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SUMMARY REPORT OF THE STEADY-STATE MODELLING

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1 INTRODUCTION

The aim of the Transenergy project is to support the harmonized thermal water and geothermal energy utilization in the western part of the Pannonian Basin and its adjacent basins (e.g. Vienna Basin), which are situated in the transboundary zone of Austria, Hungary, Slovak Republic and Slovenia.

During the day to day day management of thermal-water systems, a tool is needed to provide the decision makers with information about the future responses of the system to the effects of various interactions, as well as about available hydrogeothermal resources. This tool can be based on the results of different models. A model is defined as a simplified version of a real system (in this case a thermal water system) that approximately simulates the relevant interaction-response relations of the real system. Since the real systems are very complex, there is a need for simplification during modelling which provides information for planning and management decisions. The aim of this report is to describe the results of various models, highlighting the challenges and their solutions.

The problems of the trans-boundary thermal water utilization are sometimes locally limited, but sometimes they are related to distant hydrogeological processes, too. Therefore the modelling activity was done at two different scales (Figure 1).

The uniform system approach consisted of a series of conceptual and numerical models building on each other. Both in the supra regional and the local modelling areas these were the following:

- Geological models
- Hydrogeological (including hydrogeochemical-, flow-, and transport) models
- Geothermal models

The aim of the *geological model* was to set the common geological background (crossborder correlacion of the geological formations and units with description of their lithology and stratigraphic classification) for the hydrogeological models. The main geological units with similar hydrogeological characteristics define hydrostratigraphical units, which are one of the key inputs into the hydrogeological models.

The *hydrogeological models* described the groundwater flow systems. Hydrogeological models serve as the basis of prediction the effects of hydrological changes in the aquifer. Hydrogeological models were calibrated and verified by h*ydrogeochemical models*. The hydrogeochemical model (as part of the hydrogeological model) helped to recognize and understand the ongoing processes in the thermal water resevoir systems.

The *geothermal model* expressed the temperature distribution in the 3D and its possible changes, whose distribution is determined by the heat flow and thermal water flow. The geothermal model developed based on the hydrogeological flow model.

The aim of this report is to determine the work flow, the methods and the results of different models.

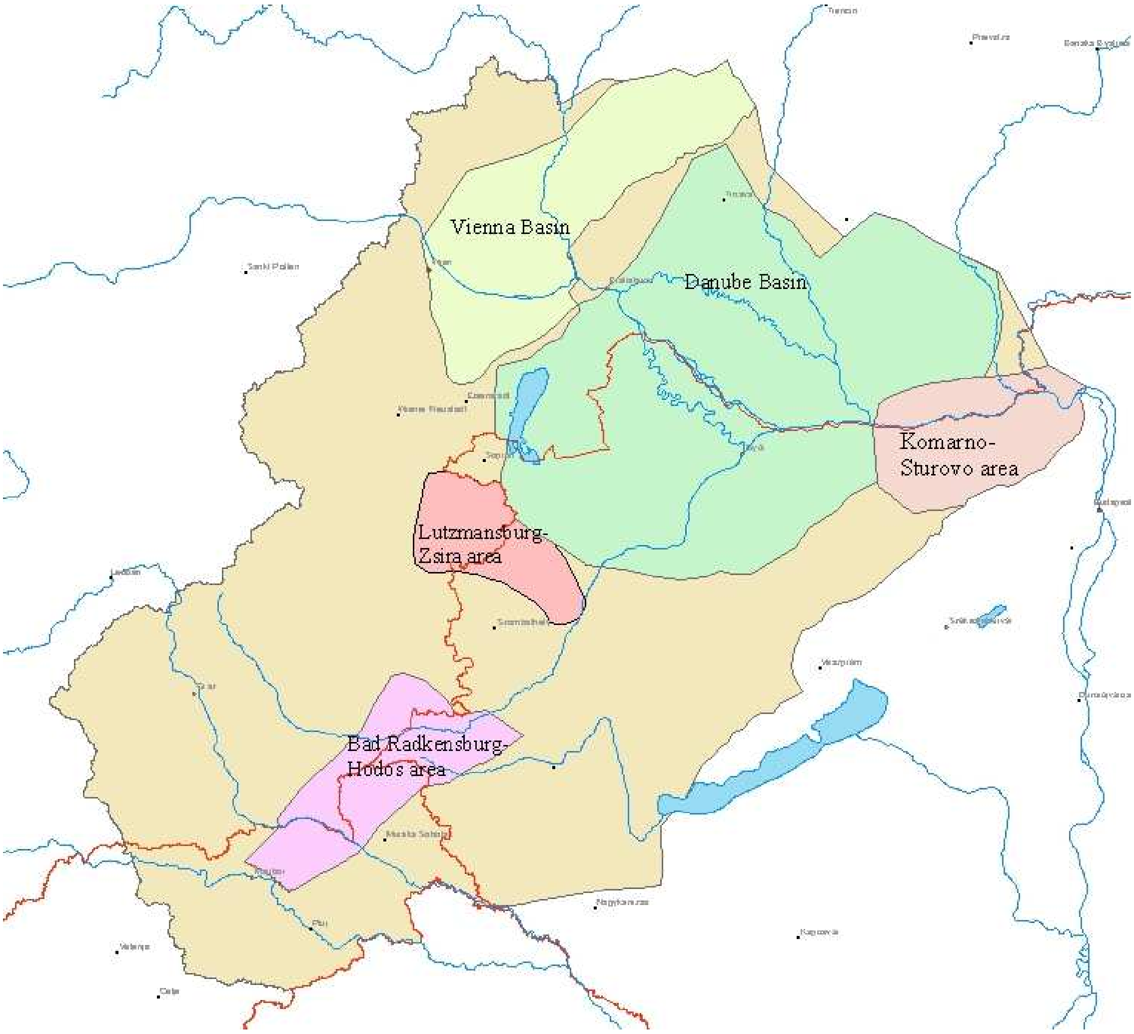


Figure 1. The supra-regional and the regional model areas

2 SUPRA-REGIONAL MODELS

The so called ***supra regional model*** includes the entire project area. The supra regional model handles this area in a uniform system approach. It has given an overview on the large-scale geological, hydrogeological and thermal characteristics of thermal water flow systems in the western part of the Pannonian Basin. Thus, we could also determine the connection among the main groundwater bodies that sometimes have very different geological-hydrogeological features. The scale of the supra-regional model was 1:500 000.

2.1 Geological model

Geological model serves as the framework and puts in relation lithogical and stratigrapical units through correlation of different formations that can be found across the state borders. For the purpose of the project the correlation table was compiled with definition of the specific symbol used for TRANSENERGY project area. Based on that, geological, hydrogeological and geothermal models were compiled. Geological models provide basic information for determining the rock-properties set of a given point in space, on the basis of which hydrogeological and geothermal models run.

2.1.1 Applied methods

2.1.1.1 Basic principles

Geological models were compiled based on known geological setup in project countries, published reports, maps and publications. Available boreholes and wells from common project database and seismic profiles were re-evaluated into certain extent. As written above, the correlation of geological units is crucial in the project area and sets the common background for hydrostatigraphic units delineation used in hydrogeological and geothermal models. . Hydrostratigraphic units are the following delination of the geological units with the same hydrogeological properties. They are defined on the basis of well-known stratigraphical units, and may comprise a wide range of different formations.

Hydrogeological and geothermal models require not only the hydrostratigraphical units, but surfaces which border them (various geological depth-contour maps). The constructed maps represent the interface of these geological units. In general we compiled the lower surfaces what we call base map. The base map plots formations below the given geological age and the topographic position of the formations below see level.

All the hydrostratigraphical units, geological surfaces and maps were combined in a 3D model. The vertical boundary of the geological models has been defined at the depth of 8000 m below see level.

2.1.1.2 Harmonized geological information

The most important task was the harmonization. For the purposes of the project the catalogue of commonly used names concerning the regions and formations were elaborated. The outputs from the geological unit harmonization is strictly for the project purposes and does not substitute the competence and results of the correlation committees.

One of the first data harmonization steps had to be the correlation of different formations. These formations describe sometimes the same lithologic and time frame of the geological buildup of a partner country with different synonymes, but more often the different names can cover slightly different rock columns as well. Harmonization started during compiling the surface geological map. Then the harmonized legend is applied for all model horizons (e.g. Pre-Sarmatian, Pre-Badenian etc.) and for the geological sections, too. Here, inevitably new formations appeared which were incorporated into the legend.

Another source of legend symbols was the database of boreholes. In those cases, where it was not possible to resolve all appropriate formations, we had to create sum-up legend units and symbols. Harmonizing borehole data needed re-evaluation of borehole information.

The unified legend and indexes were created following the philosophy of the OneGeology project. Annex I. ("Summary report of geological models" Maros et al. 2012) contains the harmonized geological formations and indexes.

To develop the harmonized legend, the scale of the maps and sections, and the agreement with a common symbol system was essential.

Time by time iterations and cross-checkings were made between the surface map, the horizont-maps, boreholes and the sections. At the end we had 197 legend units.

During the processing of the different geological surfaces, the heterogenity of available data among the project countries was the main problem. Input datasets included final grids, existing maps with isolines, geological and geophysical data, as well as geological maps. All these different of data had to be harmonized, especially along state borders.

2.1.1.3 Definition geological time horizons corresponding to hydrostratigraphical units – the buildup of the geological model

The hydrostratigraphic units are composite units which encompass different geological formations with the same hydrogeological properties.

One of the aims of the project was to delineate these main hydrostratigraphic units connected to different geological formations of certain age and lithology. The compiled model maps show the interface of these hydrostraigraphic units. In general, we compiled the lower interface, called base map. The base map shows formations appearing just below a given age horizon and the topographic surface of these formations above see level for the distribution area of the formations. For instance, the Pre-Badenian horizon map shows the surface grid and geological formation patches of pre-badenian age below the badenian rock's distribution area. So, building the model upward from the lowermost model map, the model space is filled up with all ages and formations without gaps.

The supra-regional geological model is a so called "flying carpet" model, which means that instead of a voxel model, surfaces encompass the surface space grid and geological database informations (Annex I, Maros et al. 2012). The main difference between the supra area and the pilot areas models is that only the pilot models contain modelled tectonic surfaces, and these model grids were edited more accurately based on the evaluations of 2D seismic section series and gravitational, magnetotelluric modelling.

The modeling of the Supraregional area was carried out primarily in ArcGIS (ESRI ArcGIS Desktop 9.2 and 10 versions, 3D Analyst, Spatial Analyst, as well as Surfer 10.

As a first step of modeling, an expert outlined the distribution area of the formations of a given horizon. This was based on borehole data and surface outcrops. Then after the combination of various data, the isolines of the given horizon were edited, which were interpolated by ArcGIS 3D Analyst.

Verification of the consistency between the well data and the created model-horizons was carried out by the JewelSuite 11 geological modelling software.

