Považský Inovec and Tribeč Mts. On the northeast it is

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bounded by the Central Slovakian Neovolcanics and the Burda volcanics. Units of the Transdanubian Central Range are emerging on the southeast.

3.2.1. Climate and hydrology

The region on W and N shows influence from the Atlantic climate with higher precipitation partly affected by continental climate with lower precipitation and typical cold winters. In the area on S it is influenced by the Mediterranean climate. The heterogeneity of the relief (in wider vicinity of the pilot area), the differences in the rate 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 more than 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 up to 450 mm (Atlas of Landscape of the Slovak Republic, 2002).

The Danube River in the studied area has discharge (input Slovakia – output Hungary) approximately in interval 2,500-3,000 $m^3.s^{-1}$ (based on data from 1994-1997). Main rivers that are tributaries to the Danube River on studied area are: Morava/March - 119 $m^3.s^{-1}$ (average discharge 1961-1999), Raab/Rába - 88 $m^3.s^{-1}$ (average discharge 1901-2000), Váh 161 $m^3.s^{-1}$ (average discharge 1931-1980), Hron 55 $m^3.s^{-1}$ (average discharge 1931-1980), Ipeľ/Ipoly 22 $m^3.s^{-1}$ (average discharge 1931-1980, ICPDR, 2005).

3.2.1.1. Important lakes in the Danube Basin area

Neusiedler See / Fertő tó – W edge of the Danube Basin pilot area. Neusiedler See / Fertő tó is located in the E of Austria and shared with Hungary - total surface area is 315 km^2 (at a defined water level). It has an average natural depth of only 1.1 m, its maximal water depth is 1.8 m. In the course of its history it has dried out completely several times. Since 1965 the water level has been 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 2 $g.l^{-1}$, mainly in form of sodium carbonate (Na_2CO_3).

3.2.1.2. Important wetlands

The wetlands in the Alps and Carpathians also represent valuable drinking water reserves for millions of people. The current extent of wetlands in the Danube River basin 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 oxbows 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 Neusiedler See and Fertő-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 River are protected landscape areas, including small-scale nature reserves.

3.2.2. Geology

The geology of the Danube Basin is described in very detail in the separate article on the geological model by authors Kronome et al. of this issue. In general it forms a bowl-like shaped Pre-Tertiary sedimentary basin. Its basement is composed of crystalline and metamorphic rocks and cover sequences of the Central Alpine crystalline basement, Carpathian Tatric crystalline rocks and partly Triassic to Cretaceous limestones, Palaeozoic and Mesozoic rocks of the Transdanubian Central Range, Lower and Upper Austroalpine nappe complexes, Tatric unit (a continuation of the Central Alpine units). Its geological evolution is strongly dependent on the basement movement behaviour in the Neogene. During the whole basin formation, starting in Early Miocene, different sedimentary processes took place in every part of the area. This resulted in a very complicated geological composition, with frequently alternating lithologies in both lateral as well as vertical directions. Thus, the basinal filling consists of almost all kinds of marine, lacustrine and fluvial sediments, intercepted by stratovolcanic bodies. During the Late Miocene (Pannonian) a more or less uniform Pannonian Basin developed, the formation of which may have started in the Late Badenian. Predominantly fine siliciclastic sequences of different facies accumulated in the area, which have a maximum thickness of about 6,000 metres. The overwhelming part of the successions of the deeper basin facies is made up homogeneous pelitic deposits; distal turbidites are represented by separate sand bodies. Underwater slope sediments are represented predominantly by dark grey clay marl. Deposits of the alluvial plain are represented by frequent alternation of fluvial and lacustrine fine-grained sand, silt, clay and clay marl beds locally with lignite horizons (Maros in Rotár-Szalkai et al., 2012). Because of favourable lithological and hydrogeological conditions, together with deep seating of the

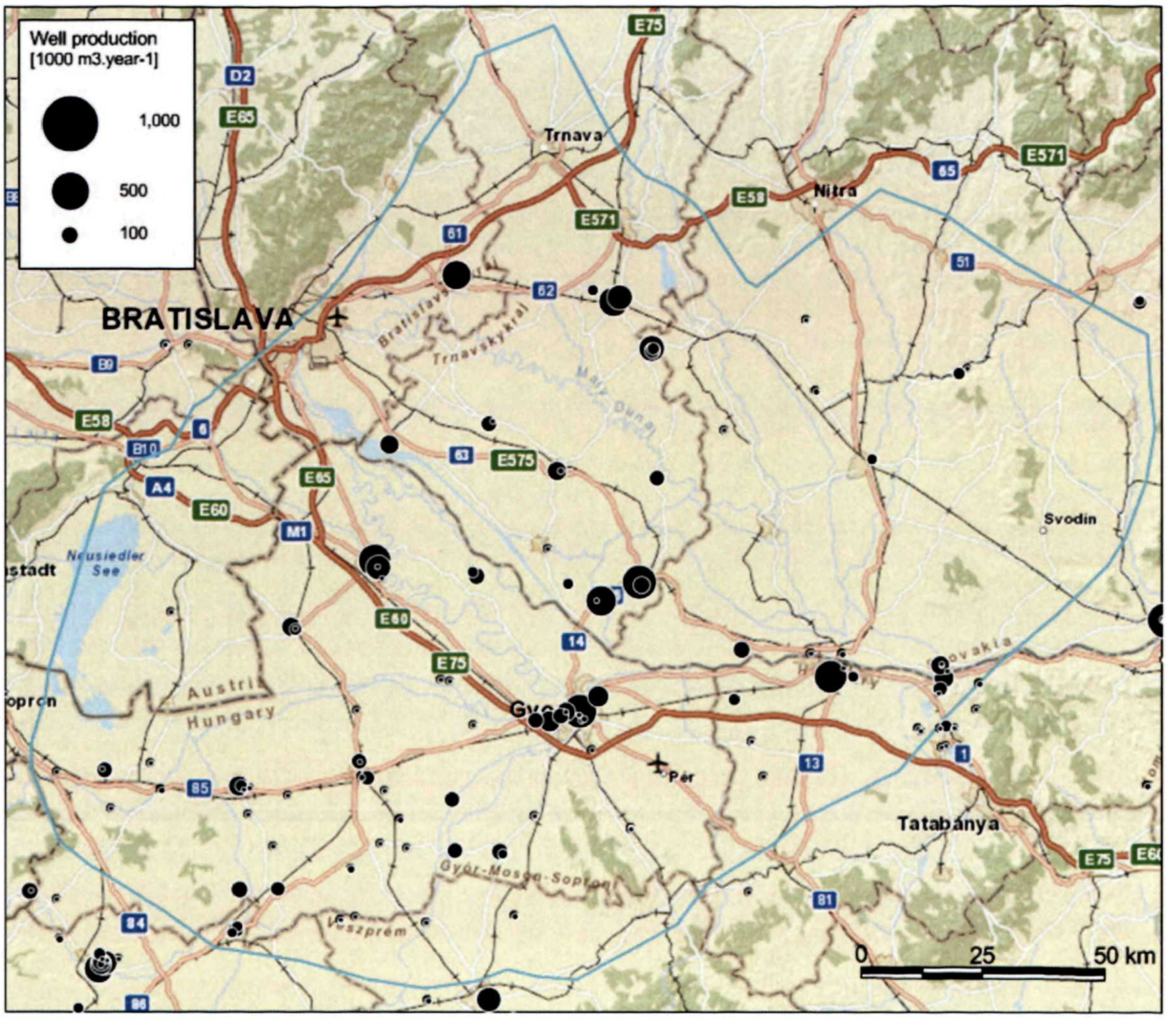

Fig. 3.1 Delineation of pilot model area with existing production wells with national and county boundaries (Topography: ArcGIS World Map © ESRI)

especially Late Pannonian sequences, these are of main interest from the geothermal point of view.

The Quaternary deposits deposited upon erosive base and accumulated in depressions. However in the Gabčíkovo Depression the deposition was continuous from the older sediments (Maros, et al., 2012).

3.2.3. Hydrogeology

The crystalline basement has no significant influence on the groundwater flow system. The crystalline rocks have fissure-type permeability. Usually they can be characterized by intensive heterogeneity, decreasing fissure aperture closing downwards causing the decreasing of permeability, and enhanced hydraulic conductivity due to tectonic effects.

From the hydrogeological build-up of the Danube Basin it can be assumed that the Carpathian crystalline basement of the Danube Basin does not contain relevant geothermal aquifers. However, suitable aquifers are bound to Mesozoic aquifer systems of separate structures and sands or sandstones of Pannonian, Pontian and Dacian age within the Tertiary basin fillings.

The Levice Block is located in the north-eastern part of the Danube Basin. It is composed of Mesozoic rocks of the higher nappes and locally underlain by the remnants of the Mesozoic envelope of the crystalline complex (Fusán 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^{-1}.

The Dubnica Depression is a special type of basement aquifer. It is filled mainly with Miocene sediments underlain by crystalline schists and granitoids of the Veporicum. The aquifer is formed by basal Badenian clastics (conglomerates, sandstone) at a depth between 1,000-2,000 meters. It represents a closed reservoir, with temperature of 52-75 °C, and mineralization ranging around 10-30 g.l^{-1}.

The *Komárno Block* extends between Komárno and Štúrovo. It is fringed by the River Danube in the S 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 of tectonic nature 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 3,000 m near Hurbanovo fault. The Pre-Tertiary substratum of the Komárno Block consists largely of Triassic dolomites and limestones up to 1,000 m in thickness. These are underlain by a very thick Early Triassic shale formation. Palaeozoic units were revealed by drilling in the north-western section of the Komárno Block. These include Permian conglomerates, sandstones, greywackes and shales and Devonian limestones and lydites. From a hydrogeothermal point of view, the area is divided into High and Marginal blocks (Remšík, et al., 1992). The geothermal activity of the High Block has partly been known for long because of thermal springs at Štúrovo 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 Komárno High Block is encircled by the Marginal Block in the West, North and East. The latter contains groundwaters whose temperature exceeds 40 °C (highest so far noted temperature is 68 °C). Transmissivity in the High Block varies from $1.54.10^{-4}$ to $1.28.10^{-3}$ $m^2 \cdot s^{-1}$. Transmissivity 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 Late 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 Wechselgebirge Mts.

The Danube Basin and the Neogene sub-basins of Kisalföld are 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 6,000 meter deep basin has brachysynclinal structure. The older layers which crop out at the edge of the basin can be found at gradually deeper position toward the centre of the basin. The Miocene and Pannonian complexes 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 covering Quaternary layers are represented by gravel and sands. The maximum thickness (520-600 meters) occurs in the region of Gabčíkovo and Baka.

The Miocene aquifers are connected in each 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 Late Miocene low permeable and thick marl and clay sequences together with the Early 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 as the Pannonian reservoir.

The structure of the lower part of the Late Pannonian formation is likely to have interlayer leakage, intergranular permeability and confined groundwater level. It contains thermal waters with temperature 42-92 °C which are bound mainly to sands and sandstones aquifers. The aquifer layers of the central part in the thermal water system crop out 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 to long distances. The sandy aquifer layers vary with aquitard clay, sandy clay layers. The vertical and lateral extent of the aquifer layers are varying abruptly. Commonly, the up to 10 meters thick sand bodies are lens-shaped which cannot be followed to long distances laterally.

The Quaternary sediments form a common unconfined reservoir. The flow system of the cold groundwater represented in this sequence is in hydraulic connection with the Pannonian flow systems. The groundwater regime depends on the discharge from the Danube. At the 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 is of specific hydrogeological importance. The thick gravel and sand layers represent a great amount of good quality water. The discharge in some places exceeds 8 $m^3.s^{-1}$ 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).

3.3. Geothermal conditions

The highest heat flow densities have been recorded in the centre of the depression ($q > 85$-90 $mW.m^{-2}$) and do not correspond neither to lower temperatures ($T < 45$ °C) nor thermal gradients. Whereas heat flow generally decreases towards the margins of the Danube Basin, temperature in depth increases. This irregularity is caused by a cold water body, which is bound to the uppermost hydrogeological unit showing a maximum thickness of 460 m. The colder zone gradually perishes downward and the temperature field corresponds to the heat flow. Badenian volcanoclastics at depths of 5,000–6,000 m may contain geothermal waters with aquifer temperature exceeding 200 °C. They can be utilized by applying reinjection for reasons of sustainability. Because of its post-Sarmatian evolution, the Danube Basin has a bowl-like brachysynclinal shape.

The upper boundary of the geothermal water body was in Slovak studies and research works located at depths of 1000 m below the surface and at the bottom it is confined by a fairly impervious substratum - an aquitard (clays) which plunges from the surrounding area towards the centre of the basin to a depth of up to 3,400 m below surface (Franko et al., 1995).

3.4. Regional modelling

The aim of the regional numerical modelling was to simulate the hydrogeological and geothermal conditions in the geothermal water body of Pre-Neogene and Neogene fill of the Danube Basin. The goal of modelling 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 modelling simulations were calculated 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.

3.4.1. Methodology

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. Programme 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 programme 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.

3.4.1.1. Horizontal extent

The model area is outlined in accordance with the TRANSENERGY project pilot area (Fig. 3.1). It encompasses all important sedimentary structures of Neogene age predominantly, in which majority of utilizable thermal groundwaters are present. The model boundary was demarcated in accordance with all hydrogeological knowledge, along well defined hydrogeological limits.

3.4.1.2. Vertical extent

From the 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.

3.4.1.3. 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, counting up to 31,114 nodes per slice (in total 373,368), forming 61,602 elements per layer (total 677,622).

3.4.1.4. Vertical resolution

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

- Quaternary - phreatic
- Late Pannonian
- Early Pannonian
- Sarmatian
- Badenian
- Badenian volcanites
- Cainozoic
- Mesozoic, Palaeozoic and crystalline basement

Late 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, Fig. 3.2).

Due to large thickness of the basement layer, it was divided into 2 numerical sub-layers. To mimic the effect of pre-sedimentation exposition of the uncovered bedrock to weathering, a separate, 10 m thick layer with elevated conductivity at the top was created. It is in accordance with findings in several deeper boreholes reaching bedrock, where often intensively altered or karstified rocks of several meters thickness were observed.

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

3.4.1.5. Flow boundary conditions

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

All across the top surface a Dirichlet boundary condition (constant groundwater head) was set (Fig. 3.4). The purpose of it was to prescribe realistic groundwater

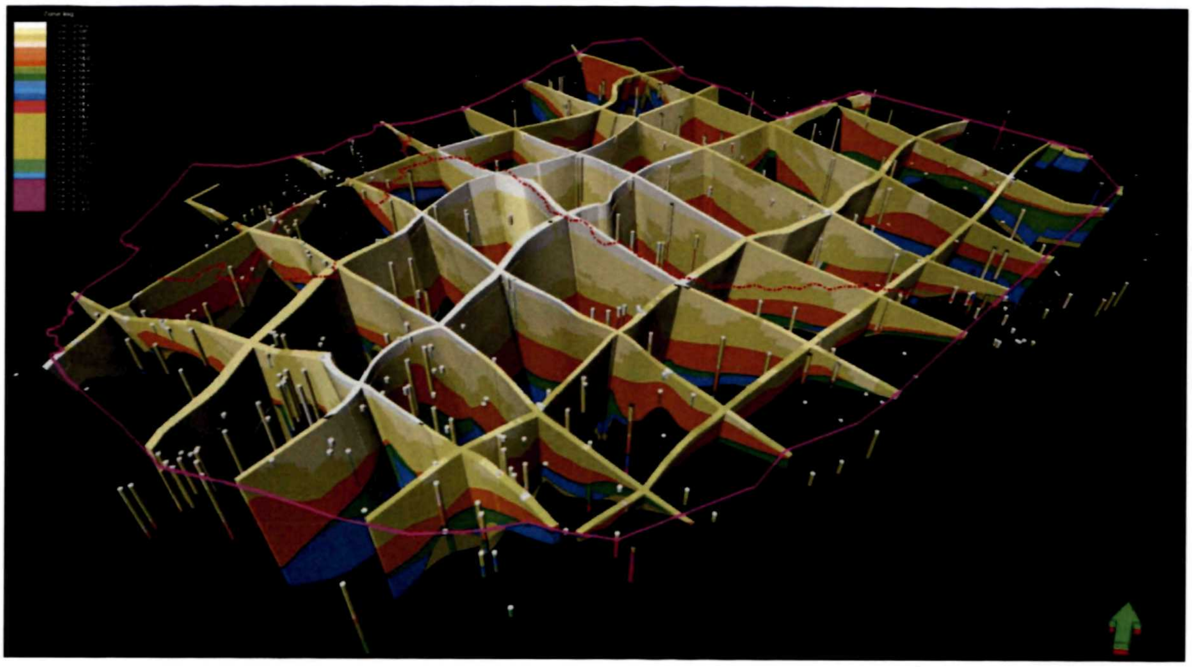

Fig. 3.2 Fence diagram of geological model. Colours depict main hydrostratigraphic units: light grey – Quaternary; pale green – delta plain facies of Late Pannonian; light green – delta front facies of Late Pannonian; ochre – Early Pannonian; dark green – Sarmatian; light blue – Badenian sediments; dark blue – Badenian volcanites; olive green – Cainozoic; magenta – Mesozoic. Green arrow points to the North

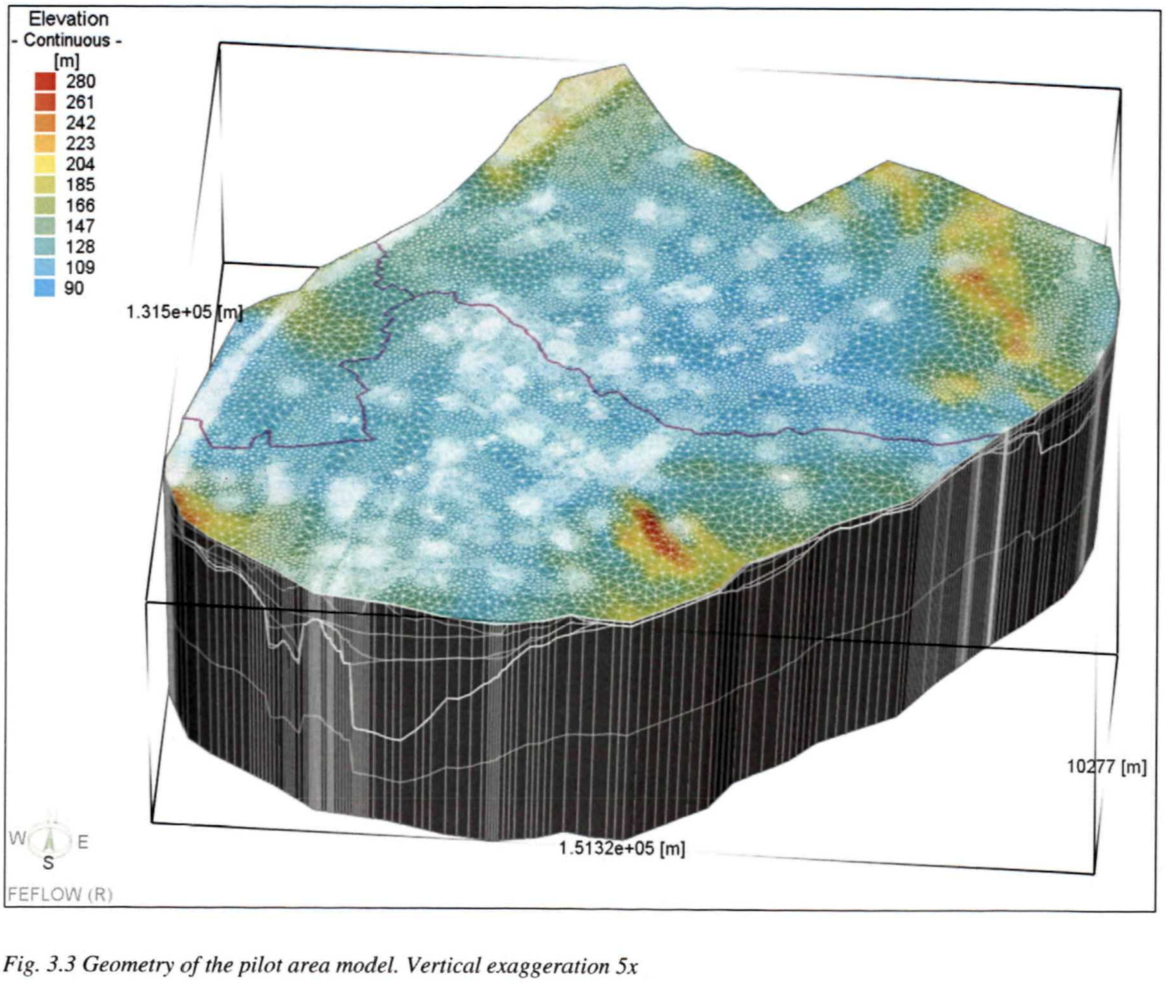

Fig. 3.3 Geometry of the pilot area model. Vertical exaggeration 5x

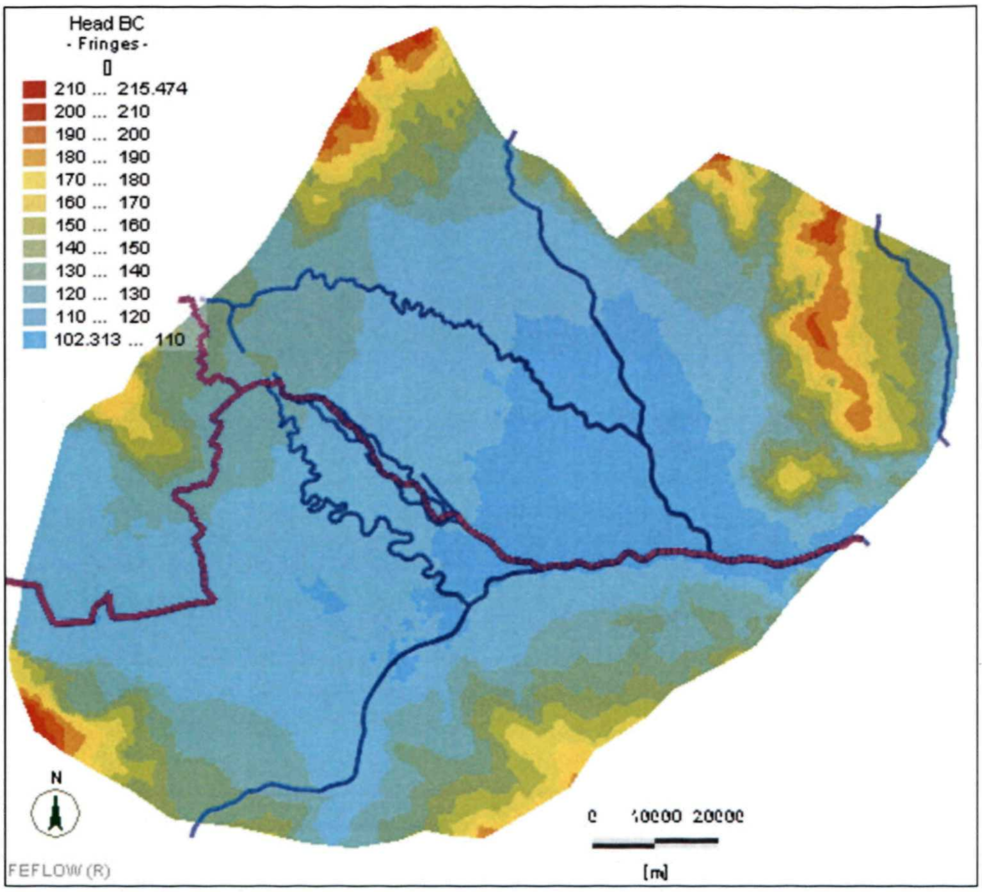

Fig. 3.4 Constant hydraulic head boundary condition (m a.s.l.) in the Quaternary aquifer

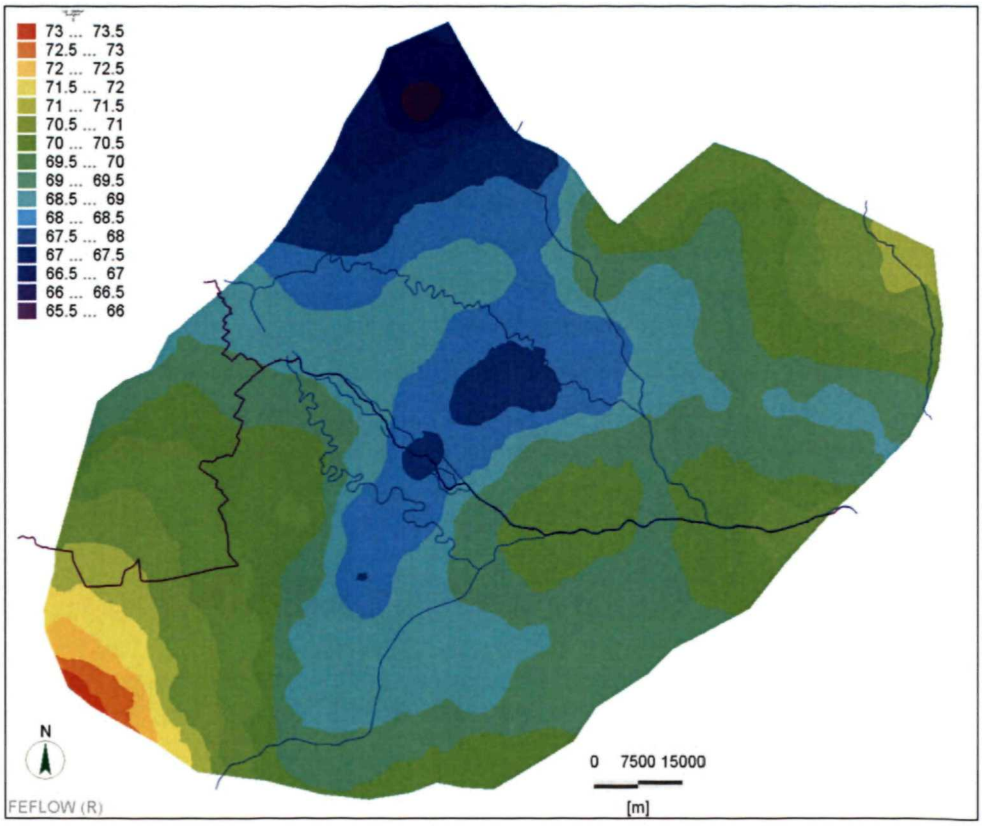

Fig 3.5 Constant basal heat flux (mW.m^{-2}) boundary condition at depth -10,000 m a.s.l. (from Lenkey et al., 2012)

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potential of cold water Quaternary aquifers lying 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 also applied at screen intervals of all active pumping wells. 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.

3.4.1.6. Thermal boundary conditions

At the base of the model a Neumann (constant heat flux) boundary condition was set out. The values of basal heat flux were taken from the supra-regional conductive thermal model of Lenkey et al. (2012) (Fig. 3.5). At the ground surface a Dirichlet boundary condition with uniform temperature 10 °C was set out, 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 in fact it acts as a boundary condition of the 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.

3.4.1.7. 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 the Quaternary aquifer groundwater fluxes and flow velocities can be unrealistically high. But as the 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.

3.4.1.8. 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 testing boreholes reach. 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 conductivi-

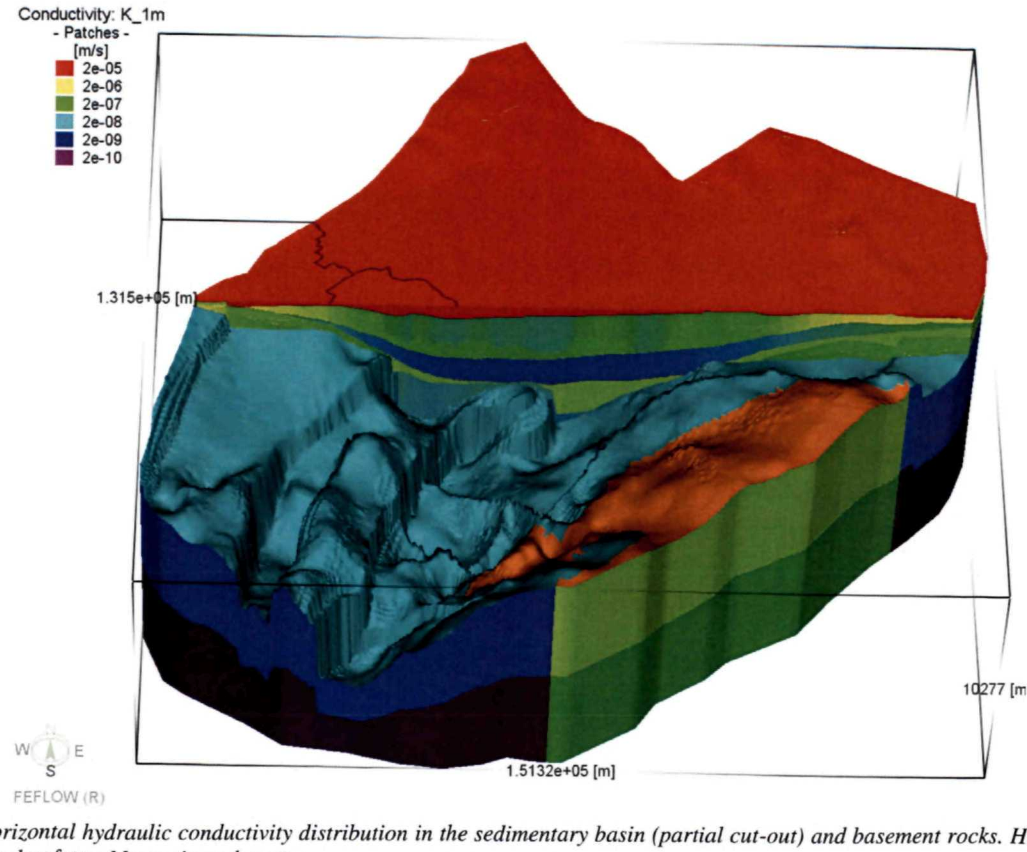

Fig. 3.6 Horizontal hydraulic conductivity distribution in the sedimentary basin (partial cut-out) and basement rocks. Higher values in the bedrock refer to Mesozoic carbonates

ties 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 of 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. Decrease of permeability and porosity with depth was also accounted for.

Igneous, metamorphic and carbonate bedrocks have 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, underwent weathering and sometimes karstification, leaving behind higher porosity and permeability.

Although in real geological settings faults and fissures often play a significant role in water movement as either highly conducting zones or hydraulic barriers. However, without a comprehensive and targeted research, their function, if any, remains obscure. Therefore it seems justifiable, especially in sedimentary basins filled with clastics, whose plasticity is able to seal any faults immediately, to exclude fault's hydraulic features and take account for only its juxtaposition.

Main heat transport parameters comprise volumetric heat capacity and thermal conductivity of rock and water, longitudinal and transversal thermal dispersivity, porosity. Fortunately, good database of these values exists for Neogene sediments and Mesozoic carbonates, too; for numerical values see Tab. 3.1. Values for the rest of the rock types present in the model were adopted from other published data.

3.4.1.9. 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 the measured ones in Figs. 3.7 and 3.8.

Since environmental groundwater heads measured at boreholes use a column of water with a density influenced by temperature and dissolved salts content that is identical to that of the water that surrounds the well, sensu Lusczynski (1961), they 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 re-evaluated. 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 $mg.l^{-1}$ 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 (Fig. 3.9).

Tab. 3.1 contains values of parameters, used in the pilot area model. The values for different model layers are coming from different sources: where possible, especially in shallow parts of the model, direct assignment of statistical means of individual parameters was applied. In the rest of the model the parameter values were obtained from inverse modelling or by guessing, based on published data.

3.4.2. Results of regional modelling

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

3.4.2.1. Hydraulic head distribution

Distribution of hydraulic heads in the model depends primarily on boundary conditions and spatial distribution of hydraulic conductivities (Fig. 3.12). In the 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.

3.4.2.2. Evaluating effects of thermal wells utilization

Simulation of theoretical infinite pumping of 112 existing operating geothermal wells, with total yield summing up to 219 $l.s^{-1}$, 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-abstraction. 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 a site.