2.1.2 Results of the geological model

As a result of supra-regional geological model the most important hydrostratigraphical units are the following:

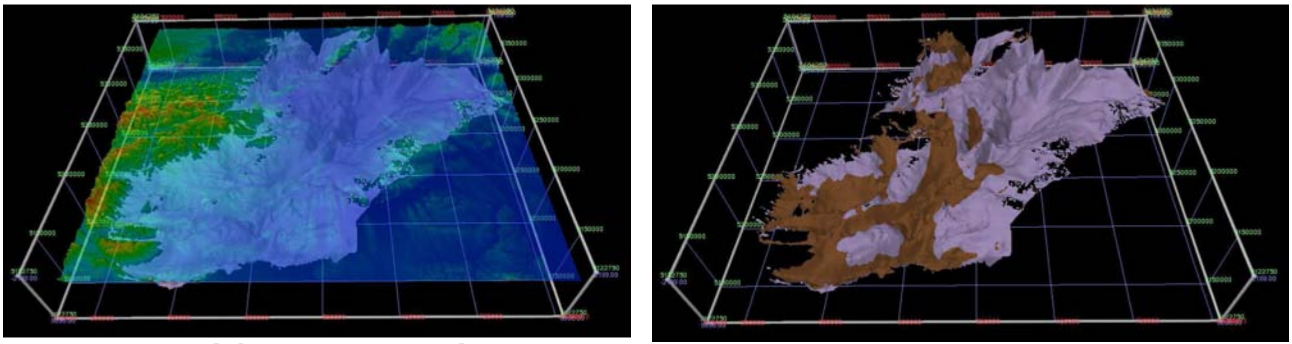
Supra regional area hydrostratigraphical units	***Supra regional area geological model maps***
Holocen-Pleistocen alluvial systems along the main rivers, Quaternary formations in the deep basins	Quaternary covered geological map (Encl.1.1.)
Upper Pannonian sediments	Base of the Quaternary formations (Pre-Quaternary) (Encl. 1.2., 1.3.)
Lower Pannonian sediments	Base of the Upper Pannonian formations (delta front sand) (Encl. 1.4., 1.5.)
Sarmatian sediments	Base of the Lower Pannonian formations (Pre-Pannonian) (Encl. 1.6., 1.7.)
Badennian sediments	Base of the Sarmatian formations (Pre-Sarmatian) (Enc. 1.8., 1.9.)
pre-Badennian sediments	Base of the Badenian formations (Pre-Badenian) (Encl. 1.10., 1.11.)
Paleogene formations	Base of the Pre-Lower Miocene formations (pre-

	Neogene) (Encl. 1.12., 1.13)
Post Triassic Formations	Base of the Cenozoic formations (pre-Cenozoic) (Encl. 1.14., 1.15)
Triassic karstified limestone and dolomite complex	Base of Senonian formations (pre-Senoniain) (Encl. 1.16., 1.17.)

The basement map and of each hydrostratigraphical unit was constructed. On the basis of geological surfaces different lithological and worm-eye maps were constructed too.

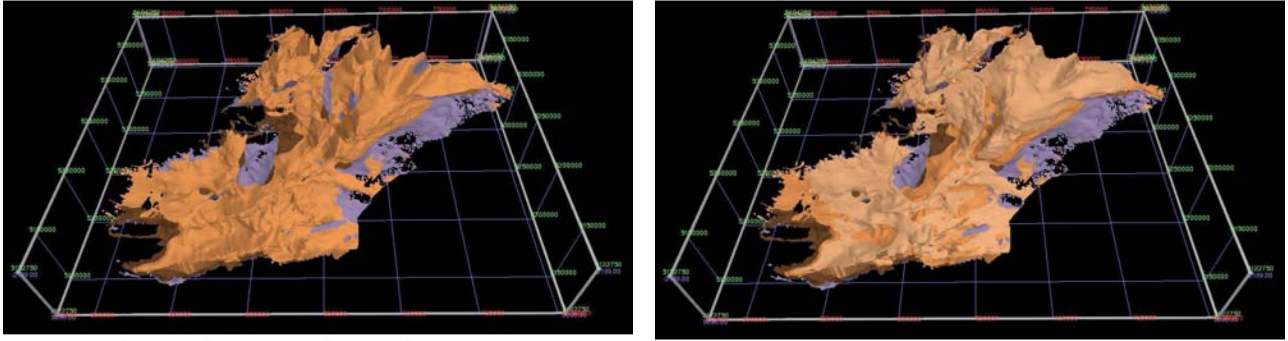
The results and detailed description of the geology of the supra-region can be found in Annex I. ("Summary report of geological models" (Maros et al. 2012) (Figure 2). The report cointains:

- detailed description of applied methods in model developing,
- descripton of the elements of correlated formations and harmonized legend,
- summary of the geological build-up,
- compiled contoured maps and cross-sections.



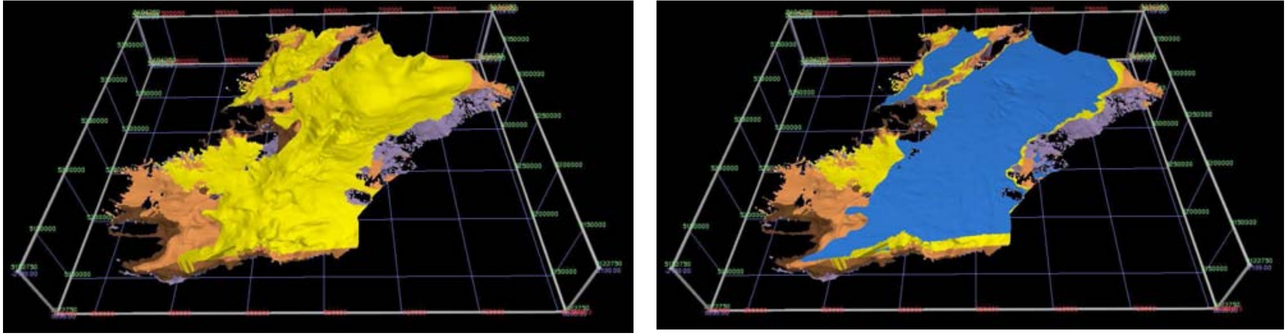
SRTM and the Pre-Cenozoic horizon

Pre-Cenozoic and the Pre-Neogene horizons



Pre-Badenian horizon above the Pre-Neogene

Pre-Sarmatian horizon on the top



Pre-Pannonian horizon on the top

Pre-Upper Pannonian horizon on the top

Figure 2. The SRTM model and different subsurface geological model horizons from the South (5x height exaggeration).

2.2 Hydrogeological model

The aim of the supra-regional hydrogeological model is to give an overview on the large-scale hydrogeological processes of thermal water flow systems in the western part of the Pannonian Basin. Thus, the connection among the main groundwater bodies (that sometimes have very different geological-hydrogeological characteristics) can be determined.

The so called supra regional model includes the entire TRANSENERGY project area. The supra regional model handled this area in a uniform system approach. A steady state three dimensional groundwater flow model was constructed, calibrated, and used to describe regional flow of the project area.

2.2.1 Conceptual model

The first step in the modeling process is the construction of a conceptual model consisting of a set of assumptions that verbally describe the system's composition, the ongoing processes that take place in it, the mechanisms that govern them, and the relevant medium properties. The conceptual model was based upon the detailed hydrogeological and hydrochemical characterisation of the model area. The conceptual model of the supra-regional hydrogeologic model can be found in Chapter 3 (General description of the Supra-Regional Area) of Annex II., "Summary report of the supra-regional hydrogeological model" (Tóth et al. 2012).

2.2.2 Applied software

Input data needed for the hydrogeological models are 3D surface managers and GIS softwares, of which the following have been used: Diger, Surfer, ArcGIS. Grapher, Microsoft Access and Microsoft Excel have been used for the evaluation of hydrogeochemical data, and other spreadsheet management.

Once input data have been prepared and the conceptual model was translated into a mathematical model in the form of governing equations, with associated boundary and initial conditions, a solution was obtained by transforming it into a numerical model.

The Visual Modflow is a very commonly used software packages in the hydrogeological modelling practise. They are useful for different purposes.

MODFLOW is a three-dimensional finite-difference groundwater model, which is a computer code that solves the groundwater flow equation. It has ability to simulate a wide range of different systems. MODFLOW has become the worldwide standard ground-water flow model. Currently, there are at least five actively developed commercial and non-commercial graphical user interfaces for MODFLOW. It consists of a Main Program and a series of highly-independent subroutines called modules. The modules are grouped in packages. Each package deals with a specific feature of the hydrologic system which is to be simulated such as flow from rivers, or flow into drains, or with a specific method of solving linear equations which describe the flow system such as the strongly implicit. The division of MODFLOW into modules permits the user to examine specific hydrologic features of the model independently. This also facilitates development of additional capabilities, because new modules or packages can be added to the program without modifying the existing ones. The input/output system of MODFLOW was designed for optimal flexibility.

Visual MODFLOW (VMOD) is a graphical interface for MODFLOW. The program also combines proprietary extensions, such as MODFLOW-SURFACT, MT3DMS (mass-transport 3D multi-species) and a 3D model explorer. Visual MODLFOW supports MODFLOW-2000, MODFLOW-2005, MODFLOW-SURFACT, and SEAWAT (Integrated

Modeling Environment for MODFLOW, MODPATH, MT3D). Visual MODFLOW provides professional 3D groundwater flow and contaminant transport modeling using MODFLOW-2000, MODPATH, MT3DMS and RT3D. Visual MODFLOW Pro seamlessly combines the standard Visual MODFLOW package with WinPEST and the Visual MODFLOW 3D-Explorer to give the most complete and powerful graphical modeling environment available.

2.2.3 Strategy and basic steps (workflow of the construction of the Supra model)

Developing the model started with simple 2D version and gradually (step by step) became to a more complicated 3D model version. This kind of model development ensures the reliability of the model in every phase.

First two different models were developed, a model considering the porous porous aquifer complex of Neogene formations and the basement model.

In the beginning of model development assigning conductivity values was simple. In the porous model each layer was assigned a global horizontal hydraulic conductivity with a global anisotropy. Vertical conductivity was assigned 3 orders of magnitude lower values (in comparison to the horizontal one). The prior values came from our former large-scale modeling experiences. These initial values were somewhat modified in the calibration phase.

For calibrating the porous model existing reconstructed equipotential maps for the cold and thermal confined system were used. Monitoring well data were used only for those parts, where reconstructions did not exist for the pre-exploited state. In the case of the deeper, high temperature zones, we had to correct the measured heads and pressures, taking into consideration the vertical distributions of the density. In this part the density usually decreases with depth, because of the high temperature gradient and a relatively low salt content. (There are no sign of free convection here, because of the low vertical conductivity of the porous basin fill sediments). At the end of the mentioned correction procedure, we got the so called environmental head relative to the shallowest cold parts (Lusczynski 1961).

The assigning of conductivity values in the basement model, the basement was split into an upper aquifer with better permeability, and into a lower one with poor permeability. The upper basement aquifer got unique parameters. However in reality it consists of regionally altering sub-systems with good (weathered, karstified mantle) and poor permeability. Furthermore in some sub-regions this unit is connected to the first permeable sediment layer. These interconnected basement and sedimentary reservoirs are of great importance.

For the calibrations of the basement aquifer complex, the reconstructed original, pre-exploited karst-water table maps, and some monitoring points were used. In the vicinities of larger thermal and luke-warm springs, the chemistry and the isotopic composition were used to give information about the mixing processes around the springs.

Finally, having the same model grid the physical merging of the two models was done by adding the basement layer to the porous model. All the applied boundary conditions and calibration elements were used in the merged model.

The detailed description of the model (model grid, hydrostratigraphical units, boundary conditions, calibration targets) can be found in Annex II., “Summary report of the supra-regional hydrogeological model” (Tóth et al. 2012).

2.2.4 Results of the model

The major outputs of the Supra Regional model are the following:

- computed shallow groundwater table, confined cold and thermal water heads in the porous parts, karst and fissured water table and thermal karst water heads (Figure 3 and Figure 4);
- computed flow lines, groundwater velocities and directions in 3D
- computed discharge at the major springs and at other discharge objects (rivers, seepage faces);
- computed and aggregated drawdown of the production wells;
- computed budgets of the major delineated groundwater bodies, including trans-boundary water transfers.