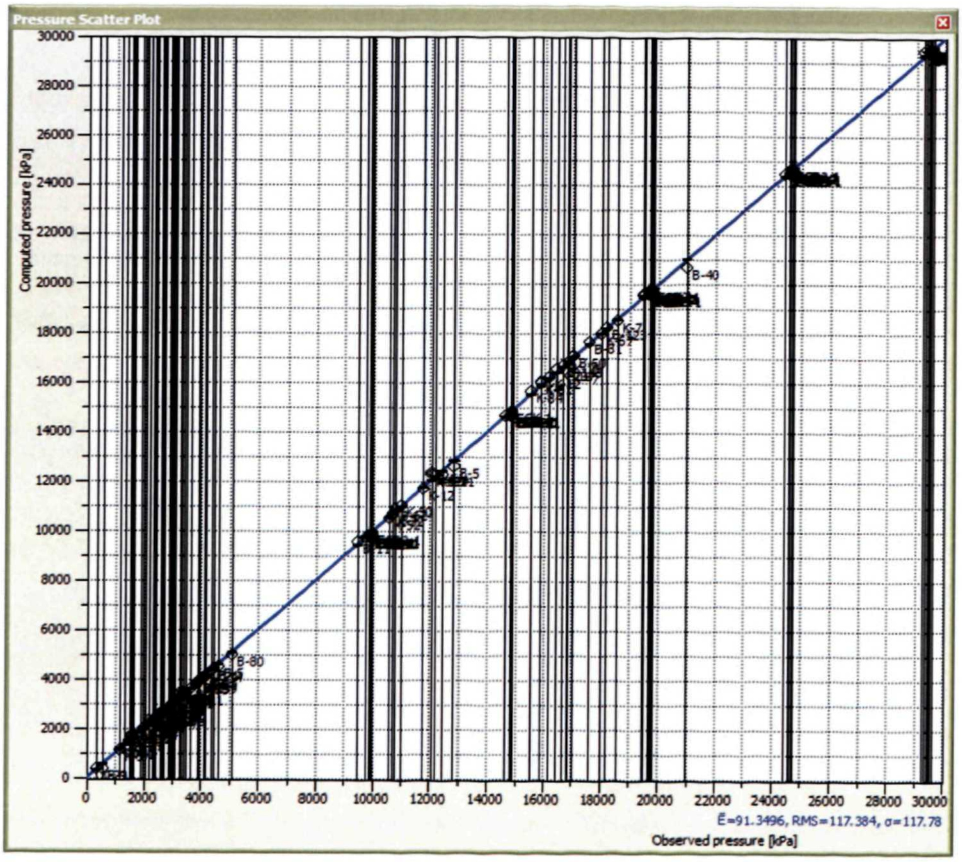

Fig. 3.7 Goodness of fit between computed and measured pressures in boreholes, natural pre-utilization state

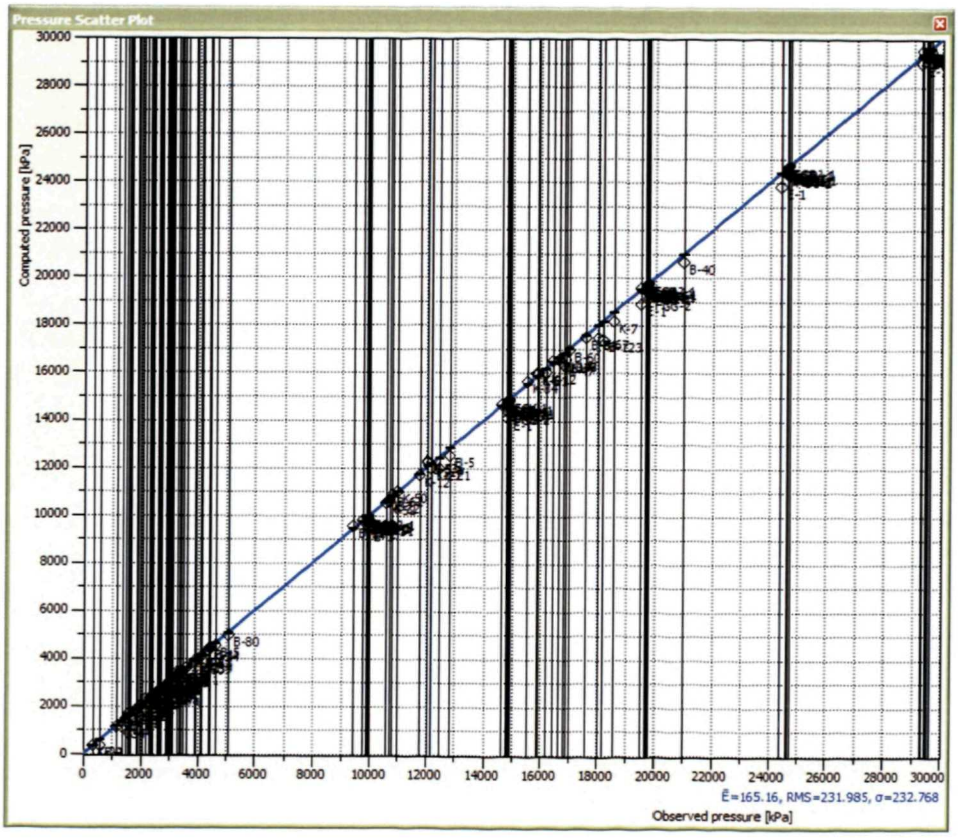

Fig. 3.8 Goodness of fit between computed and measured pressures in boreholes, steady pumping scenario

Tab. 3.1 Parameters used in the pilot area model

Model Layer	Horizontal hydraulic conductivity [m.s^{-1}]	Vertical hydraulic anisotropy [-]	Porosity	Specific storage [m^{-1}]*	Radiogenic heat production [μW.m^{-3}]	Heat conductivity of solid [W.m^{-1}.K^{-1}]	Heat conductivity of fluid [W.m^{-1}.K^{-1}]	Expansion coefficient [K^{-1}]*	Volumetric heat capacity of solid [J.K.m^{-3}]	Volumetric heat capacity of fluid [J.K.m^{-3}]	Longitudinal dispersivity [m]	Transverse dispersivity [m]*	Anisotropy of solid heat conductivity [W.m^{-1}.K^{-1}]*
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
Late Pannonian - delta front	3.228×10^{-8} - 3.526×10^{-6}	0.01 - 0.082	0.111	1×10^{-4}	1.3	2.219	0.6	0	2.737×10^{6}	4.186×10^{6}	50	5	1
Late 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
Early 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
Cainozoic	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: Palaeozoic and crystal-line	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: Palaeozoic 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: Palaeozoic 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

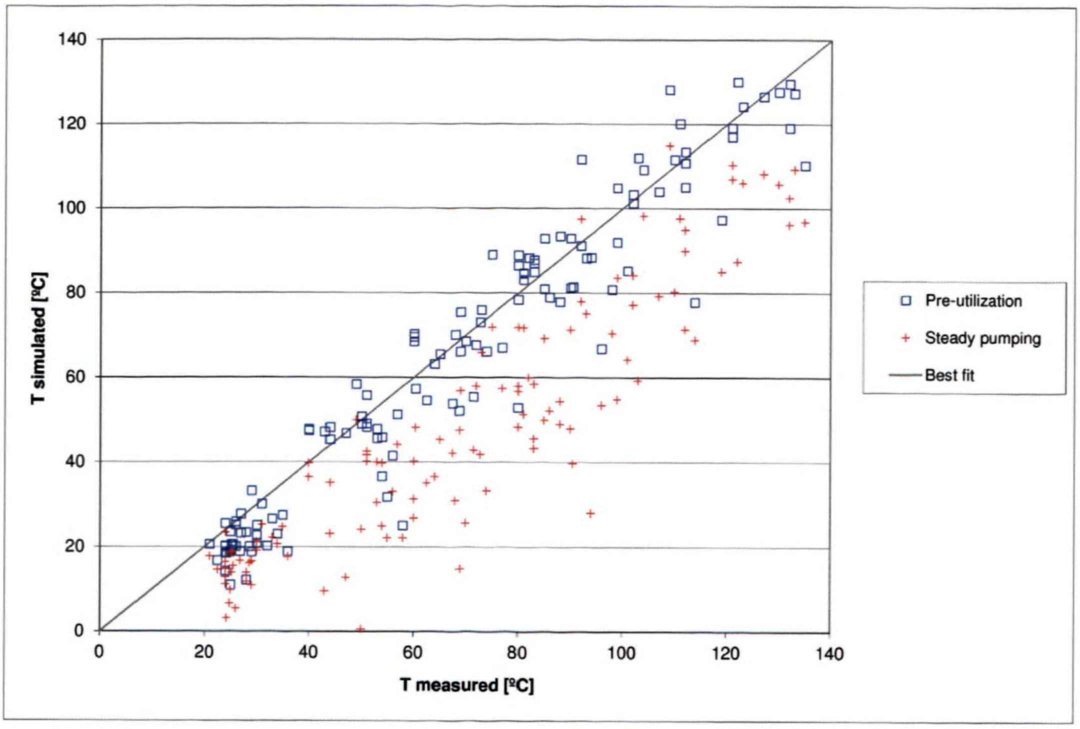

Fig. 3.9 Comparison of temperature evolution in boreholes for two model scenarios: pre-utilization and steady pumping. Obvious is systematic temperature decrease when pumping is functional, resulting from enhanced circulation of cold Quaternary waters into deeper thermal aquifers causing shortening of travel times. Root mean square error (RMSE) for first scenario is 9.32 and 13.31 for the latter

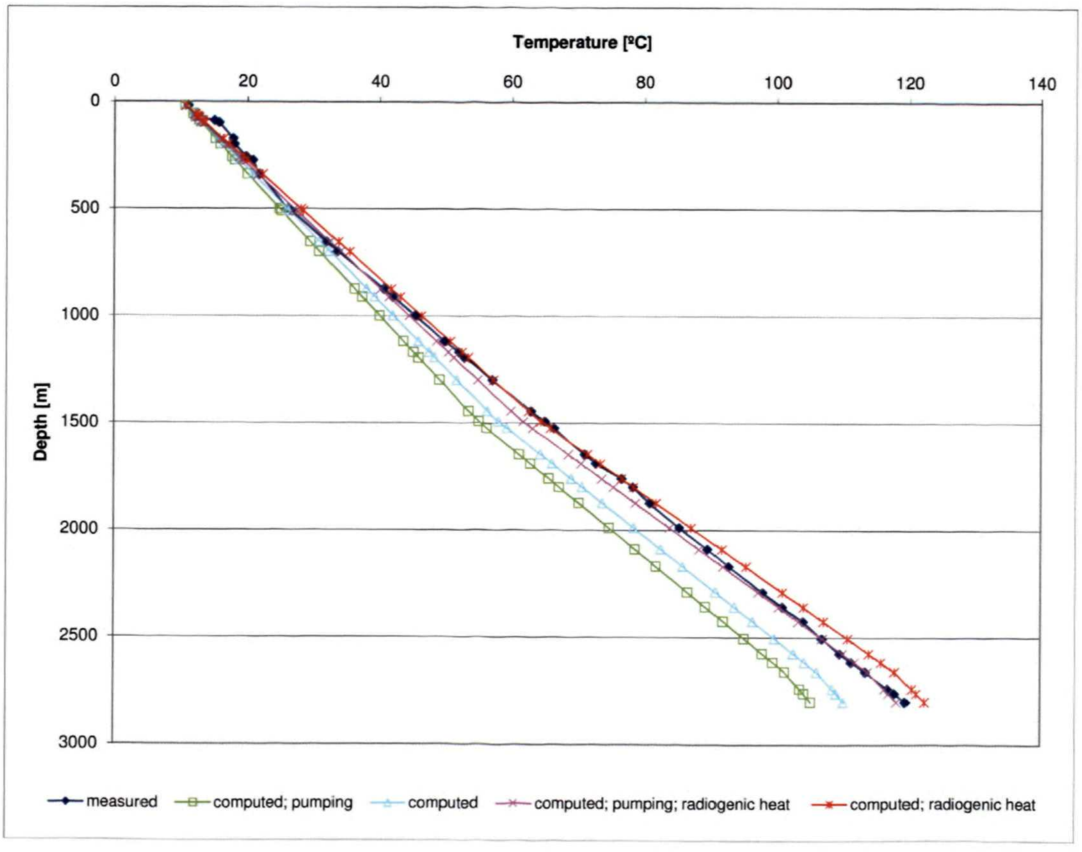

Fig. 3.10 Comparison of different model set-ups on goodness of fit between computed and measured temperatures, example from the monitoring well GPB-1 Boheľov. Best match was achieved for both scenarios, natural pre-utilization state and steady pumping, with inclusion of radiogenic heat production

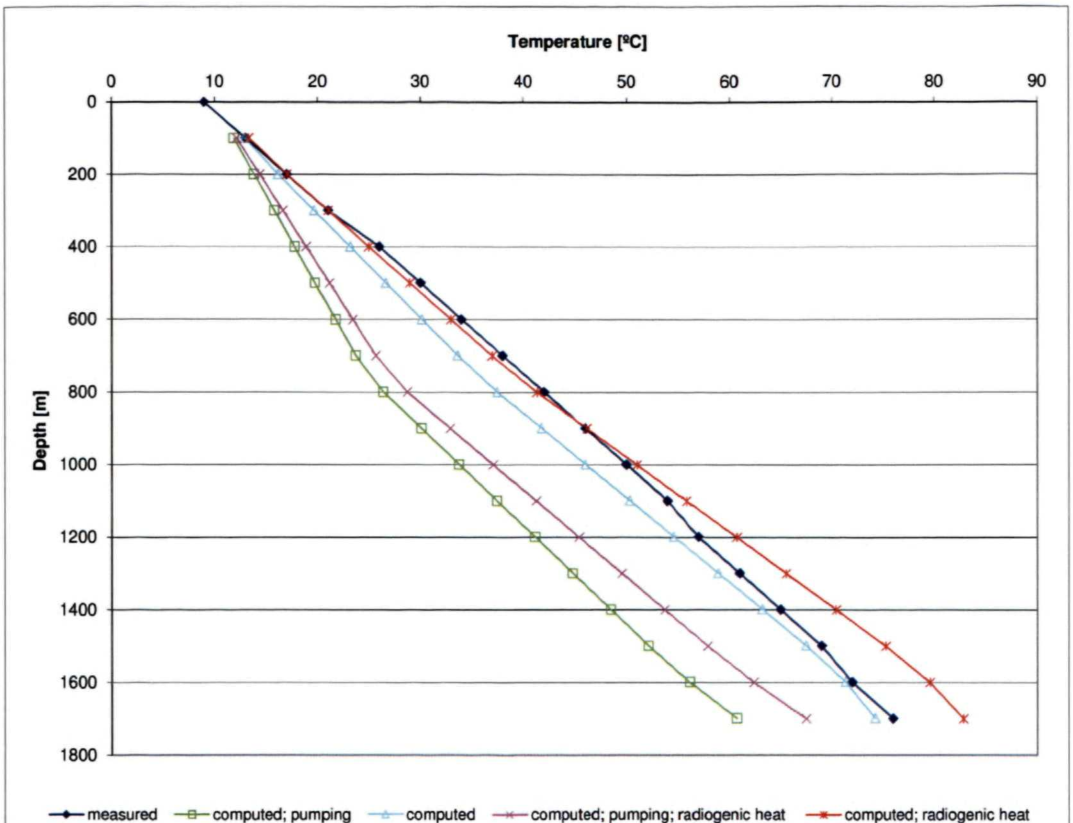

Fig. 3.11 Comparison of different model set-ups on goodness of fit between computed and measured temperatures, example from the monitoring well Di-1 Diakovce. Steady pumping scenario exhibits significant deviation from measured temperatures in upper 800 meters. It can be attributed to cooling by increased infiltration of cold Quaternary water induced by pumping

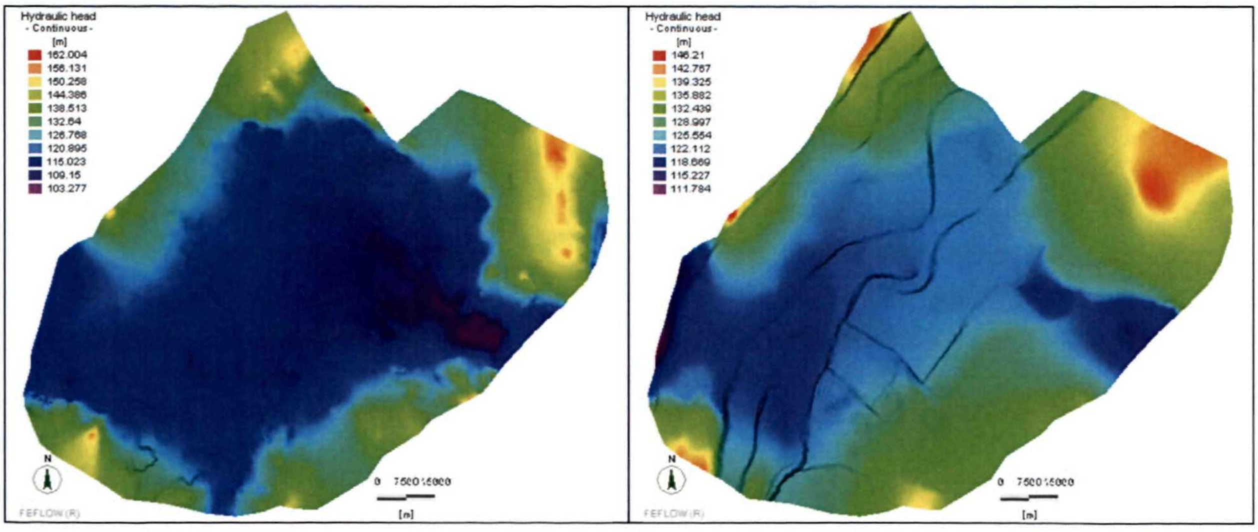

Fig. 3.12 Distribution of computed hydraulic heads at the base of Late Pannonian (left) and base of Cainozoic (right), pre-utilization state. Remember that pictures show values on whole model layer, while respective hydrostratigraphic units cover only central part of the area. The same principle applies for all similar maps in this paper

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. The impact is emphasized in mountainous areas in the southeast and northwest parts of the basin. 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 Figs. 3.13 a-d.

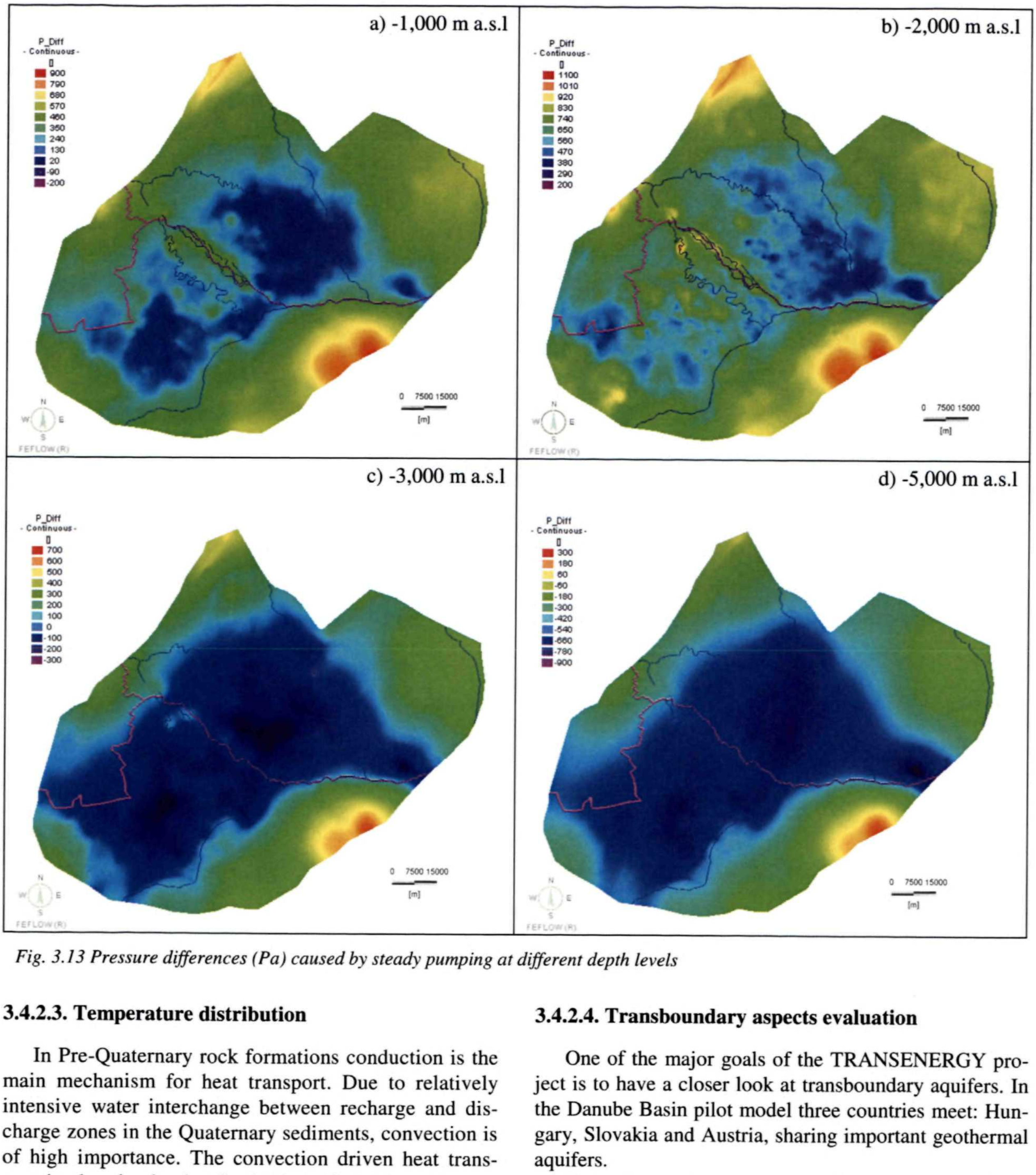

Fig. 3.13 Pressure differences (Pa) caused by steady pumping at different depth levels

3.4.2.3. 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 the Quaternary sediments, convection is of high importance. The convection driven heat transport is also dominating in the karstified Mesozoic carbonate formations in Gerecse and Pilis Mts. and Komárno High Block. Intensive recharge of precipitation is causing a considerable cooling of the whole carbonate massif (Fig. 3.14a-d).

Notable is also cooling effect of thick Quaternary gravels and sands along the central part of the 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 – the Danube River, excavates heat from underlying Neogene sediments. This cooling propagates to large depths over 3 km (Figs. 3.14a, b and c).

3.4.2.4. 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. The 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 from state to state either naturally or, in a close vicinity of operating wells, by forced convection. This promotes international cooperation in managing geothermal resources.

Figure 3.16 shows computed flow trajectories with travel times, induced by steady pumping in utilized thermal wells at long-term average rates. The most intensive

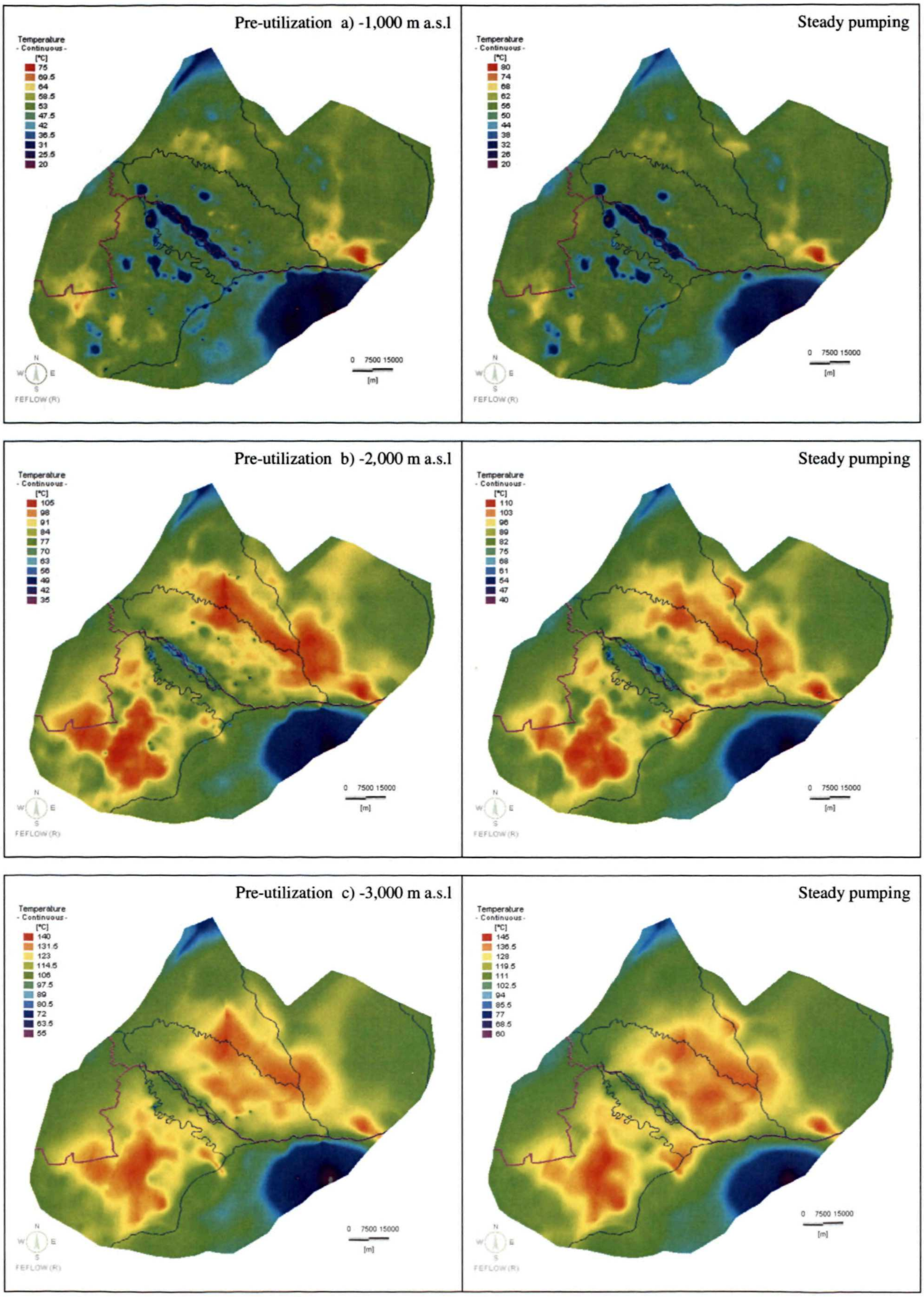
Pre-utilization a) -1,000 m a.s.l
Steady pumping
Temperature
- Continuous -
[°C]
75
69.5
64
58.5
53
47.5
42
36.5
31
25.5
20
80
74
68
62
56
50
44
38
32
26
20
Pre-utilization b) -2,000 m a.s.l
105
98
91
84
77
70
63
56
49
42
35
110
103
96
89
82
75
68
61
54
47
40
Pre-utilization c) -3,000 m a.s.l
140
131.5
123
114.5
106
97.5
89
80.5
72
63.5
55
145
136.5
128
119.5
111
102.5
94
85.5
77
68.5
60
0 7500 15000
[m]
N
W E
S
FEFLOW (R)

Fig. 3.14

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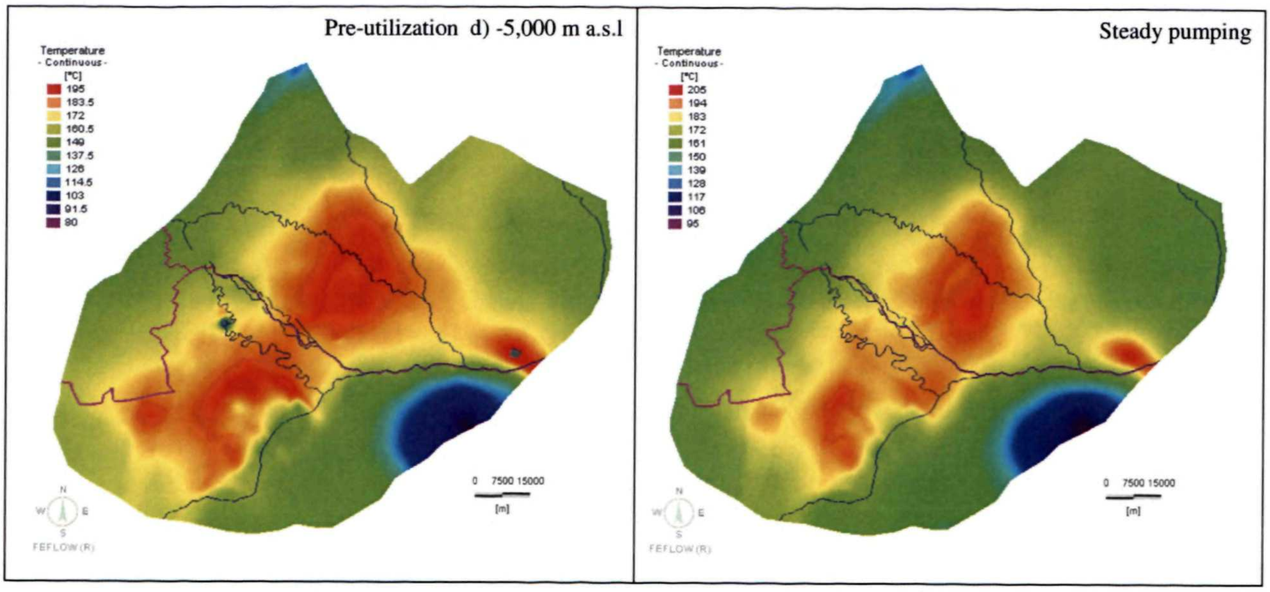

Fig. 3.14 Temperature distribution at different depth levels. Compared are both state scenarios: pre-utilization and steady pumping. Mind the different colour scales

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 the Danube River, where it seeps into the river or is partly captured by several wells. The lateral extent of well capture zones may be underestimated to some unpredictable level, because model assumes homogeneous aquifers, while in reality these are built up of interchanging permeable and impermeable layers of different thicknesses. Pumped amounts are withdrawn predominantly from more permeable layers that represent only a portion of total thickness. This forces 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 Figs. 3.17 and 3.18.

3.4.2.3. Energy balance

Geothermal modelling 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. 3.19). In this chart the total energy balance of the whole model, partitioned between individual countries, is provided by visually comparing the thermal power of existing utilized wells, radiogenic heat inflow and deep heat inflow. Here the power of geothermal wells is calculated as energy released from pumped amount of water by cooling from reservoir temperature to the reference temperature 25 °C. Within the portion of the model at the Slovakian territory there are 33 wells, in Hungary 78 and in Austria only 1 well. The radiogenic heat inflow contributes to the total heat contained in the rock and pore water depending on the volume of rock, porosity and radiogenic heat production, see Tab. 3.1. The so-called "deep heat inflow" is the heat flux across the bottom boundary of the model, situated at the depth 10,000 m b.s.l., summed for the respective portion of the area of each country.

3.4.3. Geothermal utilization scenarios

The Danube Basin, occupied by Slovakia, Hungary and partly Austria is a true transboundary geothermal structure. Although no utilization conflicts exist yet on this large area, the current utilization magnitudes and forecasted growing demand for future geothermal installations and balneological sites may cause problems. Modelled groundwater temperatures and pressures may significantly drop due to excessive production, especially after long-term exploitation.

The steady state models allowed identifying sensitive areas within the large territory of this pilot area, where future monitoring of the main geothermal aquifer (Late Pannonian porous reservoir) should be established. Scenarios of additional direct use of thermal groundwater proved the necessity of reinjection.

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

A detailed study on bilateral cooperation (SK-HU) on geothermal energy exploitation was performed as well.

The scenario analysed common use of geothermal energy right at the state border by two geothermal doublets, organized in a tight 2 by 2 diagonal cluster. The main goal of this study, performed by transient coupled flow and heat simulations, was to test the proposed wells configuration and estimate operating life-time of the system by prediction of thermal breakthrough.

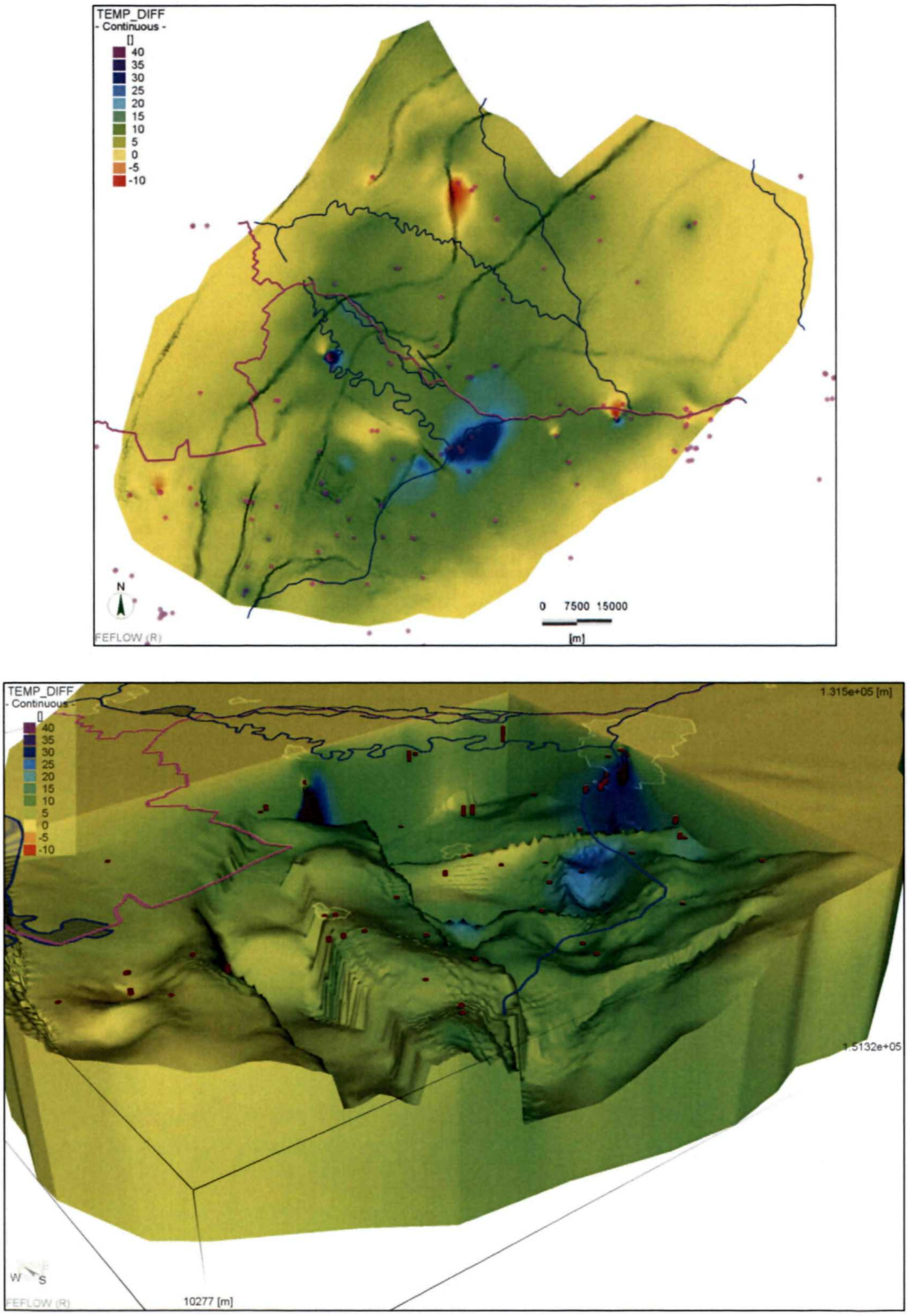

Fig. 3.15. Difference in temperature between the pre-utilization state and the steady pumping scenario. a) Basement of Late Pannonian; b) Example of temperature decrease around production wells in Hungary, partial cut out of sedimentary fillings. Wells locations are indicated by red cylinders