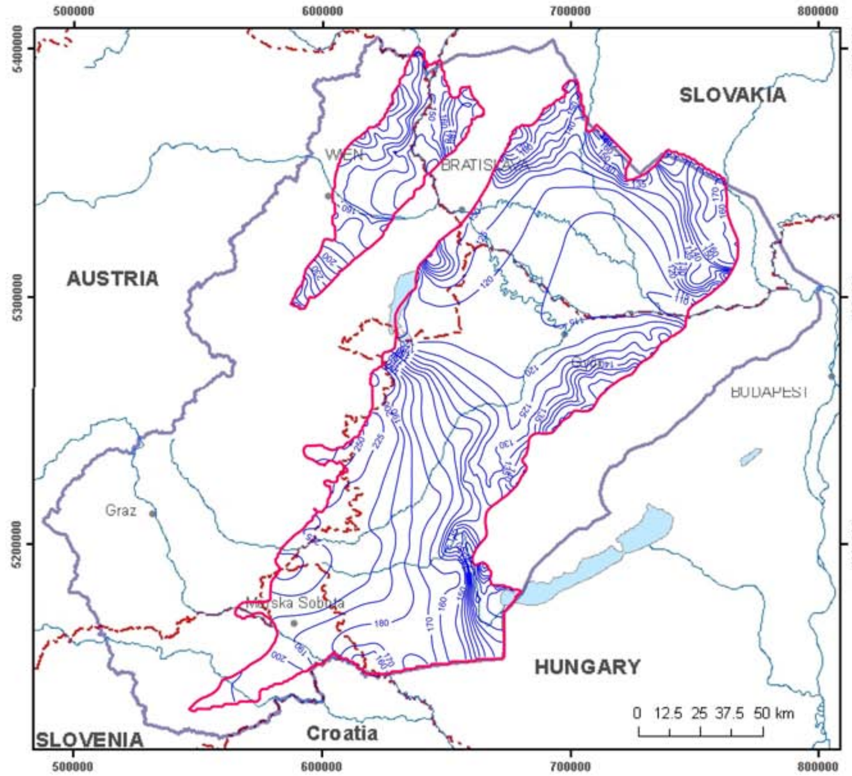


Figure 3. Maps showing hydraulic heads of the cold water aquifer layer of the Upper Pannonian (Model layer 3)

Figure 5 was compiled on the basis of the results of hydrogeological modelIt shows that major groundwater flow existing between the cold and thermal groundwater bodies and the thermal water flows through the national borders. The budget of these transboundary zones are calculated by the supra-regional model (Figure 5, Table 1. **Table**).

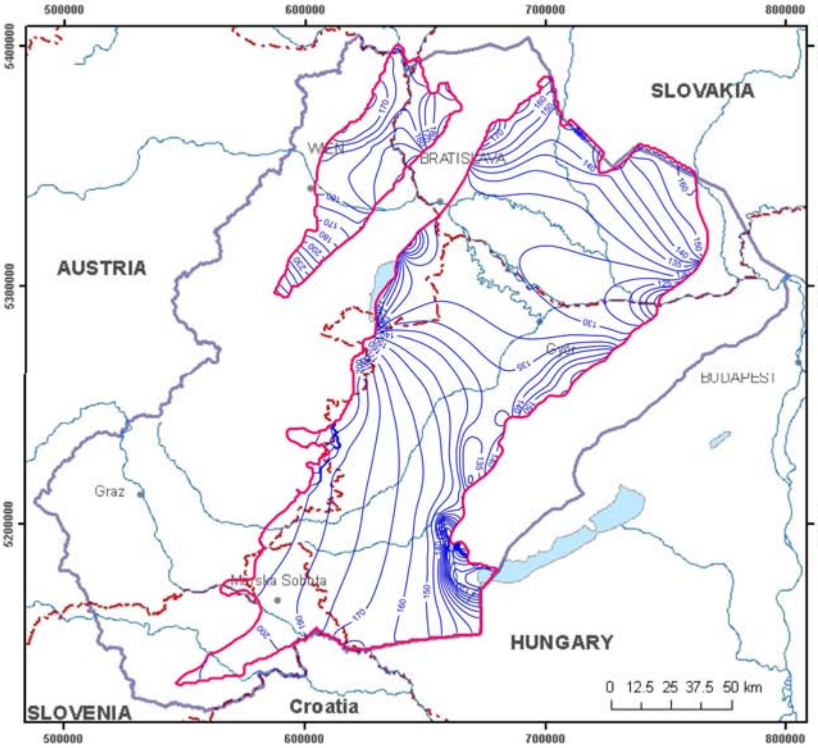
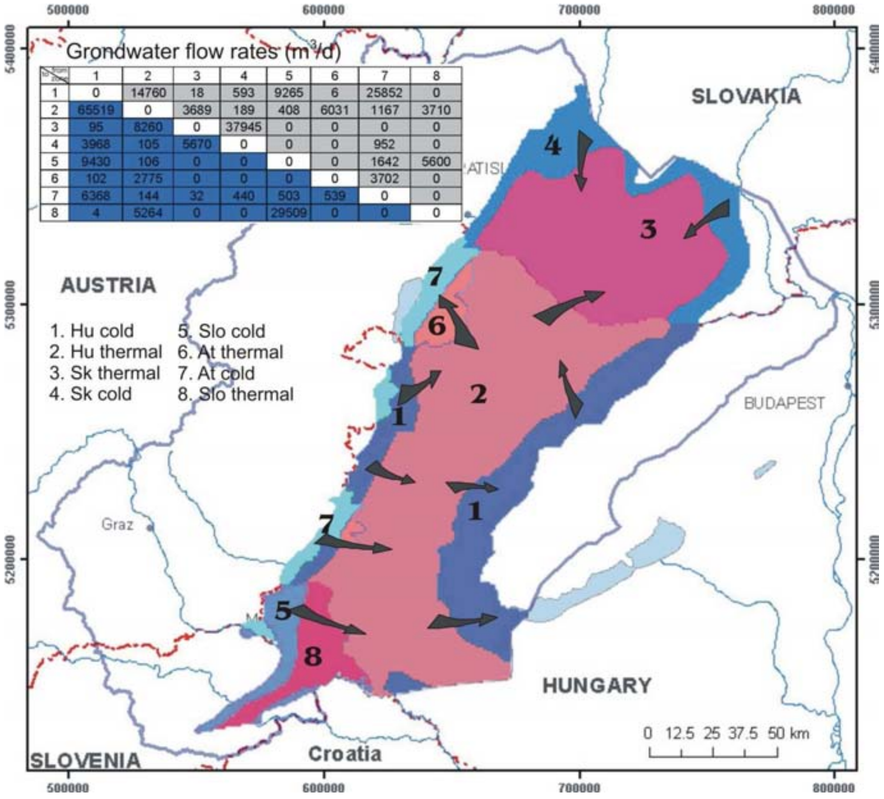


Figure 4: Maps showing hydraulic heads of the thermal water aquifer komplex of the Upper Pannonian (Model layer 6)



Grondwater flow rates (m³/d)

	1	2	3	4	5	6	7	8
1	0	14760	18	593	9265	6	25852	0
2	65519	0	3689	189	408	6031	1167	3710
3	95	8260	0	37945	0	0	0	0
4	3968	105	5670	0	0	0	952	0
5	9430	106	0	0	0	0	1642	5600
6	102	2775	0	0	0	0	3702	0
7	6368	144	32	440	503	539	0	0
8	4	5264	0	0	29509	0	0	0

Figure 5: Main flow directions between cold and thermal water

1. Table demonstrates the possible water transfers between the cold and thermal groundwater bodies. It also gives information on the trans-boundary budgets. Similar tables can be produced for the present state abstractions, or any reasonable scenarios. The supra-model can be used this way also for the trans-boundary management purpose.

The supra-regional model is a unique hydrogeological flow model both in scale and regarding its the transboundary character. It is based on a special theory of combining the upper porous and the lower basement model of the fractured-karstified formations.

1. Table: Zone budget of the transboundary areas (values are in m^3/d)

		To								
		Cold unconfined (14)	AT Cold confined Pa2 (11)	AT thermal Pa2 (10)	SK Cold confined Pa2 (7)	SK thermal Pa2 (6)	SLO Cold confined Pa2 (8)	SLO thermal Pa2 (12)	HU Cold confined Pa2 (4)	HU thermal Pa2 (5)
From	Cold unconfined (14)		**24180**		**63250**		**15330**		**101410**	
	AT Cold confined Pa2 (11)	**10840**		**1570**	**390**	**2**	**910**		**22320**	**390**
	AT thermal Pa2 (10)		**2480**						**60**	**1960**
	SK Cold confined Pa2 (7)	**73620**	**150**			**16960**			**610**	**100**
	SK thermal Pa2 (6)	**180**			**20510**				**130**	**8560**
	SLO Cold confined Pa2 (8)	**14540**	**460**					**11690**	**9800**	**440**
	SLO thermal Pa2 (12)						**8360**			**6650**
	HU Cold confined Pa2 (4)	**144660**	**6570**	**90**	**3410**	**60**	**9170**	**1**		**30470**
	HU thermal Pa2 (5)	**330**	**170**	**2690**	**170**	**2560**	**550**	**2720**	**36700**	

The most important result of the supra-regional hydrogeological model is providing an overview on the hydrogeological thermal water flow systems of the entire TRANSENERGY project area. The relation between the main thermal water regimes was determined. Cross-sections in Figure 6-Figure 9 show the Supra-regional main flow systems and flow directions.