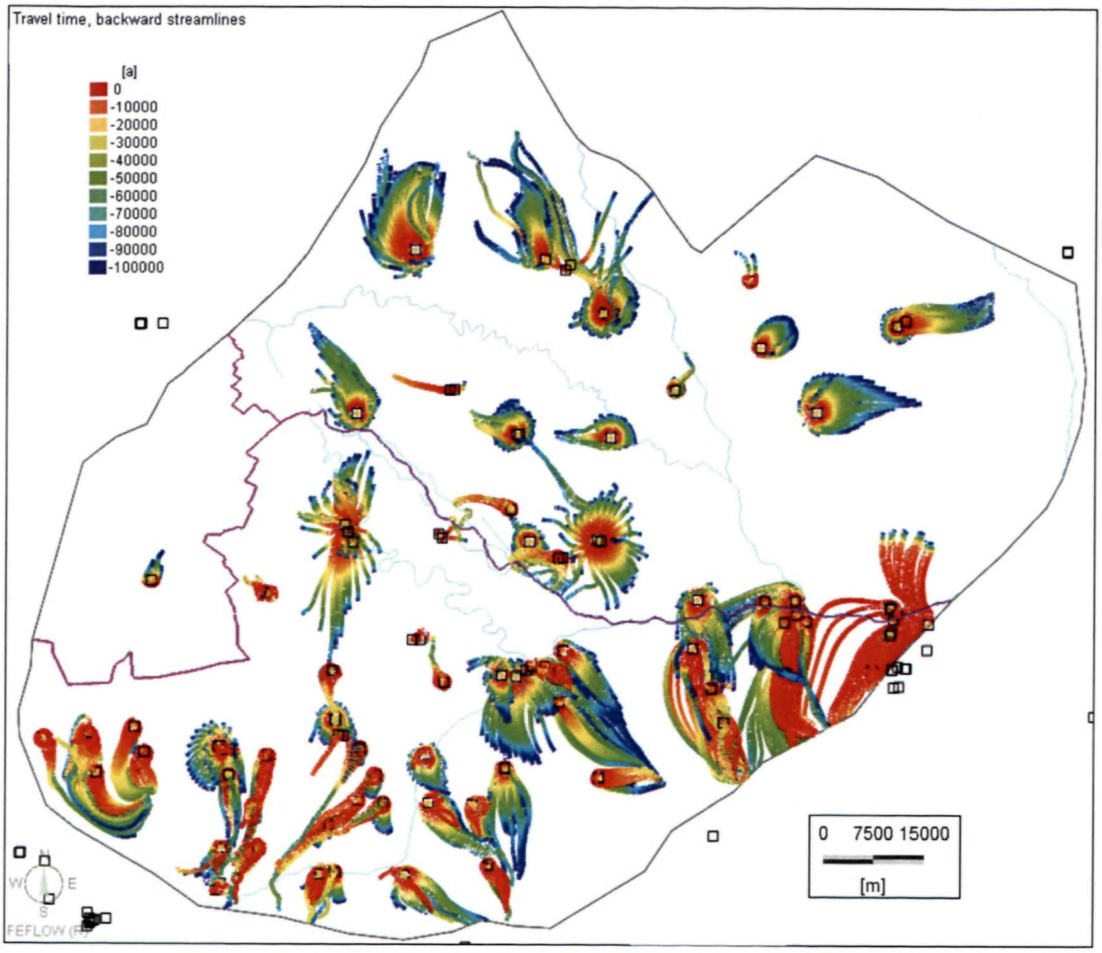

Fig. 3.16 Vertical projection of 3D flow paths towards thermal wells with travel time [years]

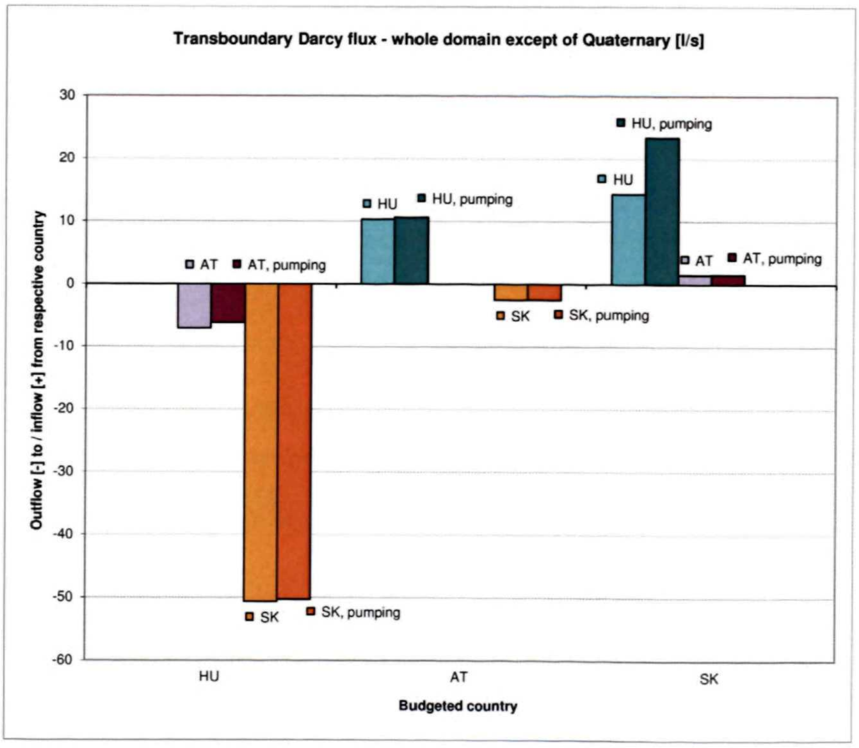

Fig. 3.17 Transboundary flow within Pre-Quaternary rock formations among Hungary, Slovakia and Austria quantified for two model scenarios

New hypothetical well installations were emplaced in the area of the Late Pannonian geothermal play, containing thermal water over 30 °C. In total 21 suggested geothermal doublets were inserted uniformly within this area away from existing geothermal installations. Pumping and re-injection wells were separated by a distance of 2 km. Due to limited permeability of the Late Pannonian sediments, pumping and re-injection rates were set to 20 l.s^{-1} only, with temperature of re-injected water at 25 °C. For simplicity, the entire thickness of the Late Pannonian hydrostratigraphic unit (0–2,580 m) was supposed to be screened.

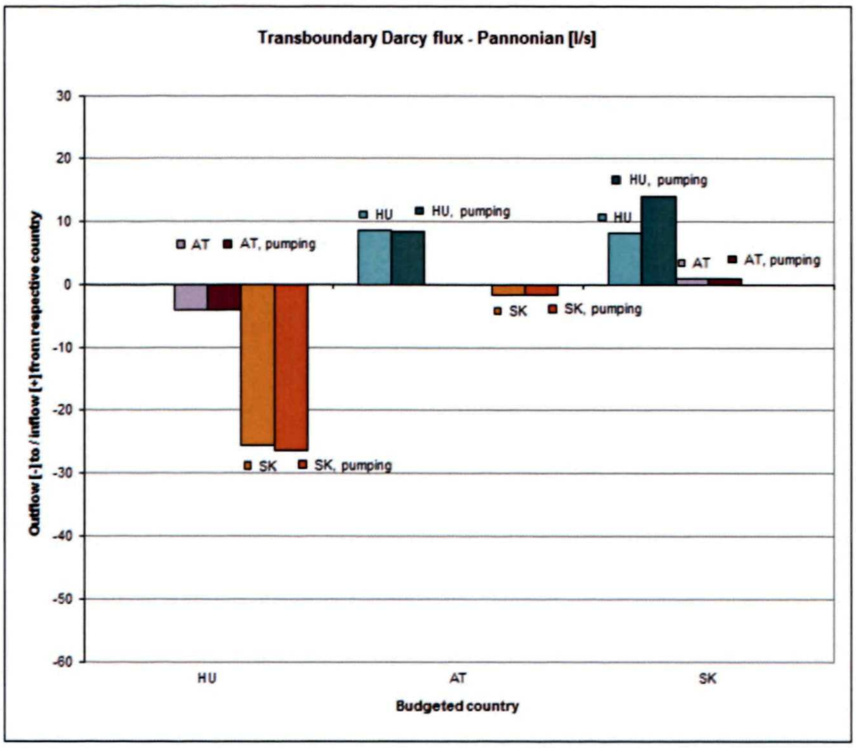

Fig. 3.18 Transboundary flow exclusively within Late Pannonian sediments among Hungary, Slovakia and Austria quantified for two model scenarios

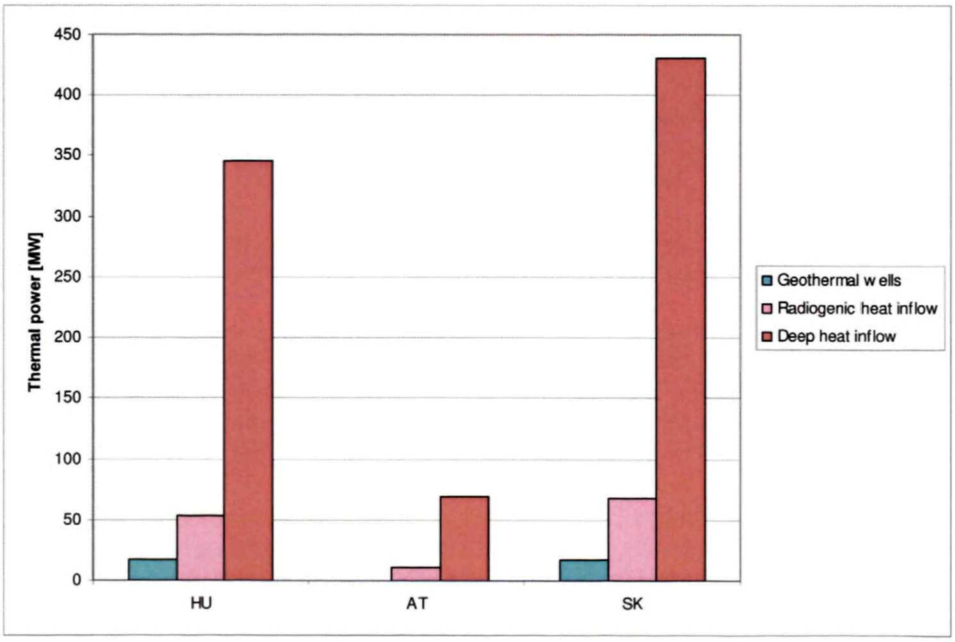

Fig. 3.19 Thermal power of wells, radiogenic heat generation and basal heat inflow in the whole model, divided among Hungary, Slovakia and Austria

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3.4.2.4. Potential installations scenarios

The aim of the numerical modelling was to investigate impacts of additional geothermal installations on thermal and pressure conditions in the Late 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, i.e. running for infinity and assuming recharge-open structures. 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.

The area where new hypothetical well installations were emplaced is the area of the Late Pannonian geothermal aquifer, which extent was defined by recoverable heat in place (identified resources), with temperature of water over 30 °C (Fig. 3.20).

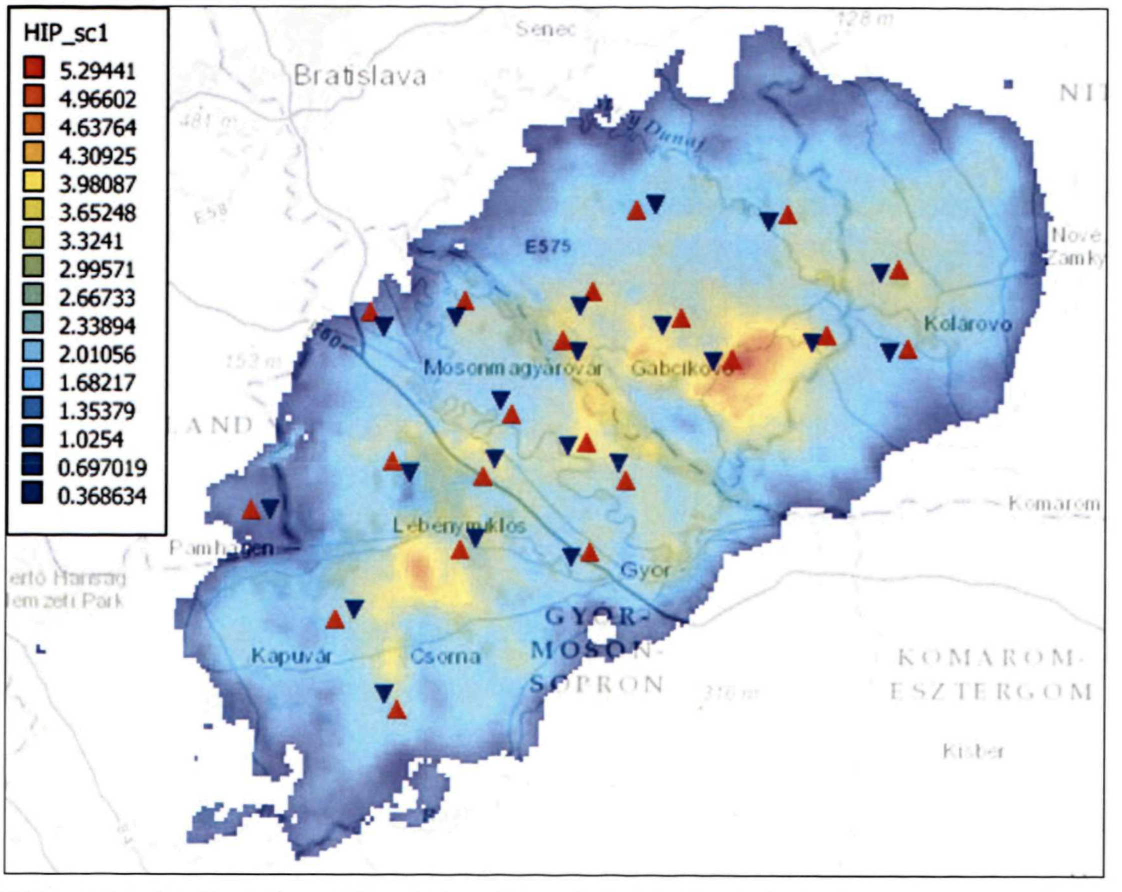

Fig. 3.20 Extent of the Late Pannonian geothermal play with hypothetical doublets (red triangles – suggested pumping wells; blue triangles – suggested reinjection boreholes). Colour indicates identified geothermal resources (MW)

Steady state simulation with additional 21 geothermal doublets revealed a significant effectiveness of the thermal energy harvesting (Fig. 3.21). It also showed that in some areas a potential for additional installations still remains.

Utilization of pumping wells without re-injection shows significant cooling of the area in broader vicinity of the wells (Fig. 3.22). Comparing to the doublet scenario, the temperature decrease is much more striking.

While temperature effects show generally similar pattern in both models, the two scenarios differ more significantly when it comes to hydraulics, especially groundwater pressure. As in the doublets scenario the extracted water is returned into the same aquifer and the negative pressure changes are compensated by the increasing groundwater head near the reinjection wells, these changes are limited only to the relatively close vicinity of the wells (Fig. 3.23).

This picture is radically different from the scenario without re-injection (Fig. 3.24), where pressure drop affects the entire aquifer, with magnitude increasing towards the basin centre. In large areas the groundwater head drops over more than 100 meters, which would significantly affect technical limits of pumping, not only at new wells, but also at existing ones.