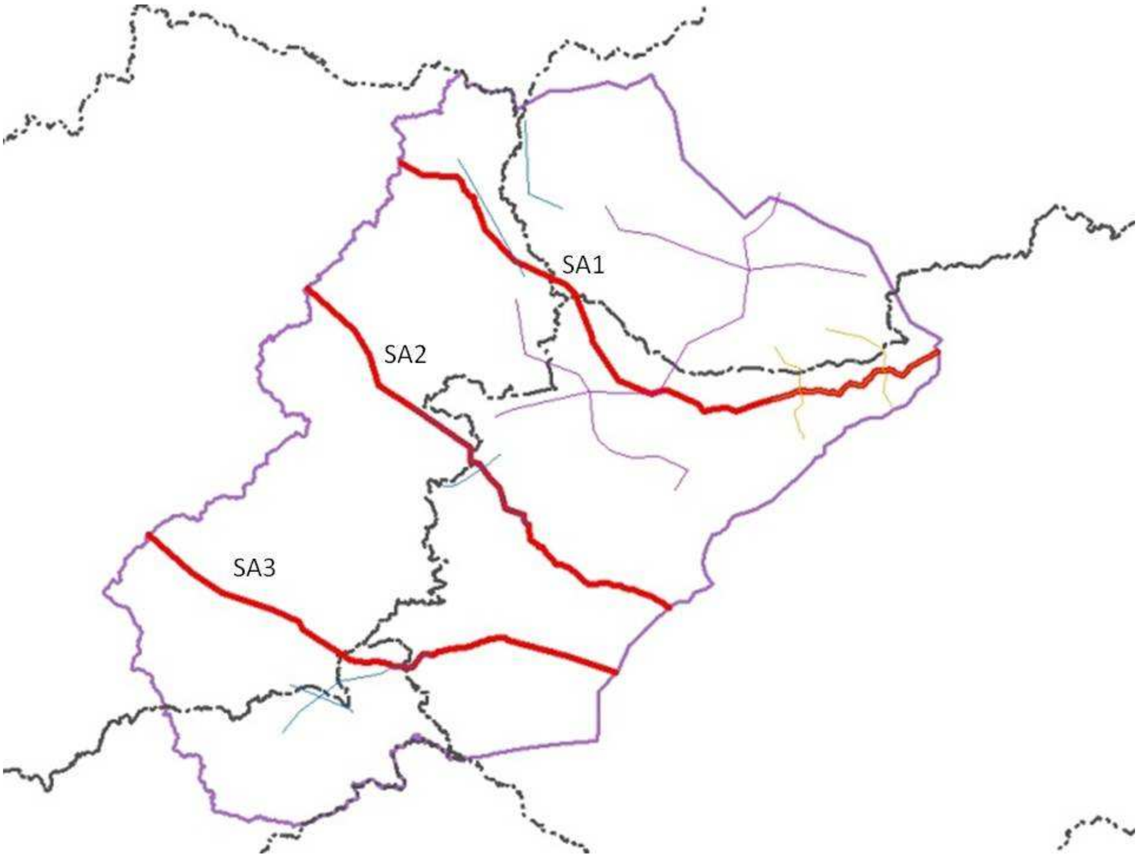


Figure 6: Position of hydrogeological cross-sections

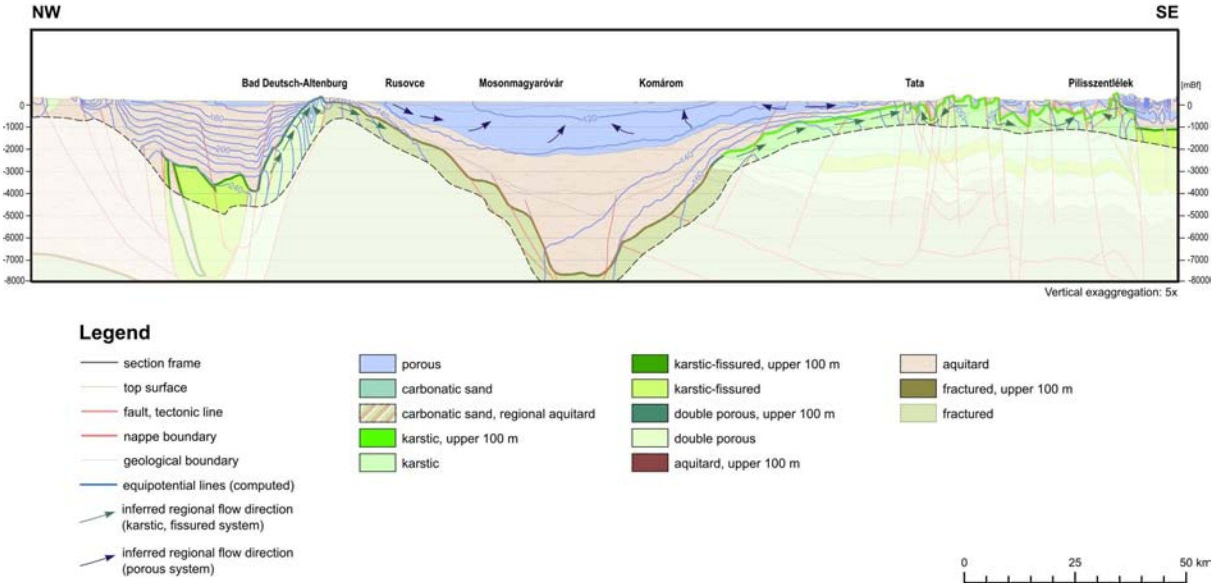


Figure 7: SA1 Hydrogeologeological cross-section

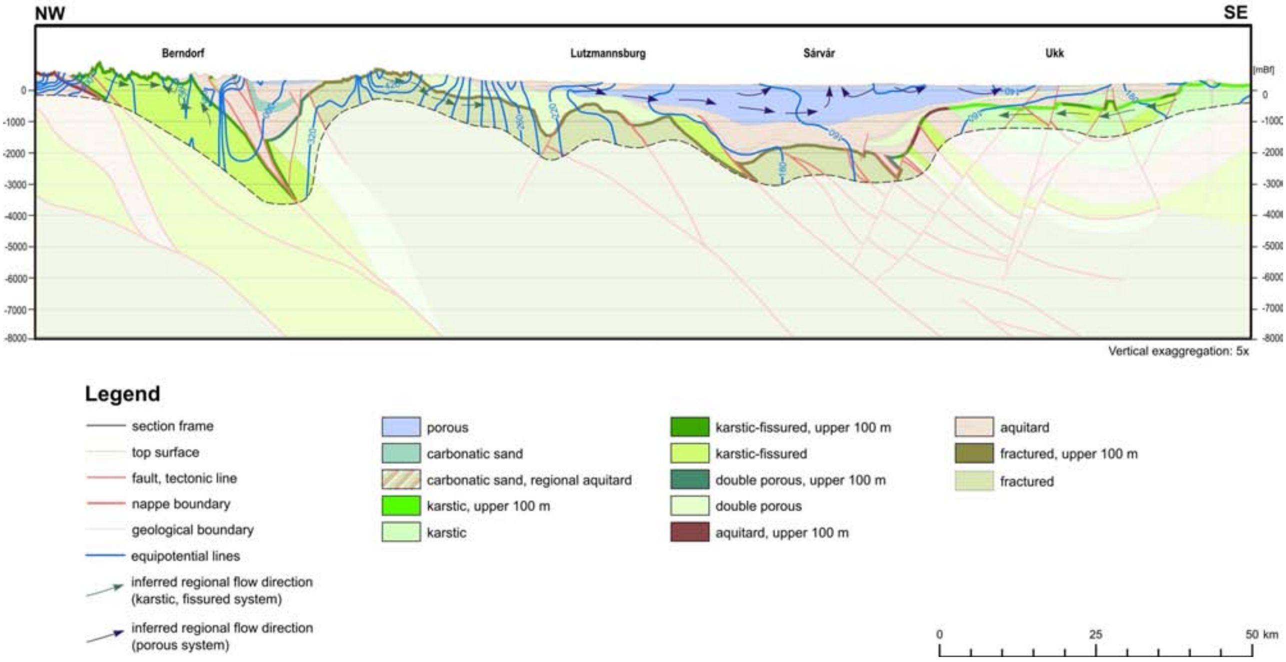


Figure 8: SA2 Hydrogeologeological cross-section

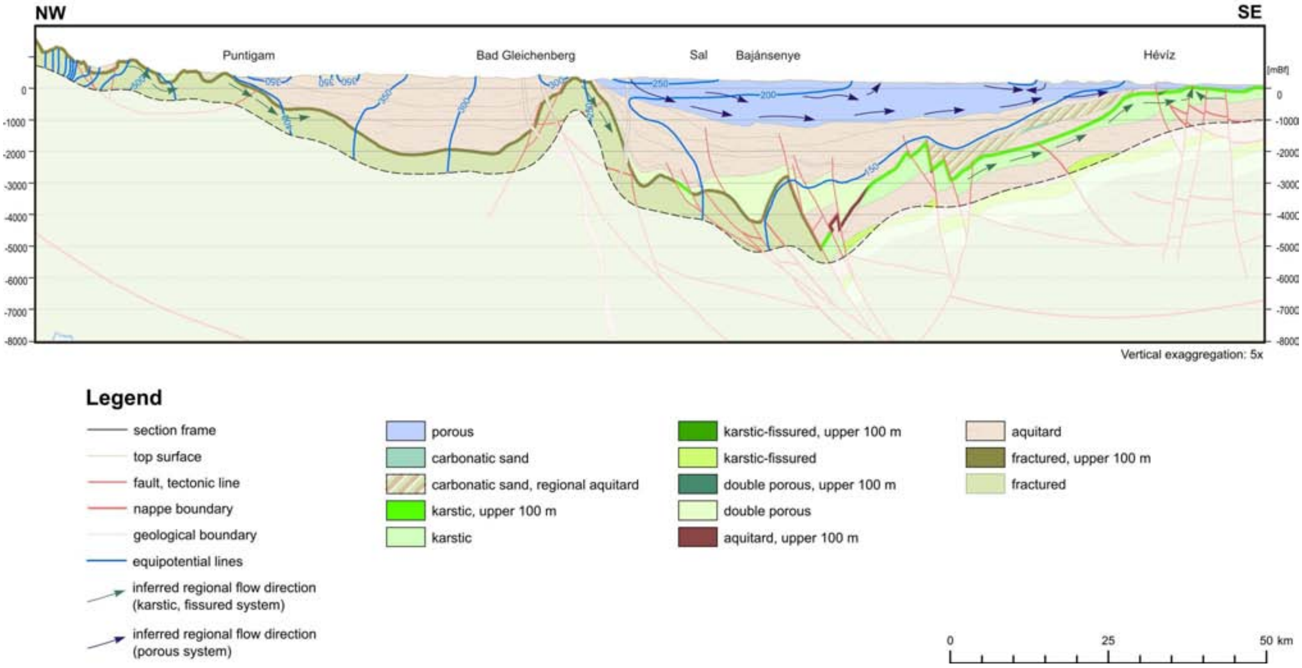


Figure 9: SA3 Hydrogeologeological cross-section

The calibrated model was used to calculate the groundwater budget components of the delineated cold groundwater and thermal water bodies across the different parts of the country borders. Furthermore, the supra-regional model will serve as a basis for the pilot models. The model is ready:

1. for scenario evaluations, modeling the drawdown (depression effects) of different production states jointly evaluated by the experts of the partner countries,as an important input for the management recommendations;

2. for hydrogeochemical and isotope-hydrological evaluations by its quantitative information on the flow systems, like flow-lines, velocities, budgets, and vice versa: the model is ready for developing the age and detailed mixing information of the region: connection to the hydrogeochemical studies;

3. for the coupled flow and transport models, especially for the regional pure convective and density (buoyancy) driven heat transport system: connection to the geothermal evaluations;

4. for the construction of the pilot study areas, by providing them concept, prior parameters, boundary conditions and formulating questions raised on during supra modeling

2.3 Geothermal model

One of the goals of the geothermal modelling at supra-regional scale was to present an overview of the geothermal conditions for the entire project area in order to enhance the awareness and understanding about existing resources. Furthermore geothermal boundary conditions could be determined for regional scale geothermal models within the pilot areas. Based on that, the geothermal potentials and resources within the area could be estimated to allow a sustainable (and balanced) utilization of the existing hydrogeothermal resources.

Geothermal resource assessment was accomplished by a 3 level approach (Figure 10):

i. Supra-regional scale 1:500.000 covering the entire project area
ii. Regional scale (1:100.000 up to 1:200.000) for selected pilot areas
iii. Local scale (<1:100.000) for selected geothermal reservoirs within the pilot areas.

Considering the different operating scales, the elaborated geothermal models certainly pursue different goals. The actual report only treats the supra-regional scale geothermal models, regional scale and local scale geothermal models will be discussed in subsequent, individual reports.

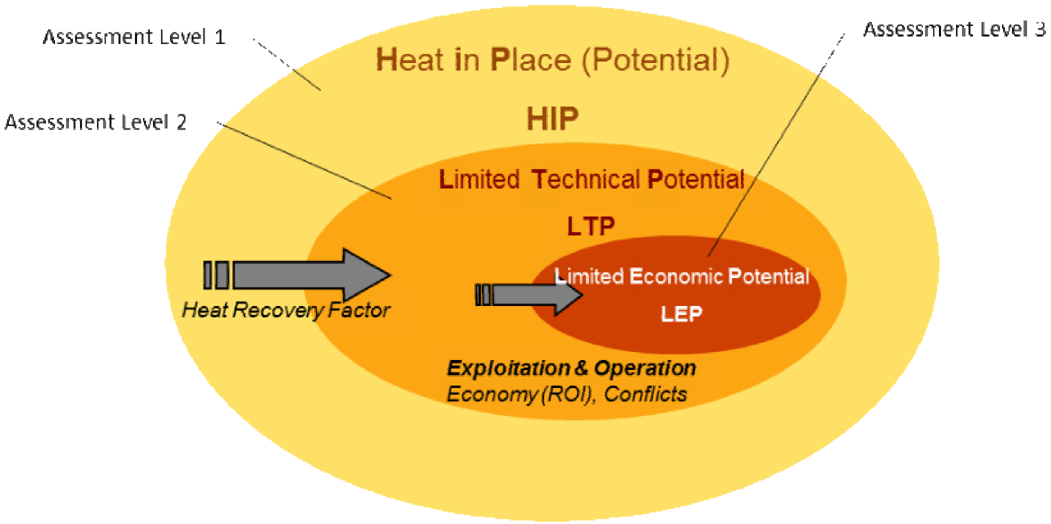


Figure 10. General scheme of the chosen geothermal resource assessment approach

2.3.1 Data background and workflow

The geothermal regime of the supra-regional model is represented by means of temperature maps for several depths as well as by a surface heat flow density map. By using continuous thermal logs, bottom-hole-temperature (BHT) and drill-stem-test (DST) data obtained from wells, it was possible to estimate the geothermal regime. In addition to the in situ-data, outflowing water temperatures were included in the thermal processing.

Apart from temperature data, parameters such as thermal conductivity and porosity had to be known for a determination of heat flow density. These data come from published works as well as archive data and new measurements.
In general the mapping of the geothermal regime was based on the following workflow:

1. Thermal Data Processing
2. Modelling of petrophysical data
3. Estimation of Heat Flow Density (in a borehole)
4. Estimation of Temperatures in various depths:
    a. 1000 m.b.s
    b. 2500 m.b.s
    c. 5000 m.b.s
    d. Top of pre-Tertiary basement
5. Estimation of Depth of different isothermal surfaces
    a. 50°C
    b. 100°C
    c. 150°C
6. Estimation of Specific Heat In Place and Specific Identified Resources
7. Interpolation and Visualization of Data from 4.-6
8. Modelling of the basal (background heat flow density)

The compilation of the parameters Specific Heat in Place and Specific Identified Resources was performed for four different cases:

i. in the Neogene sediments
ii. in the 50m upper part of pre-tertiary basement
iii. until a depth of 5km
iv. until a depth of 7km

2.3.2 Description of the applied methodologies and approaches

For modelling of petrophysical data generally the following parameters governed the heat transport are needed:

a. Thermal conductivity
b. Specific heat capacity
c. Bulk porosity and density
d. Effective porosity
e. Radiogenic heat production

These formation characteristics were obtained for individual rock types from previous studies as well as from literature and exploration data. Since only values for individual rock types are known, generalized models for the pre-specified geological units at supra-regional scale (see Summary report of geological models) had to be defined.

The surface heat flow density was determined by using two different approaches:

i. 1D Fourier inversion
ii. Interval method

The origin of the Slovakian data (used in TRANSENERGY project) is cited in the Geothermal Atlas of Slovakia (Franko, Remšik & Fendek, 1995). The data were collected during the systematic research and prospection of geothermal water structures from 70-ties to 90-ties of 20th century

Temperature data were extrapolated within a borehole. According to Hurtig et al. (1992), it is possible to extrapolate the temperature linearly until a depth of +50% of the total length of a borehole. However, a constant temperature gradient at greater depths is not necessarily correct. Considering different drilling lengths of wells and mostly low penetration depths, an extrapolation of temperature data was necessary.

Temperature data extracted from contour lines of existing geothermal maps in addition to data from individual wells were interpolated. The 3D interpolation was applied by using the numerical modelling software FEFLOW.

Heat in Place (HIP) values werecalculated according to the method of Muffler and Cataldi (1978). The recovery factor was estimateded on the basis of approach Hurter and Haenel (2002). The “Specific Identified Resources” was calculated with the combination of the Specific Heat in Place and the heat recovery factor.

We calculated the three-dimensional temperature distribution in the lithosphere under the area of the TRANSENERGY project assuming conductive heat transport using the finite element modelling software Comsol Multiphysics. We made a steady-state model and two transient models. One of transient models takes into account the lithosphere extention during the

Middle Miocene and the other additionally takes into account the thermal effect of the Neogene and Quaternary sedimentation.

2.3.3 Results of geothermal model

The detailed description and all the results of geothermal model can be found in Annex III., "Summary Report, Geothermal Models at Supra-Regional Scale" (Götzl et al 2012).
The main outputs of the model are the followings:

- Surface heatflow density map
- Temperature map series
- Contour map series of specific isotherms
- Geothermal cross-sections
- Geothermal potential map series
- Distribution of Background Heat Flow Density

The joint interpolation and modelling of harmonized geothermal data led to a compilation of geothermal maps in scale of 1:500.000. The quality and significance of the elaborated heat flow density and temperature maps reflect the data situation of 2010. By applying easily applicable, well documented approaches the existing maps can be updated in future without great effort.

The elaborated potential maps and balances only allow taking a first look on the available geothermal resources and actual degree of exploitation at the project area, irrespective to known or estimated geothermal plays and reservoirs. However, the achieved results imply, that only a very small amount of the available believed geothermal resources is already utilized (<1%) and therefore, hydrogeothermal utilization is able to play an important role in the future energy supply in the TRANSENERGY project area.

2.3.3.1 Surface Heat Flow Density and temperature maps

The surface heat flow density (Enclosure 1) and temperature maps (Enclosure 2a-2d) indicate that in some parts of the supra-regional area positive geothermal anomalies occur in the subsurface. Therefore the elaborated maps represent a first step towards the evaluation of the geothermal resources in specific regions.

The south-western part of the project area covering the parts of the Styrian and Mura – Zala Basin is a region with favourable geothermal conditions (> 120mW/m2). The increased HFD values (in the Mura – Zala Basin) are related to the convection zones in the pre-Tertiary basement rocks and to various geological conditions like e.g. reduced lithospheric thickness and tectonic evolution. This conclusion has already been confirmed by exploration and production wells in Slovenia and Austria.

Additionally several local to regional scale geothermal anomalies are depicted on the elaborated maps. The positive geothermal anomalies in the southern part of Vienna ("Oberlaaer High") and between Bratislava and Vienna (Bad Deutsch-Altenburg) are likewise related to naturally ascending thermal water (hydrodynamic systems), which supposedly are not interconnected.

At the central part of the Danube basin westwards of the city Győr and the western part of the Danube Basin in Slovakia high HFD values can be observed. This is probably a result of increased heat flow density from the mantle due to thinner lithosphere. In the region of Komarno and Sturovo (SK, eastern part of the project area) the positive geothermal anomalies are correlated with groundwater flow systems.

The different temperature maps give an overview on the expectable rock temperatures in certain regions. The observed positive anomalies in 1000m below surface correspond to shallow hydrodynamic systems, whereas deeper subsurface temperature distributions are mainly influenced by large scale crustal structures.

As a result of the compiled map series, areas with favourable geothermal conditions could be outlined. Within the pilot areas, further detailed studies of these outlined regions will be performed.

2.3.3.2 Potential Map Series

The Specific Identified Resources maps imply that a huge amount of heat is stored in the subsurface. The derived potential is enough to cover the heat demand of the countries participating in the TRANSENERGY project for many hundreds of years. However, only the heat stored in porous, permeable rocks or fractures in karst systems can be utilized economically by production of hot water or steam, and these rocks comprise only a small fraction of the total volume of rocks.

Although the calculation of parameters describing the geothermal potential at a certain area, such as “Specific Heat in Place” and “Specific Identified Resources”, is only accompanied of mathematical uncertainty of approximately ±25%, the interpretation of these values towards the realistic amount of energy, which can be technically extracted is very unconfident, as the Heat Recovery Factor is not exactly known. Nevertheless a geothermal balancing of the entire TRANSENERGY project areas has been executed in order to demonstrate the great range of variation accompanied to the interpretation of parameters describing the geothermal potential. This balance covers the following parameters:

- Already installed hydrogeothermal capacities for energetic utilization
- Natural heat recovery based on the observed SHFD
- Identified Resources at the uppermost 50 meters of the pre-Tertiary basement
- Identified Resources at the sedimentary fillings.

The calculated balances are shown in the and Figure 11, Table 2.

Table 2: Overview on calculated geothermal balances for the entire project area

Estimated installed capacity (excluding balneology)	0.097	GW
Natural het recovers (based on SHFD)	**27**	**GW**
„Identified resources„ (sedimentary basin fillings)*	**9000**	**GW**
„Identified resources“ (top 50 meter basement)*	**193**	**GW**

* Referring to an operational period of 100 years

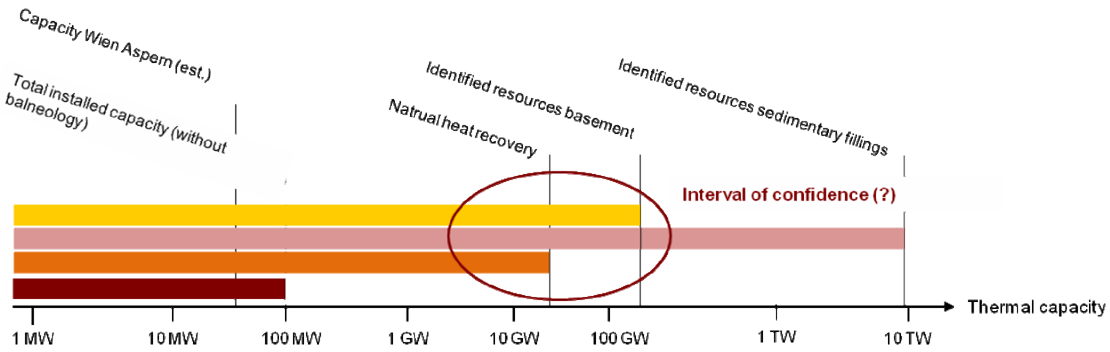


Figure 11: Overview on the different ranges of the estimated geothermal potentials in the Transenergy project area.

For comparison reasons an actually developed hydrogeothermal heating plat at the city of Vienna (Aspern) with a planned thermal capacity of 40 MW is also shown on the capacity bar. The red ellipse outlines the estimated interval of confidence of the inferred geothermal resources including both, hydrogeothermal and petrothermal utilization.

Figure 11 clearly show, that the range of variance accompanied to the interpretation of the parameter Identified Resources is covering the range of several thousands of Gigawatts and therefore not suitable for a detailed resource management. However, a relevant parameter for thermal balancing is given by the Natural heat recovery, which was calculated by spatial integration of the observed SHFD over the entire project area. The Natural heat recovery is limiting the extractable amount of heat with respect to a sustainable use – that means the amount of extracted heat is covered by the terrestrial heat flow. With respect to the Natural heat recovery (27 GW) only 0.37% of the available geothermal heat flux is already used for energetic utilization (already installed capacity 97 MW).

Of course in this balance existing geothermal plays and reservoirs are not taken into account. Therefore, as a next interpretative working step, outlines and attributes of known geothermal reservoirs will be combined with the elaborated geothermal potential maps in order to derive more precise parameters in terms of “Inferred Resources” and “Identified Resources”, which are in accordance with the Canadian Geothermal Code for Public Reporting (Deibert & Toohey, 2010).

2.3.3.3 Background Heat Flow Density (Lenkey L. & Raáb D.)

The transient model Trans-T, in which the Middle Miocene lithospheric stretching determines the initial geotherm, results in reasonable fitting to the observed temperatures and heat flow density. The modelled heat flow density increases from NW towards the centre of the area and southward, which is in agreement with the long wavelength variation of the observed heat flow density. The observed and modelled heat flow densities and temperatures are different significantly in those areas, where groundwater flow is occurring. Thus, the model results are in accordance with the a priori hydrological information. Specifying the initial geotherm is analogous with prescribing the mantle heat flow density (Figure 12**Hiba! A hivatkozási forrás nem található.Hiba! A hivatkozási forrás nem található.**).