By analysing the energetic balance of the models, the energetic impact of the two scenarios was also studied. In the scenario with re-injection, 55.46 MW of potential sustainable geothermal energy to be used was identified. For the scenario without reinjection, the calculated thermal power is higher, 82.32 MW, due to lower reference temperature, comparing to the return temperature of doublets: 30 °C. However the real energetic use would 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. At the same time a decrease of thermal power of existing geothermal wells of 3.64 MW was observed, which is due to the cooling of significant portions of the targeted aquifer.

Utilization of pumping wells without re-injection shows significant cooling of the area in broader vicinity of the wells (Fig. 3.22). Comparing to the doublet scenario, the temperature decrease is much more striking.

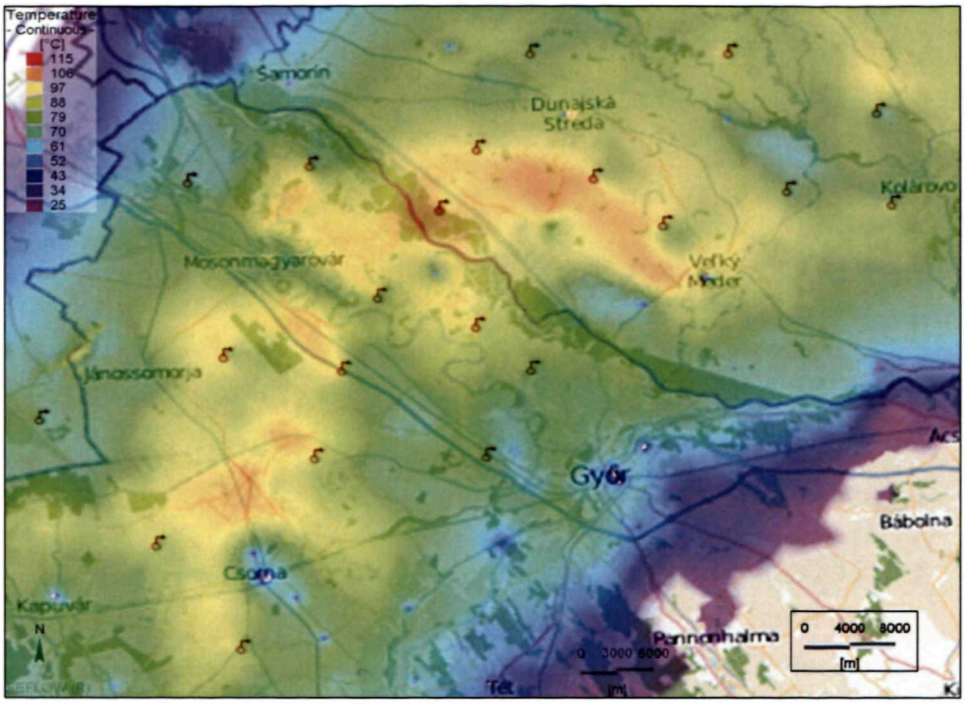

Fig. 3.21 Alteration of the thermal field (temperature changes: scale at top left) at the top of the Late Pannonian geothermal play caused by 21 hypothetical geothermal doublets (triangles: red - pumping, blue - reinjection wells). Purple squares are existing utilized geothermal wells

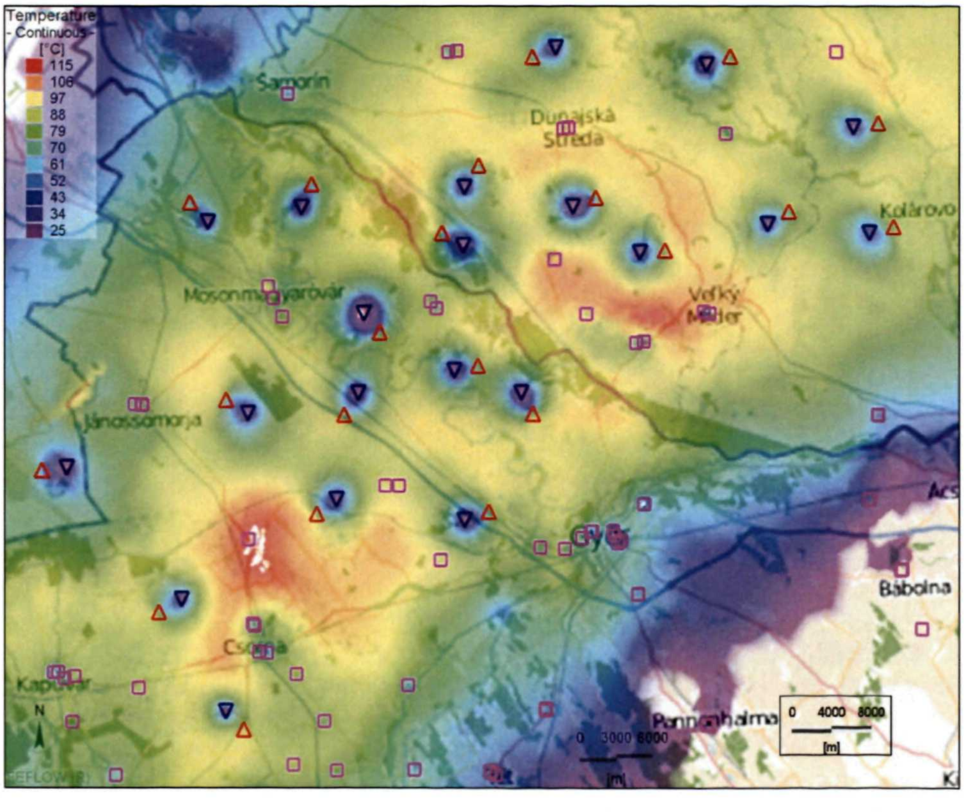

Fig. 3.22 Modification of the thermal field at the top of the Late Pannonian geothermal play caused by pumping wells (symbols)

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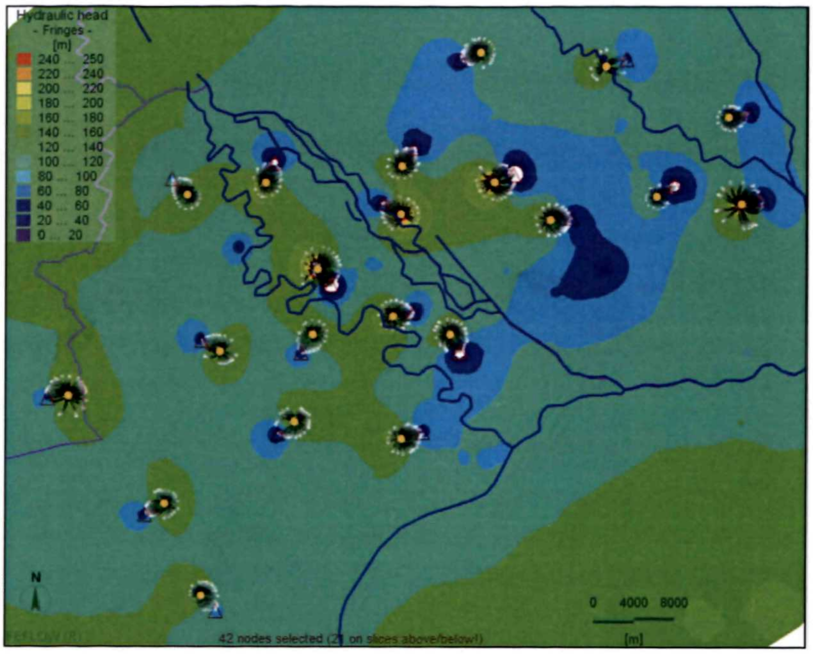


Fig. 3.23 Hydraulic heads field in the Late Pannonian geothermal aquifer, doublets scenario

3.4.4. Boundary doublet cluster scenarios

To investigate thermal and hydraulic response under 2 doublets utilization configuration in the Slovak – Hungary transboundary area a detailed model was set up. As a demonstration site for fissure – karst type aquifer in the Danube Basin pilot area the Mesozoic carbonates of the Komárno Marginal Block (sensu Slovak interpretation of the geothermal water bodies and geothermal structures) was chosen. The fissure – karst type permeability is suitable for reinjection of the energetically used water as proven by practical experience. The configuration of two doublets can be seen on Fig. 3.25.

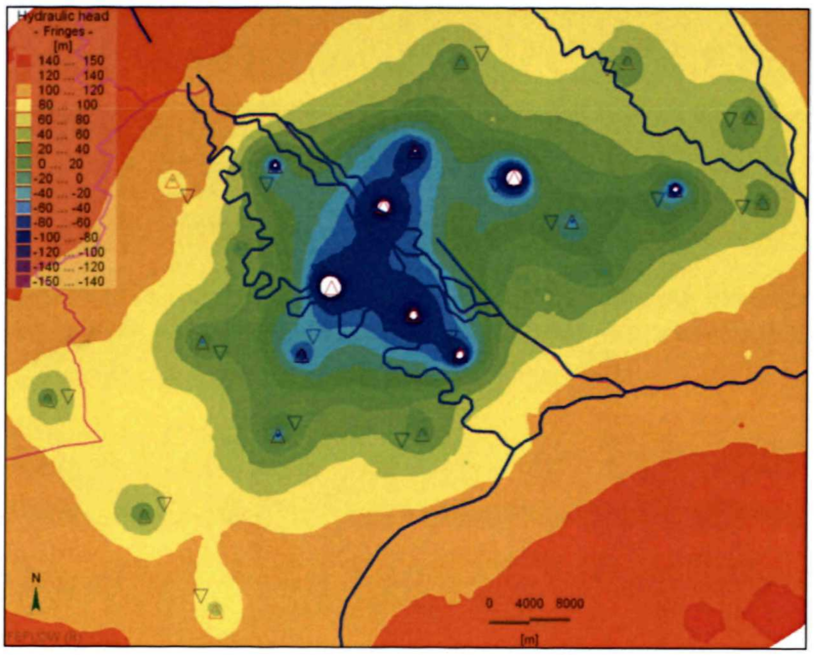


Fig. 3.24 Hydraulic heads field in the Late Pannonian geothermal aquifer, production/ pumping wells scenario

The evaluated hydrogeological structure (Komárno Marginal Block basement reservoir) is closed, and there is no water transfer from the surrounding structures. For modelling purposes a relatively small area of approximately 5x5 km has been chosen (Fig. 3.25.). The extent was determined by the impact of the doublets. For production two wells were designed to pump the geothermal water and two for its subsequent re-injection at a temperature of 15 °C. These two doublets are designed in the transboundary area of Slovakia and Hungary in a way that in each country there 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 used.

3.4.4.1. Model geometry

In horizontal direction the model domain was discretized into two-dimensional mesh of triangular elements (Fig. 3.26). This mesh was adjusted by linear gradation of nodes in places of suggested wells. The fining of mesh towards wells assures better conversion of simulations.

The basic layout of the model in vertical direction is shown in Fig. 3.27. In vertical direction the model is composed of four layers representing four main geological formations. The first stratum from the surface is formed by the Quaternary sediments, where fresh water table exists. The second layer consists of a sequence of the Tertiary sediments, overall acting as a hydrogeological isolator. Underneath are the Mesozoic rocks (limestones and dolomites), which form the principal geothermal aquifer, lying atop the crystalline basement, representing a hydrogeological isolator. The geometry of individual layers was adopted from the faulted geological model of the Danube Basin (Baráth, Fordinál, Kronome, Maglay & Nagy in Maros et al., 2012) and is visualized in Fig. 3.27.

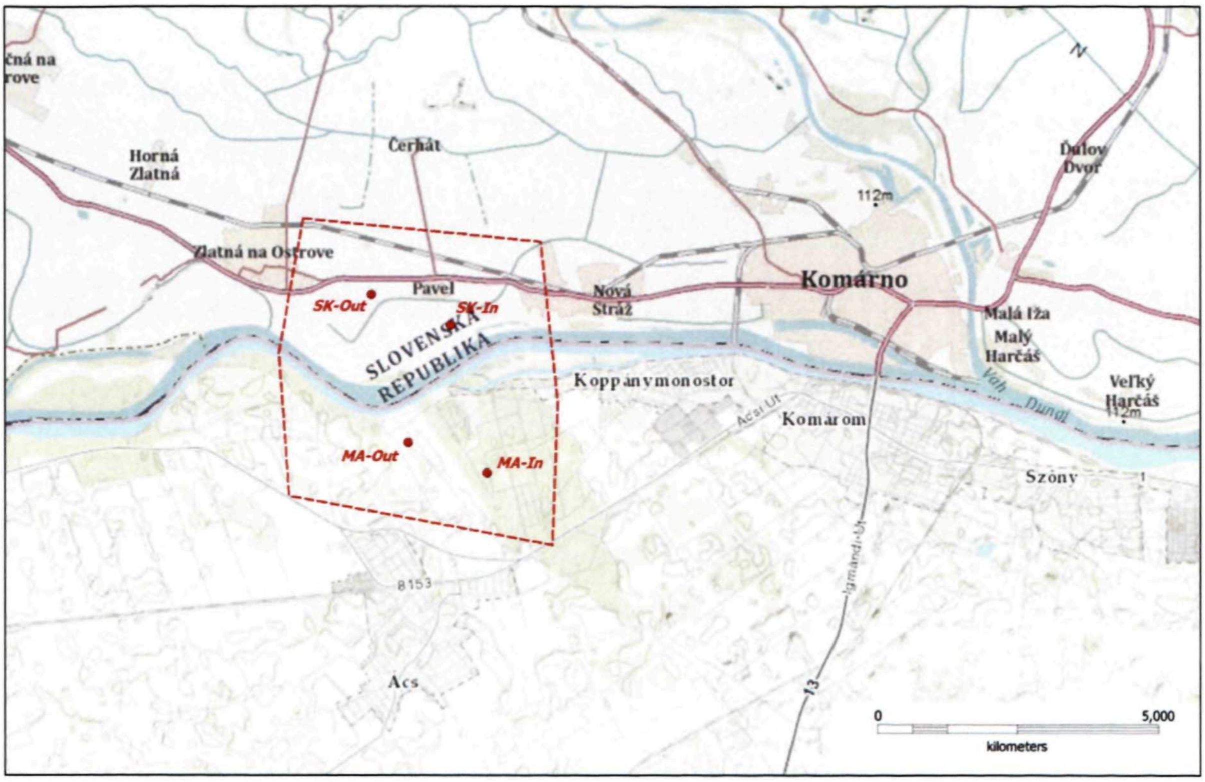


Fig. 3.25 Model area and design of the doublet cluster

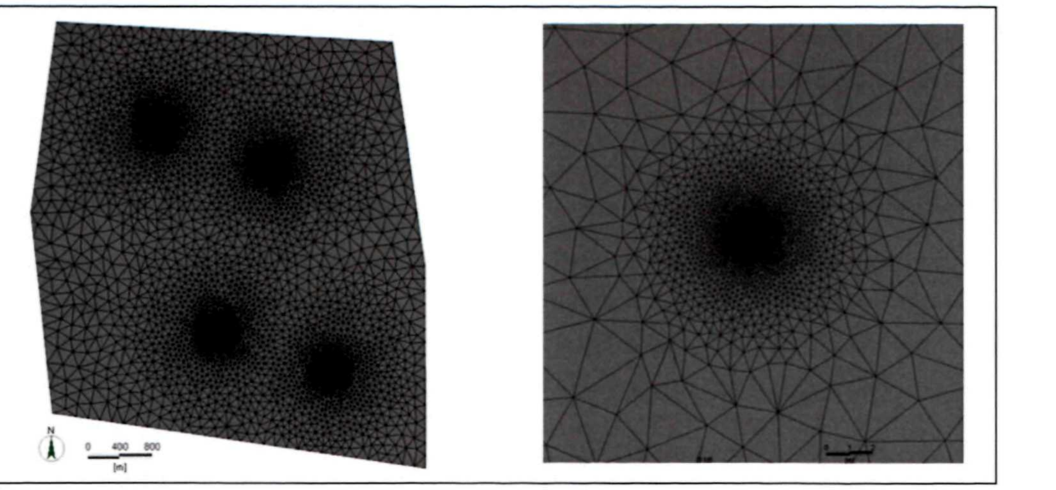


Fig. 3.26 Horizontal definition of the computing mesh (A – general overview of the model; B – detail of nodes refinement around wells)

Overall, it is obvious that layers are inclined in the SE-NW direction. Because no deep drilling exploration was performed in the close vicinity of the evaluated area, the thickness of the Mesozoic carbonates formation may not be exactly designated. It was estimated to be 300 m by expert judgement. This uniform thickness was assigned across the whole model. The lowermost layer was extended to a depth of 10 km b.s.l.

This division formed the basis of vertical network definition of the model. For the sake of better conversion and accuracy of results, these layers were further divided into several sub-layers with the same parameters. This led to final number of 11 layers delineated.