As the Trans-T model version results fits to the observed temperatures and HFD very good, it has simple material properties, and it is based on reasonable geological and physical considerations, we consider it as the best model in the moment.

The model results can be further improved by coupled groundwater and heat transport modelling, which will be carried out in the pilot areas. The aim of these models is to determine the natural groundwater flux and calculate its thermal effect. The mantle heat flow density at the Moho discontinuity (**Hiba! A hivatkozási forrás nem található.**), or heat flow density, or temperature in large depth (e.g. in 10 or 20 km) derived from the Trans-T model (Annex III. "Summary Report, Geothermal Models at Supra-Regional Scale. Goetzl et al. 2012) can be used as thermal boundary condition prescribed in the bottom of those models. If the thermal anomalies in the pilot areas can be obtained with this boundary condition than the Trans-T model is good, otherwise it must be revised.

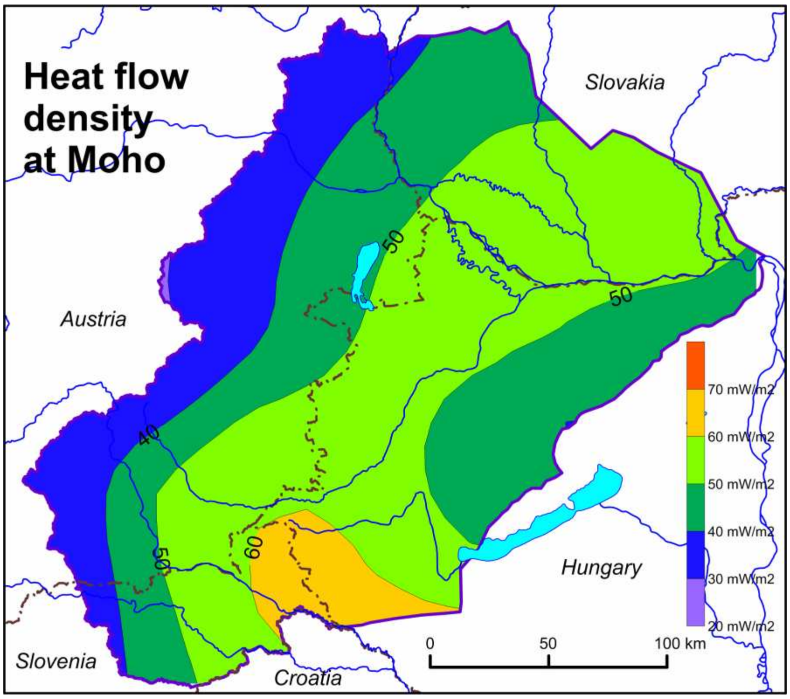


Figure 12: Heat flow density from the mantle at the base of the crust calculated from the Trans-T model version.

3 PILOT MODELS

The supra-regional model area encompasses the main geothermal reservoirs of the NW Pannonian Basin and the adjacent areas where the different natural and human processes have effects on the geothermal systems. Within the project area several sub-regions of enhanced hydrogeothermal utilization potential (pilot areas) have been identified and investigated in a more detailed way. Five ***pilot areas,*** focused on the local transboundary problems, were selected:

- Vienna Basin
- Danube Basin
- Komarno-Sturovo area
- Lutzmansburg-Zsira area
- Bad Radkensburg-Hodos area

The Vienna Basin is a several thousands meters deep sedimentary basin surrounded by mountains, the outer border of the Eastern Alps and Central West Charpatians. The Danube Basin is a deep sedimentary basin. The border of the model area was appointed along the pinch out, truncation and thinning of sedimentary formations. Due to the location of its recharge area, it locally overlaps to the Komarno-Sturovo model area, outlined along regional fault systems which correspond to the border line of groundwater bodies. The Bad-Radkersburg-Hodos model area is mainly bordered by tectonic structures, forming a tectonic halftrench. The Lutzmansburg-Zsira model area is not connected to a specific geologic or hydrogeologic unit. The western border of the area forms the margin of the Neogen basin. The other parts are appointed along artifical borders, taking into account that the area includes the important Hungarian spa „Bük" and "Sárvár".

The scale of the local models were 1:200 000, expect for the Lutzmansburg-Zsira area where the scale was 1:100 000.

3.1 Geological models

The geological models of the pilot areas were deducted from the relevant parts of the supra-regional models. However, as the scale of the pilot area models were more detailed (generally 1:200 000), it made it possible to provide a more accurate description on the geological buildup. In some areas additional geological horizons (compared to those ones which were edited for the supra-regional area) were constructed. A major step forward is that tectonics has been incorporated into the pilot area geological models. The pilot models contain modelled tectonic surfaces, and these model grids were edited more accurately based on the evaluations of 2D seismic section series and various geophysical datasets. Another important difference is that the pilot area geological models were prepared by different 3D geological modelling softwares (Jewel, GoCAD, Petrel), therefore they are more advanced, compared to the "flying carpet" model of the supra-regional area and provide more rich input information for the pilot area hydrogeological and geothermal models.

Detailed descriptions of the pilot geological models can be found in Annex I. ("Summary report of geological models" Maros et al. 2012). The following chapters of pilot models has the same structure:

1. Geological frame and history
2. Additional horizons
3. Descriptions of additional horizon's formations
4. Geophysical evaluations: gravity, seismics, magnetotellury
5. Tectonics
6. Cross sections
7. Modelling

3.2 Hydrogeological and geothermal models

3.2.1 Common methods in the modelling

Altough each pilot model has different aim, and different solutions, the basic methods of modelling were the same.

3.2.1.1 Outlining of model areas

The first step in the modelling activity is the vertical and horizontal outline of the model areas.

The same considerations will be used to outline the model boundaries both in the supra-regional and the local models. The most important point of outlining is to define the natural model boundaries, where the following aspects have to be regarded:

- Geological framework of the areas,

- Important tectonic structures
- Recharge areas, supplying the thermal water system (the recharge areas do not include the entire mountain regions, only those parts where the main thermal water bearing layers outcrop at the surface)
- Rivers as main discharges
- Contours of groundwater bodies
- Groundwater divides

The final borders of the model areas consist of the mixture of different boundary types mentioned above.

3.2.1.2 Development of the models

In order to investigate the natural state of the groundwater flow field and the geothermal temperature distribution in the study area, a three-dimensional finite element model was constructed. The construction of the hydrogeothermal model of the study area included the following steps:

- Construction of a steady state groundwater flow model ;
- Calibration of groundwater flow model using pre-extraction hydraulic head data;
- Assignment of thermal properties and coupling of fluid flow and heat transport processes ;
- Calibration of the coupled model based on reference temperature data;
- Sensitivity analysis.

The calibration of the coupled flow and heat transport model was undertaken in two stages:

- First, the flow model was optimised neglecting the thermal component;
- Secondly, the heat transport component was added, and the thermal properties of the flow medium were optimised.

3.2.1.3 Applied softwares

A three-dimensional (3D) model was developed using FEFLOW 6.1 (Diersch, 2006). **FEFLOW** (Finite Element subsurface FLOW system) is a computer program for simulating groundwater flow, mass transfer and heat transfer in porous media. The program uses finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions, as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems. FEFLOW is a finite-element package for simulating 3D and 2D fluid density-coupled flow, contaminant mass (salinity) and heat transport in the subsurface. It can handle complex geometric and parametric situations.

The package is fully graphics-based and interactive. Pre-, main- and post-processing are integrated. There is a data interface to GIS and a programming interface. The implemented numerical features allow the solution of large problems. Adaptive techniques are incorporated.

Geothermal model of Vienna Basin in the regional scale (approach i) was carried out using the software package COMSOL Multiphysics, a state-of-the-art finite element simulation software.

Modell parameters are usually optimised with PEST (WNC, 2004) which is a nonlinear parameter estimation code. Parameter optimisation is achieved using the Gauss-Marquardt-Levenberg method to drive the differences between model predictions and corresponding field data to a minimum in a weighted least squares sense. The implementation of this search algorithm in PEST is particularly robust; hence PEST can be used to estimate parameters for both simple and complex models including large numerical spatial models with distributed parameters.

3.2.2 Lutzmannsburg Zsira model area

3.2.2.1 Model objectives

The Zsira-Lutzmannsburg pilot area of the TRANSENERGY project is situated at the border between Hungary and Austria. Within the frameworks of TRASENERGY project three different thermal water reservoirs were outlined in the investigation area (Rotár-Szalkai, 2012). The identified geothermal reservoirs extend to both countries. Several famous spas are operated in the region within a relatively short distance to each other. The effect of thermal water withdrawals on hydraulic heads has been observed in both countries. Furthermore, the relation between the three identified reservoirs (Upper Pannonian, Miocene, and basement reservoirs), the recharge and thermal conditions require further clarification.

The aim of the presented steady state model is to describe the system in natural condition (before thermal water withdrawals began). The steady state model provides the basis for the scenario models. The steady state model expresses the temperature distribution in 3D considering the effects of groundwater flow. Both the hydraulic and thermal model was based on detailed geological model, which determined the geometry and parameter distribution of the model.

The detailed description of the model can be found in Annex IV. “Report on the Lutzmannsburg - Zsira pilot area model” (Kovács and Rotár-Szalkai 2013).

3.2.2.2 Geographical settings and model domain

Originally the pilot area was outlined according the location of the most important spas in the region, Lutzmannsburg (Locsmánd), Bük and Sárvár. During the delineation of the model area, the pilot area was extended, with respect to the extent of supposed flow systems and a more accurate definition of hydraulic boundary conditions.

The model area (**Figure 13**) extends along the national border between Hungary and Austria, sorrunded by Sopron-Ödenburger Mountains, the Rosalia Mountains, Bucklige Welt and the Kőszeg-Rehnitz (Rohonc) Mountains. Towards east and north the area continues on Kisalföld Lowland.

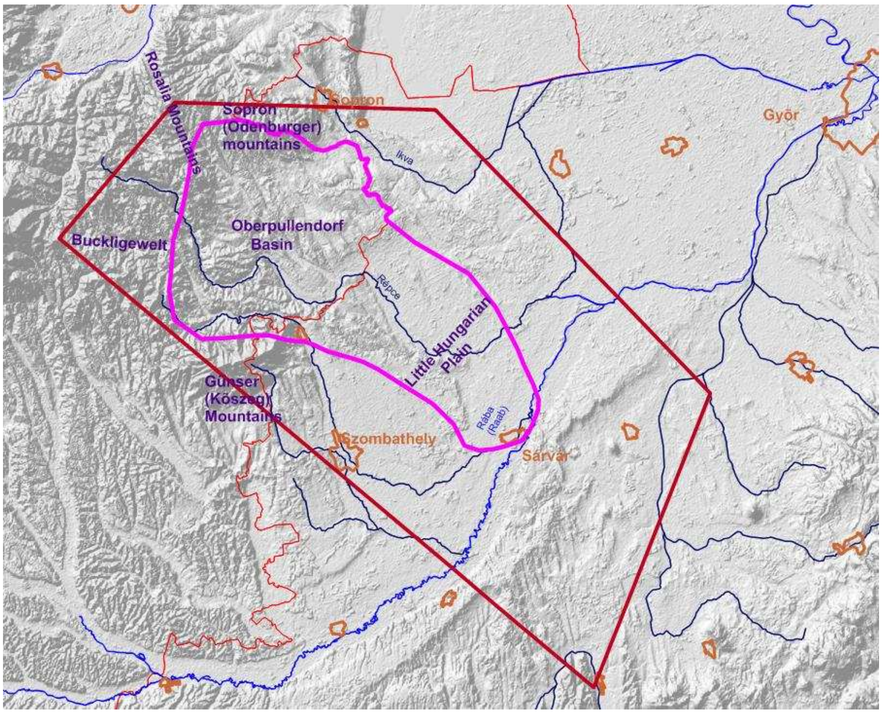


Figure 13: Geographical settings of the Lutzmannsburg-Zsira pilot area and the model region

The surface extension of the model follows a pentagon-shaped polygonal area which was delineated based on the following aspects:

- The model includes locations of the main water extractions including the major well fields at Bük, Zsira, Lutzmannsburg and Szombathely;
- The model includes the aquifers supplying the above extraction bores;
- The model extends to the south-Eastern boundary of the upper-Pannonian aquifer so that it can be applied for studying both the pre-Neogene and the upper-Pannonian aquifer systems.
- The model extends to the main regional-scale surface water features including water divides and rivers;
- Sufficient buffer zone is included around the study sites to avoid boundary effects.

The coordinates of the corners of the model domain are the following (Table 3):

Table 3. Coordinates of model corners.

Model domain corner	UTM X	UTM Y
1	582000	5262000
2	599000	5281000
3	635000	5280000
4	674000	5241000
5	657000	5200000

3.2.2.3 Model layerig

Model layering was based on conceptual hydrostratigraphy developed from the pilot-scale geological model (Maros et al., 2012). Vertical model discretisation was defined to provide sufficient accuracy and to maintain computational efficiency and short model run times. The following layers were distinguished (**Figure 14**):

- Quaternary
- Upper Pannonian
- Lower Pannonian
- Sarmatian
- Badenian
- Lower Miocene
- Devonian
- Crystalline basement upper
- Crystalline basement lower

Within the frameworks of TRASENERGY project three different thermal water reservoirs were outlined in the investigation area (upper-Pannonian, Miocene, and basement reservoirs). The model extends to the south-Eastern boundary of the upper-Pannonian aquifer so that it can be applied for studying both the pre-Neogene and the upper-Pannonian aquifer systems. The model extends to the depth of -5000 mASL.

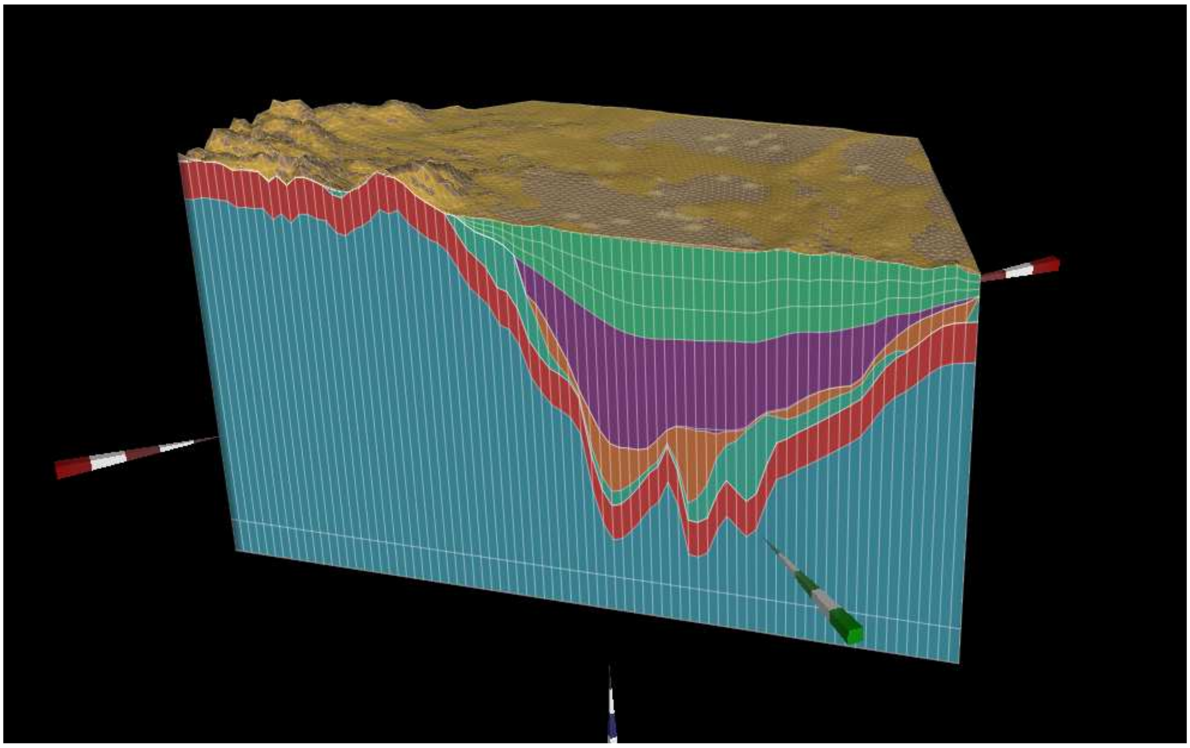


Figure 14: Model layering of Lutzmannsburg-Zsira pilot area.

3.2.2.4 Results of the model

The geothermal system of the Lutzmannsburg - Zsira pilot area in the western part of the Pannonian Basin is located in a trans-boundary position across the Hungary-Austria political border. The sustainable utilization of transboundary geothermal systems requires a harmonized management of geothermal energy and thermal water resources. The coupled groundwater flow and heat transport model of the pilot area serves as a management tool needed for decision makers to provide information about the future responses of the system given to the effects of various interactions, as well as about available hydrogeothermal resources. In order to investigate the natural state of the groundwater flow field and geothermal temperature distribution in the study area, a three-dimensional finite element model was constructed. This report presents the results of steady state hydrogeological modelling of the Lutzmannsburg - Zsira pilot area of the TRANSENERGY project.

Within the frameworks of TRASENERGY project three different thermal water reservoirs were outlined in the investigation area (upper-Pannonian, Miocene, and basement reservoirs). The model extends to the south-Eastern boundary of the upper-Pannonian aquifer so that it can be applied for studying both the pre-Neogene and the upper-Pannonian aquifer systems. The model extends to the depth of -5000 mASL.

The finite element code FEFLOW 6.1 was applied for coupled simulation of groundwater flow and heat transport. The applied finite element mesh consisted of 12 model layers and 136440 linear triangular finite elements. The mesh was refined around extraction bore locations. Boundary conditions were assigned based on natural hydraulic boundaries and the results of the supra-regional model. Initial model parameters were based on field measurements, literature data and parameters applied in the supra-regional model and were adjusted during model calibration. Model calibration was performed by means of manual and automated calibration.

The coupled groundwater flow and heat transport model provided three-dimensional information on hydraulic head distribution, groundwater fluxes and temperature distribution. The simulated groundwater head distribution and calculated flux distribution indicate that the dominant flow direction is towards the east following a semi-radial pattern. Regional flow system feeds the model domain along the western model boundary. The Marcal Valley represents the regional discharge area, while the north-eastern side of the model is a cross-flow area.

The simulated groundwater head distribution and calculated flux distribution indicate that the dominant flow direction within the model domain is from west towards the north-east, east and south-east (Figure 15 and Figure 16). The flow field follows a semi-radial pattern. The water budget of the area is indicated in Table 4.

The simulated temperature distribution indicates little vertical variations of temperature within the upper pannonian sediments, and gradually increasing temperatures within older sediments and the fractured basement.

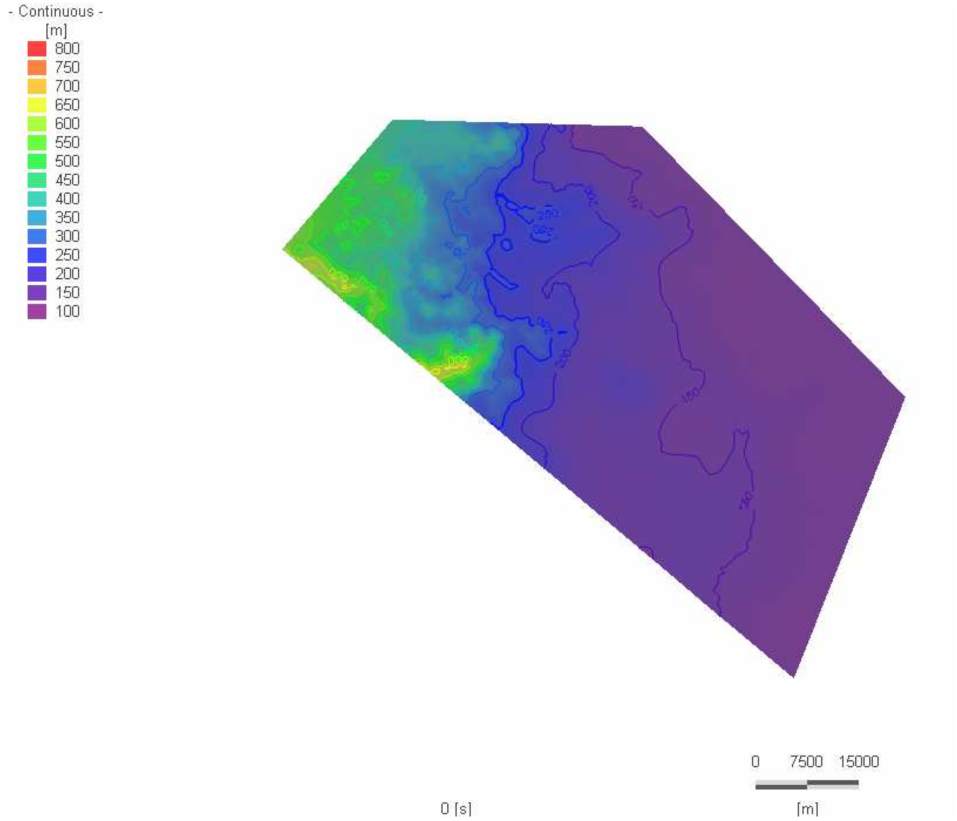


Figure 15: Simulated hydraulic head distribution at the base of the upper-Pannonian aquifer (slice 5).

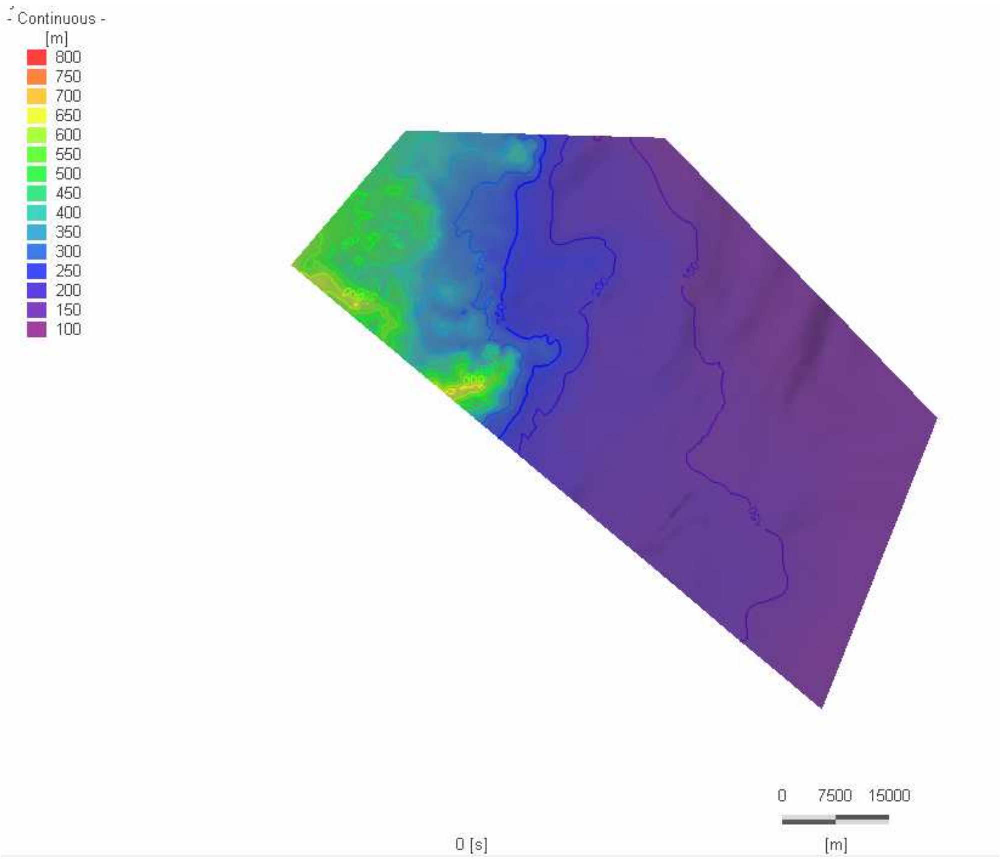


Figure 16: Simulated hydraulic head distribution at the base of the Tertiary layers (slice 9).