3.4.4.2. Material properties

Properties of rocks are the determining parameter of groundwater flow and heat transport. These properties are schematically shown in Figs. 3.28 and 3.29.

For groundwater flow the conductivity is a decisive parameter, which tensor is assigned to all materials individually along X, Y and Z directions. An example of this setup is in Fig. 3.28 and values for individual layers displays Tab. 3.2.

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

Tab. 3.2 Hydraulic parameters of rocks

Layer	Conductivity ($m.s^{-1}$)		
	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	$1.055*10^{-9}$	$1.055*10^{-9}$	$1.055*10^{-10}$

Similarly there were defined the parameters relevant for the transport of heat. These values are shown in Fig. 3.29 and in Tab. 3.3. In this case, values were also based on previous studies and on the results of the steady flow/steady heat transport model calibration.

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, the values range from $3.42*10^6$ to $2.4*10^6$ $Jm^{-3}K^{-1}$. The opposite character of values has the parameter of thermal conductivity of solid, which ranges from 1.0 in the Quaternary sediments to 3.0 $Jm^{-1}s^{-1}K^{-1}$ in the crystalline rocks.

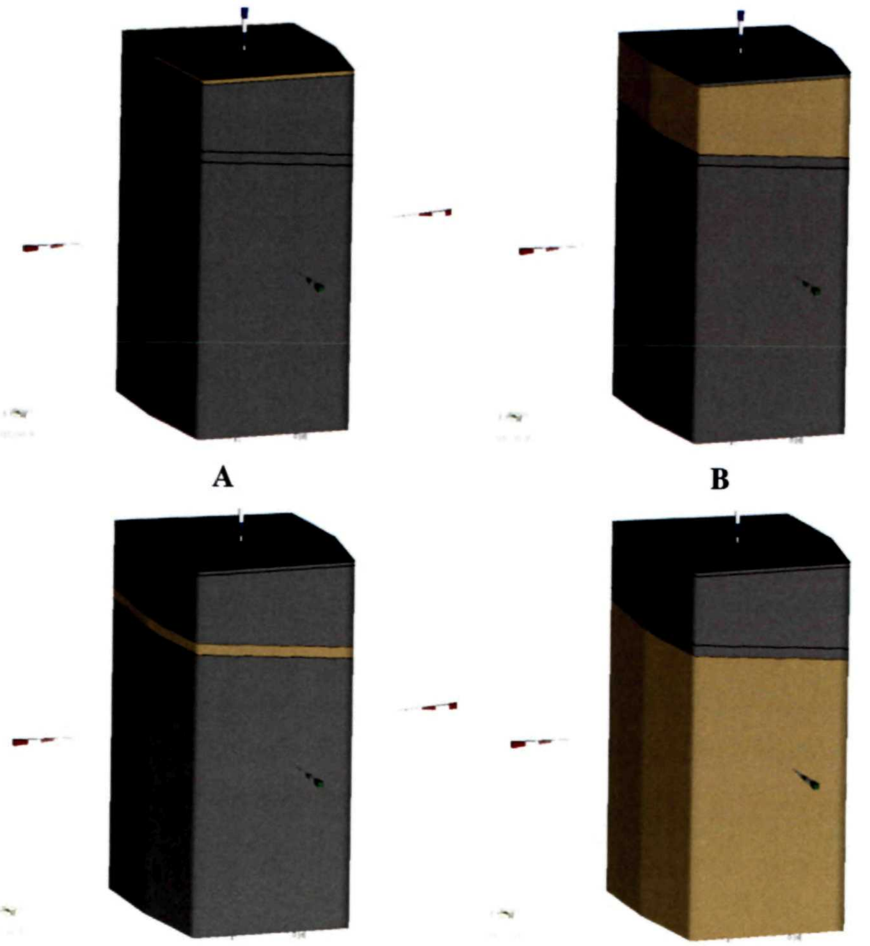


Fig. 3.27 Vertical stratification of the model (A – Quaternary sediments; B – Tertiary sediments; C – limestones and dolomites – geothermal aquifer; D – Crystalline – impermeable bedrock)

3.4.4.3. Boundary conditions

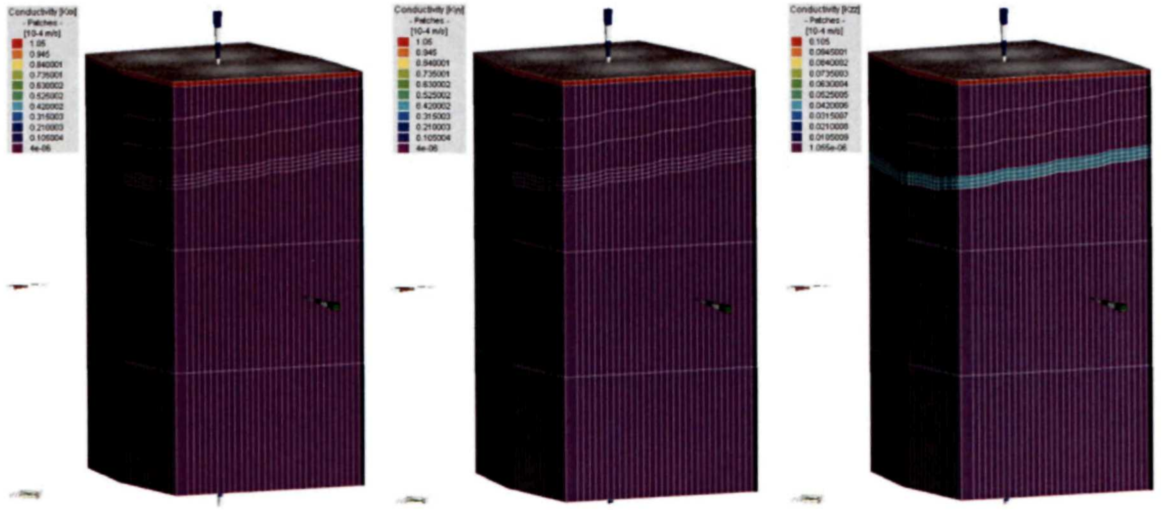
Boundary conditions determine the processes occurring at the edges of a model, and as such are crucial for any flow and heat transport simulations. For the steady-state modelling of the groundwater flow a static groundwater level was set in the top layer - the fresh water (Quaternary) aquifer. Absolute values of hydraulic potential in the first aquifer were imported from the results of accomplished regional modelling.

Boundary conditions for heat transport were set in a similar manner. Their distribution is shown in Fig. 3.29.

On the surface of the model a constant temperature boundary condition was set out, 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 below the surface a constant heat-flux type boundary condition was set out. Heat flux values have been imported from the supraregional conductive thermal model of Lenkey et al. (2012). On average, this parameter reaches values around 0,06 Wm^{-2}.

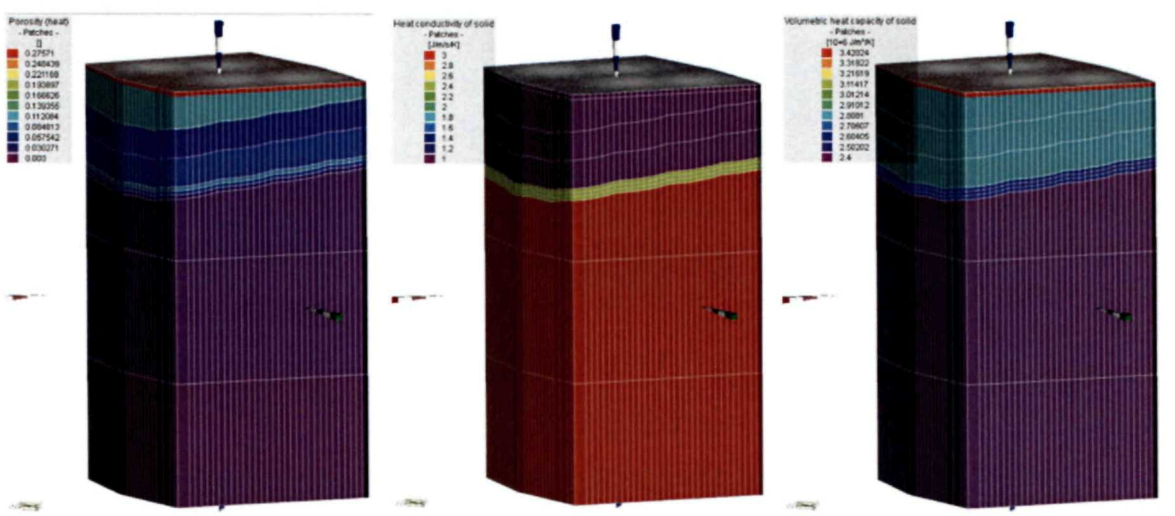
3.4.4.4. Steady flow and heat transport simulation

For the purpose of transient flow and heat transport modelling it is necessary to have defined initial pressure and water temperature conditions. To determine these spatial properties, a steady flow/steady heat transport model was created first. The purpose of this simulation was to determine the long-term steady temperature–pressure conditions in the geothermal structure, which shall initially define the conditions prior to the modelling the use of geothermal water. In this step the individual material properties were calibrated according to measured values of water temperature in existing geothermal wells.



A B C

Fig. 3.28 Values of conductivity in X (A), Y (B) and Z (C) direction



A B C

Fig. 3.29 Parameters for heat transport (A – Porosity; B – Volumetric heat capacity of solid; C – Heat conductivity of solid)

3.4.4.5. Transient heat modelling

The calibrated steady state model serves as a starting point of transient simulations. For this purpose, the model boundary conditions were modified by adding two pumping and two re-injection wells with constant flow rates assigned. These quantities are being varied during different model runs and the impact of using geothermal water was analysed. The whole thickness of the carbonate aquifer (300 m) was screened, i.e. from top depths between 1,890-2,170 m to bottom depths between 2,180-2,480 m b.s.l. The temperature of the re-injected water was set constant in all cases. We assumed that the technology allows pumped water to cool down to 15 °C. The transport

Tab. 3.3 Material parameters of rocks for heat transport modelling

Layer	Porosity	Volumetric heat capacity of solid ($J.m^{-3}.K^{-1}$)	Heat conductivity of solid ($J.m^{-1}.s^{-1}.K^{-1}$)
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

of cooled water in geothermal collector in the direction from the injection wells to pumping wells was observed.

The results of this simulation are shown in Fig. 3.30. The visualization shows streamlines in the Slovak part of the geothermal water use system, while pathlines from wells on Hungarian side are not displayed. It displays the range of flow pathlines in direction from injection well to pumping well after 35 years, what is the expected lifetime of system for geothermal water use. It is obvious that during the system lifetime the cooled water does not reach the pumping system.

Cross-sectional view of the cooled water injection impact is shown in Fig. 3.31. Individual images show the effect of cooled water injection into the geothermal structure at time steps 0, 20,000, 60,000, 100,000 and 200,000 days of continuous pumping and injection of 50 $l.s^{-1}$ water from individual wells. In this picture the progress of cooled water transport between wells can be seen.

Similarly, this progress shows Fig. 3.32, 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 3.34 shows results of heat transport modelling at different rates of pumped and injected water after 35 years.

The results of these simulations prove that while using the projected system the cooled and re-injected water does not arrive into pumping wells. This result is identical for all simulated rates of pumped and re-injected water. From Fig. 3.35, it is clear that the re-injected water only begins to influence the temperature in pumping wells after not less than 100 years of continuous use. This result demonstrates that the evaluated structure is theoretically suitable for utilization of heat by means of thermal water re-injection.

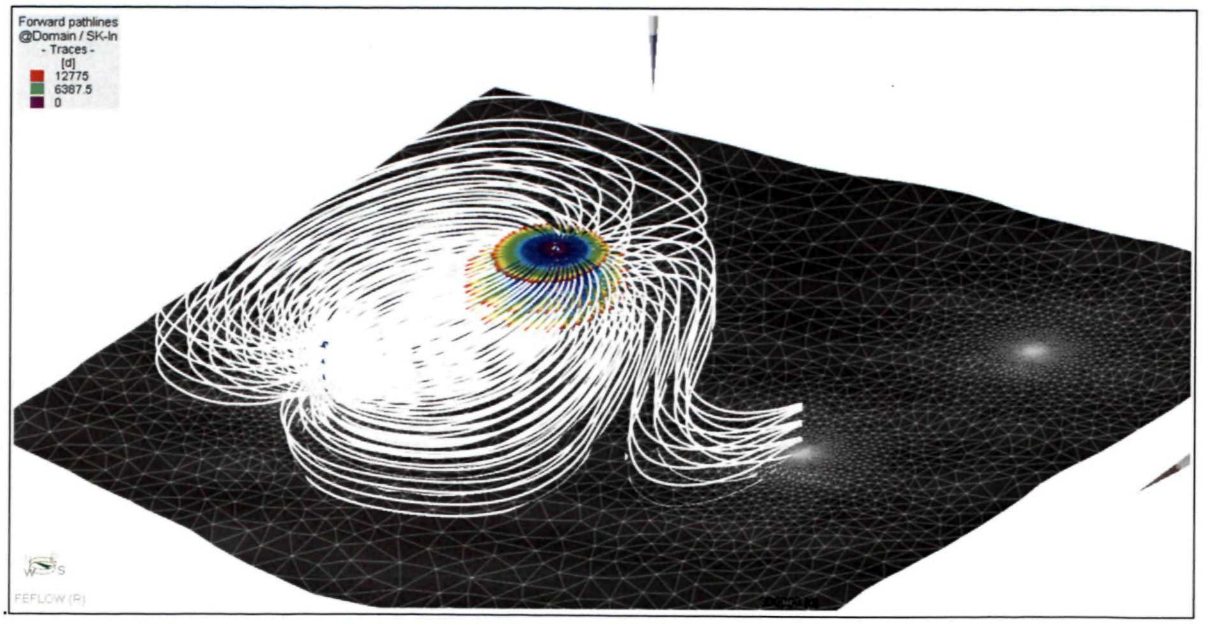


Fig. 3.30 Visualization of flow pathlines; white lines – long-term pathlines of water from Slovak-side injection well to pumping well; colour – travel time along pathline [days] 35 years after the operation start

3.4.4.6. Long-term impacts evaluation

Lastly, a thermal recovery of the structure was investigated, meaning that the time needed to return groundwater and rock matrix temperatures back to its pre-utilization state was questioned. To find the answer, a model was set up, in which starting water temperature and pressure conditions were the result of previous 35-years long utilization of a doublet system with the pumping/re-injecting rate of 35 $l.s^{-1}$. After 35 years the wells are

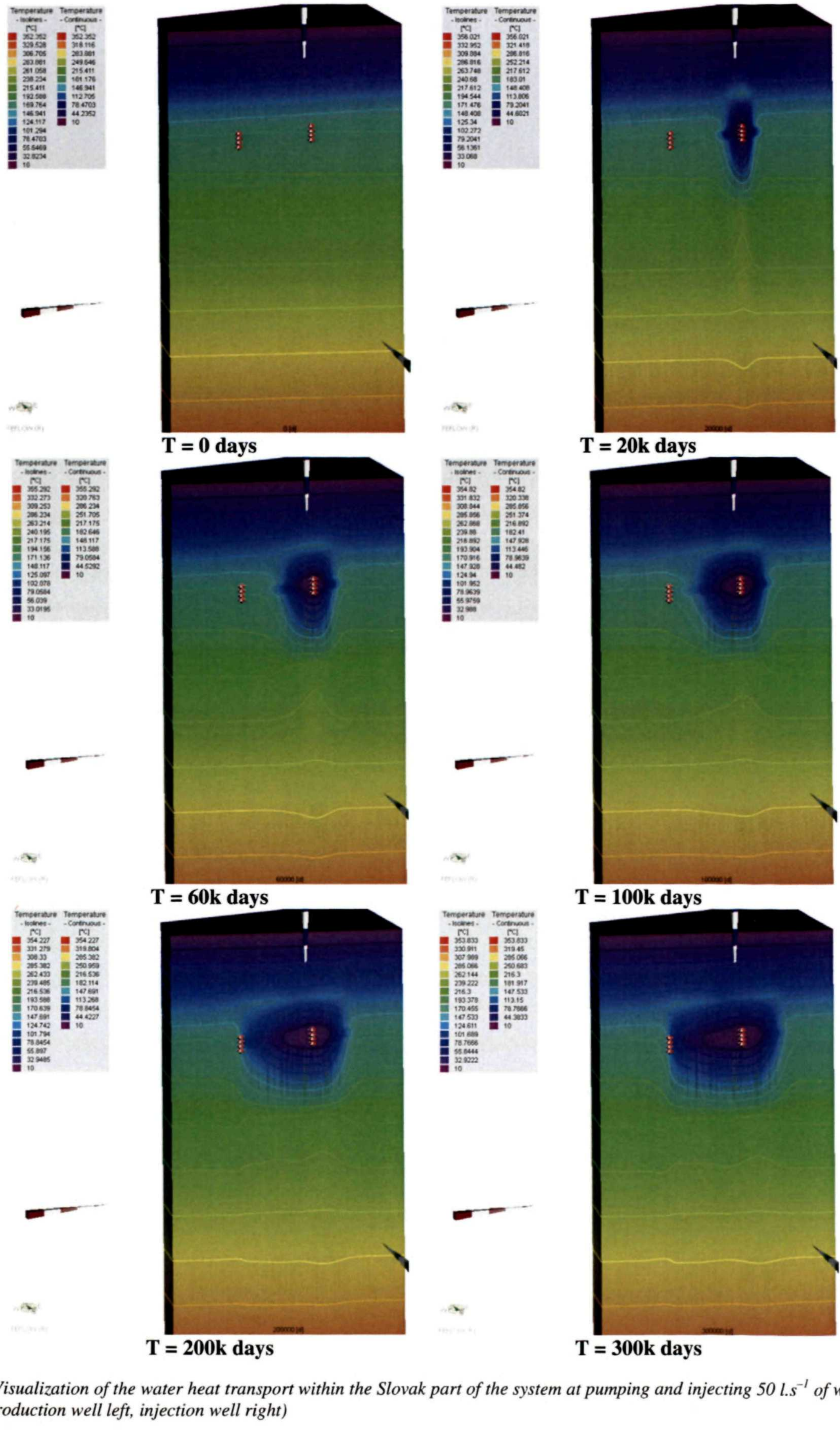


Fig. 3.31 Visualization of the water heat transport within the Slovak part of the system at pumping and injecting 50 l.s^{-1} of water in a doublet (production well left, injection well right)

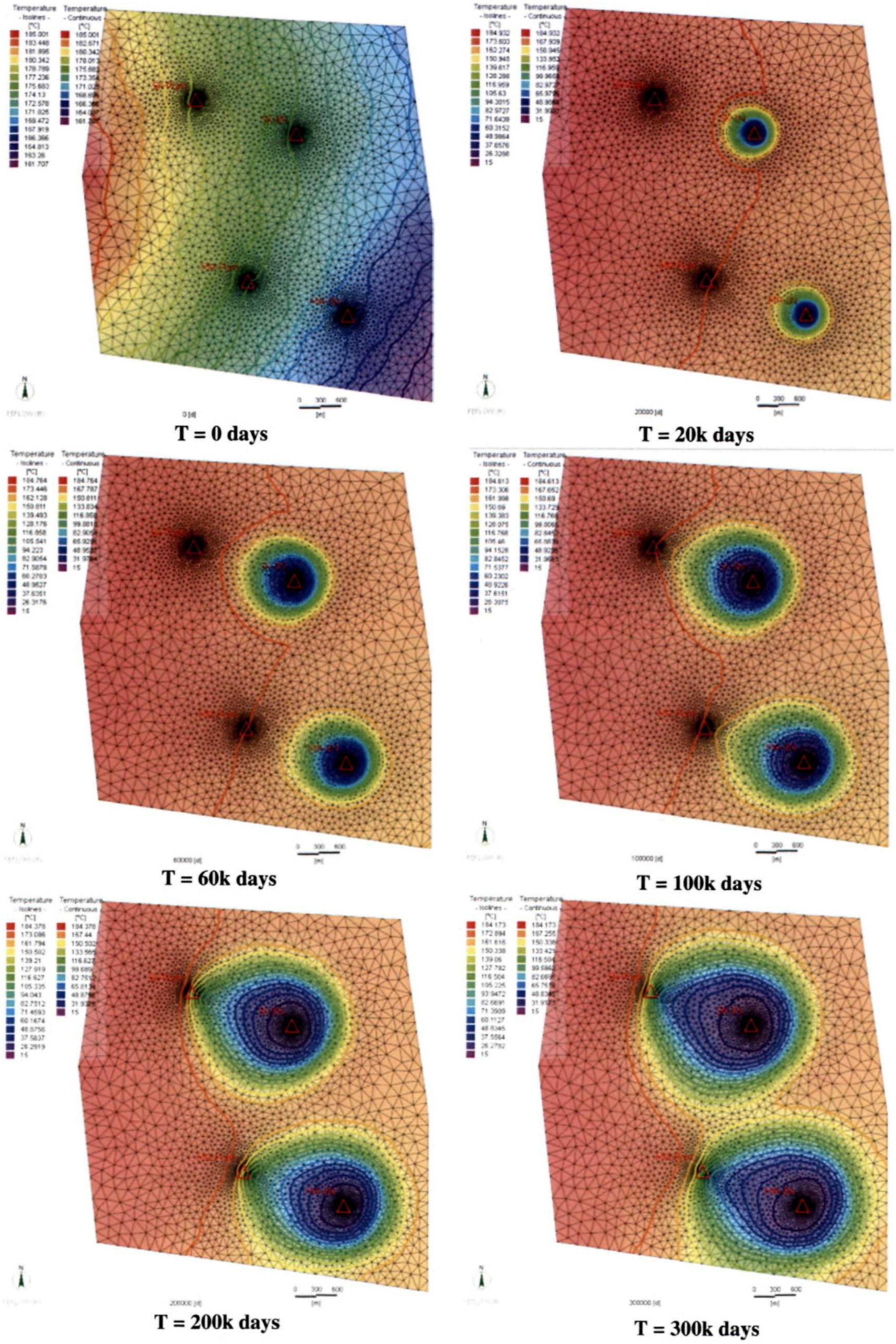


Fig. 3.32 Visualization of the thermal field development on the base of carbonate aquifer during pumping and injecting 50 $l.s^{-1}$ of water

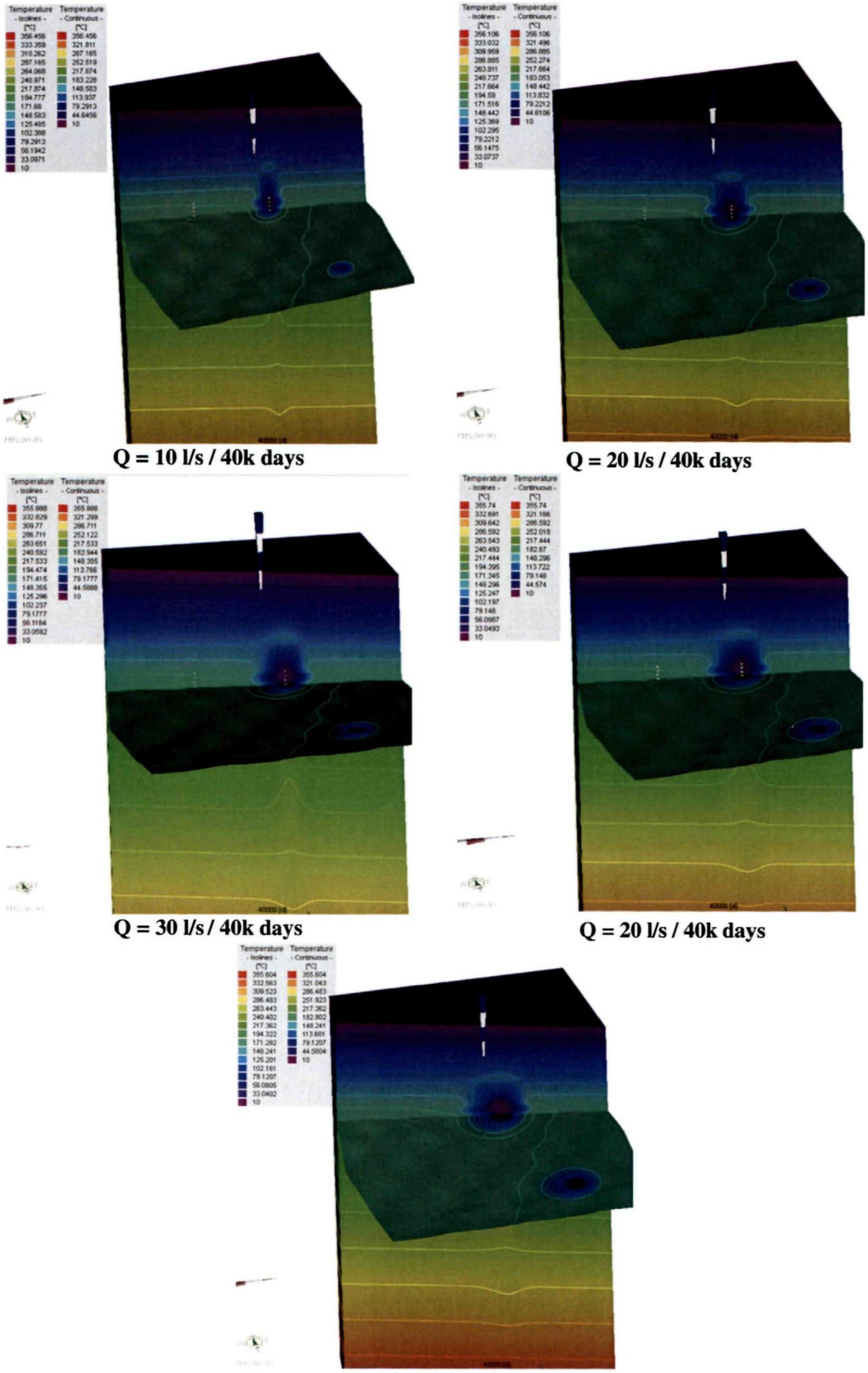


Fig. 3.33 Water cooling impact in geothermal aquifer at different levels of geothermal system utilization

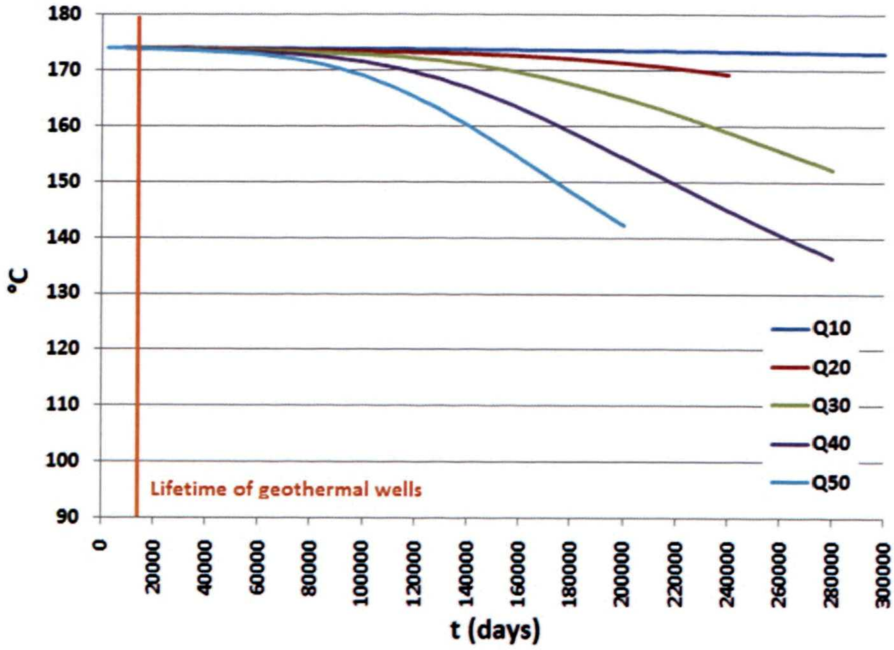


Fig. 3.34 The course of changes in water temperature in the pumping (production) well from the long-term point of view at different rates of pumped/injected water (Q, from 10 to 50 $l.s^{-1}$)

switched off and the thermal field of the structure begins to rebound. Because the carbonate structure is hydrodynamically closed (sealed), there is no direct water influx across the border and the only process that affects the water temperature is diffusion and heat conduction. The results of the simulation, depicted in the schematic Fig. 3.35, show that restoring of the disturbed thermal field can take as long as 2,500 years.

3.5. Conclusions

The aim of the numerical modelling was to simulate the hydrogeological and geothermal conditions in the geothermal aquifer of the Danube Basin. For the purpose of modelling 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 modelling layers. The coupled hydraulic and geothermal modelling of the Danube Basin pilot area was focused on Late Pannonian geothermal aquifers. The constructed models show simulations of natural hydrogeological and geothermal conditions, expected to have existed before utilization of thermal waters by artificial pumping started. This scenario is compared to hypothetical conditions of continuous pumping of geothermal water, 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 enables 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-exploitation.

In Pre-Quaternary rock formations conduction is the main mechanism for heat transport. Due to relatively intensive water interchange among recharge and discharge zones in the Quaternary sediments, forced 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 modelling 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.

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, favouring re-injection.

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

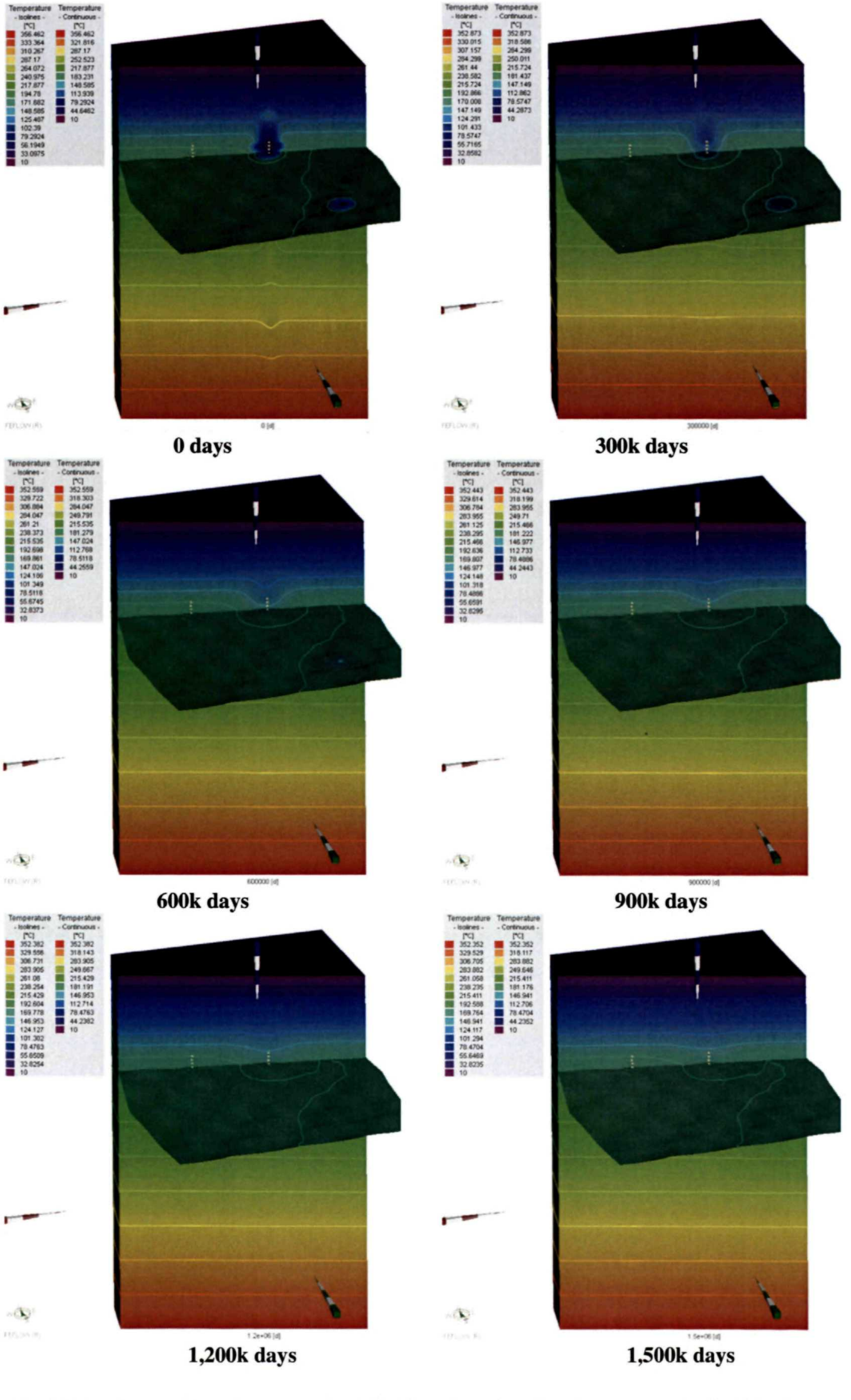


Fig. 3.35 Simulation of thermal recovery of an isolated geothermal aquifer after 35-years of a doublet utilization

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• Modelled closed hydrogeological structure made of the Mesozoic carbonates is suitable for use by re-injection.

• It was found that re-injected cooled water within a period of system lifetime (35 years) does not affect pumping wells, what has a positive effect on the system performance and payback.

• Provided 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 $l.s^{-1}$ without affecting the lifetime of the system.

• Parallel coexistence of two re-injection systems does not interact with each other.

• After system closure, restitution of thermal field back to the original state can take a very long time, but this effect has relatively small spatial extent.

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