Table 4. Simulated water budget.

Boundary	In (m^3/d)	Out (m^3/d)
Prescribed head	1.29e+6	2.02e+6
Infiltration	7.24e+5	N/A

The coupling of the hydraulic and heat transport models made it possible to calculate a 3D temperature distribution over the study area. The simulated temperature distribution indicates little vertical variations of temperature within the upper-Pannonian sediments, and gradually increasing temperatures within older sediments and the fractured basement (Figure 17).

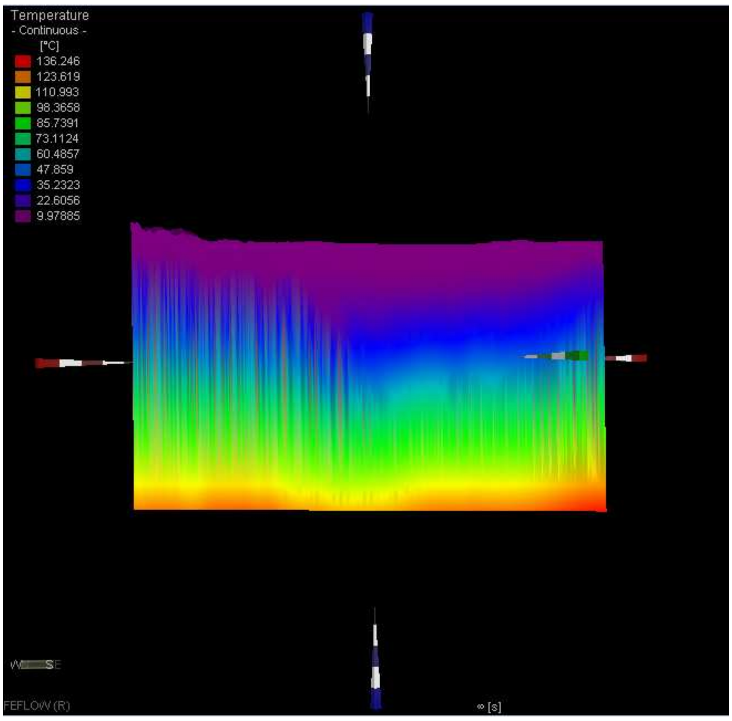


Figure 17: Simulated NW-SE temperature profile.

3.2.3 Bad Radkersburg-Hodos model area

3.2.3.1 Model objectives

The model focused in aquifer in the Pre-neogene basement that is positioned in the narrow and deep Radgona –Vas tectonic halftrench south of the Burgerland swell. The Radgona – Vas tectonic halftrench is developed along the Rába fault system in SWS – ENE direction.

The main utilization in the area takes place in Benedikt and in the transboundary zone between Austria and Slovenia. In Bad Radkersburg (A) there is a thermal spa in the vicinity of state border with Slovenia. In 2008 a research borehole in Korovci (SI) in the vicinity of state border intended to capture the same aquifer less than 5 km from Bad Radkersburg spa was drilled which resulted several questions between the two countries.

By analysing older cores from borehole BS-2/76 and temperature measurements Ravnik et al. (1987) have determined a higher value of heat surface heat flow density in the Neogene rocks in Benedikt area compared to those around.

In 2004 a borehole Be-2 was drilled in Benedikt. Measurements carried out by Nafta Geoterm (Kraljič et al., 2005) have shown a very low temperature gradient in metamorphic rocks of the Pre-Neogene basement. In the interval from 800 to 1857 m a temperature difference of around 3 °C was determined.

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 utilisation of the geothermal resources.

Presented approach is first attempt of conceptual and numerical presentation of studied geothermal system. It is based on current state of knowledge and data, which all have certain limitations. To account part of uncertainty, related to estimation of parameters of hydrogeological model, sensitivity analysis was performed. The detailed description of the model can be found in Annex V. "Report on Bad Radkersburg – Hodoš pilot area model" (Fuks et al. 2013)

3.2.3.2 Geographical settings and model domain

The Bad Radkersburg – Hodoš pilot area is situated at the national borders of Austria, Slovenia and Hungary. The south-western border is defined by the water divided between Drava and Pesnica Rivers. Towards the northeast the pilot are passes across Mura River, Goričko hills to the Hungarian national territory. The NW and SE borders are set along geological structures, South Burgenland Swell and Murska Sobota extension block respectively. It covers an area around 2078 km^2 (Figure **18**).

Figure 18: .Delineation of Bad-Radkersburg-Hodos pilot model area with the production wells.

The model area is outlined in accordance with the TE project pilot area. The upper boundary is defined along the topography - surface, whereas the lower boundary is set at the depth of 5 km in the Pre-Neogene basement rocks.

3.2.3.3 Model layerig

In the model two geological layers were defined (Neogene sediments and Pre-Neogene basement). Those geological layers were further subdivided into several numerical layers. Altogether, 16 numerical layers and 17 slices have been created (Figure **19**). The uppermost slice is defined by the surface (DMR), followed by 7 layers in the Neogene. After the geological boundary between the Neogene sequence and the basement, 9 layers in the basement follow. The lowermost boundary in the model was set arbitrarily at 5 km depth.

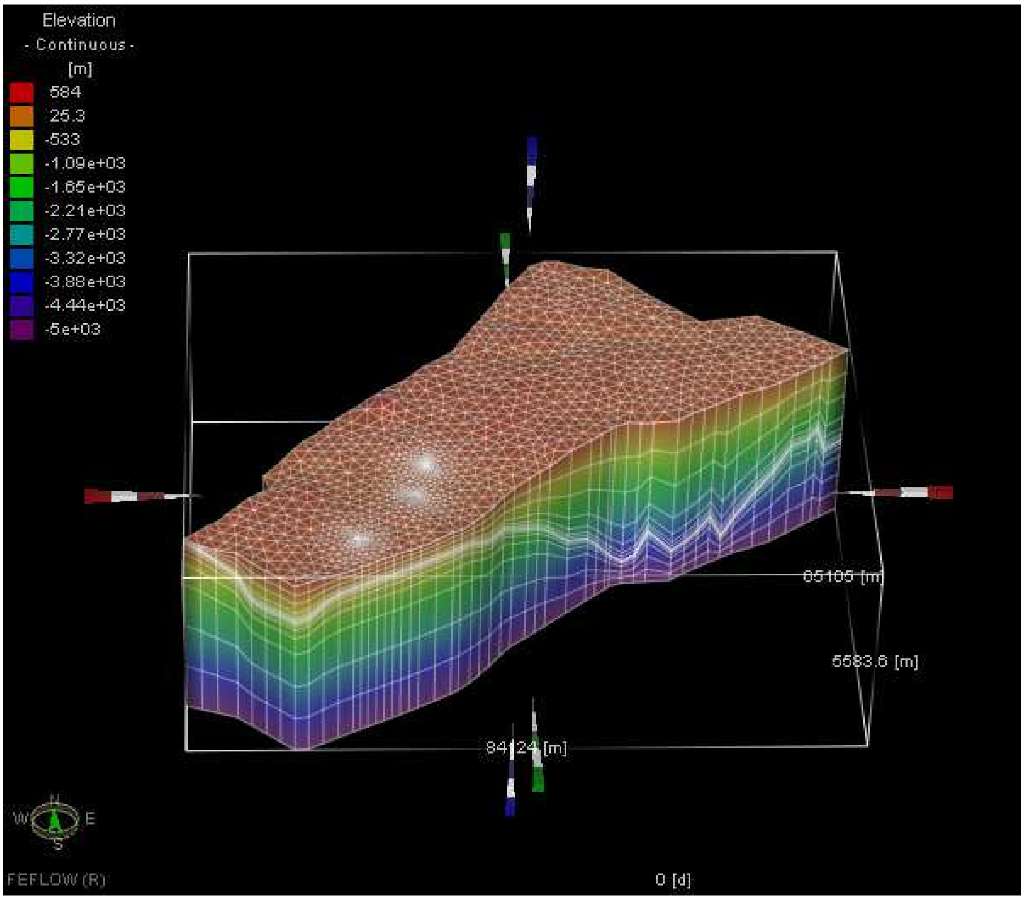


Figure 19: Geometry of Bad-Radkersburg-Hodos pilot area model.

3.2.3.4 Results of the model

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.

Due to the implementation of uniform recharge through infiltration, distribution of hydraulic heads in the model depends on boundary conditions and spatial distribution of hydraulic conductivities (Figure **20**).

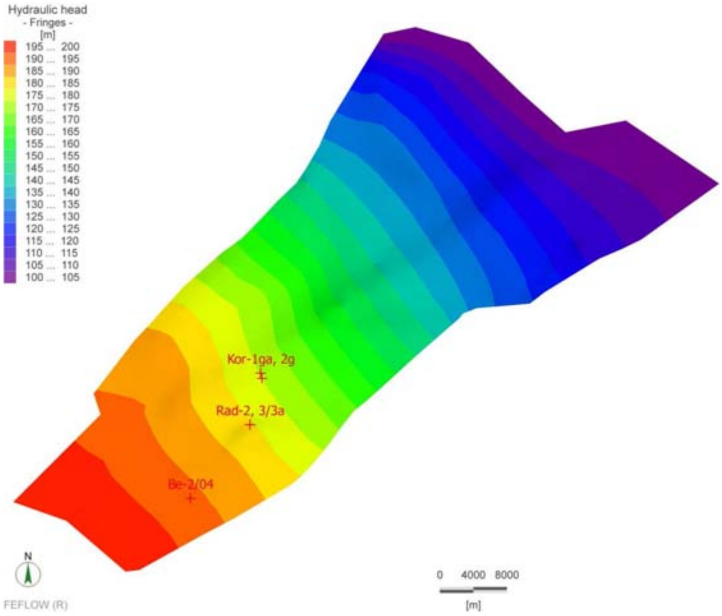


Figure 20: Computed hydraulic head distribution in slice 8 (base of Neogene)of Bad-Radkersburg model.

Direction of groundwater flow is from SW towards NE. The flow velocity is higher in the Raba fault zone, where the hydraulic conductivity is higher. Outside the Raba fault zone, the groundwater flow velocity is below 1.18×10^{-5} m/d.

The main mechanism for heat transport in the regional model is conduction. Due to higher thermal conductivity in the basement layers, the temperature in the NE part of the area, where the thickness of the Neogene layers is greater, temperature is higher in the basement (Figure 21 and Figure 22). It is a manifestation of insolation effect of Neogene layers which slowing down the heat conduction.

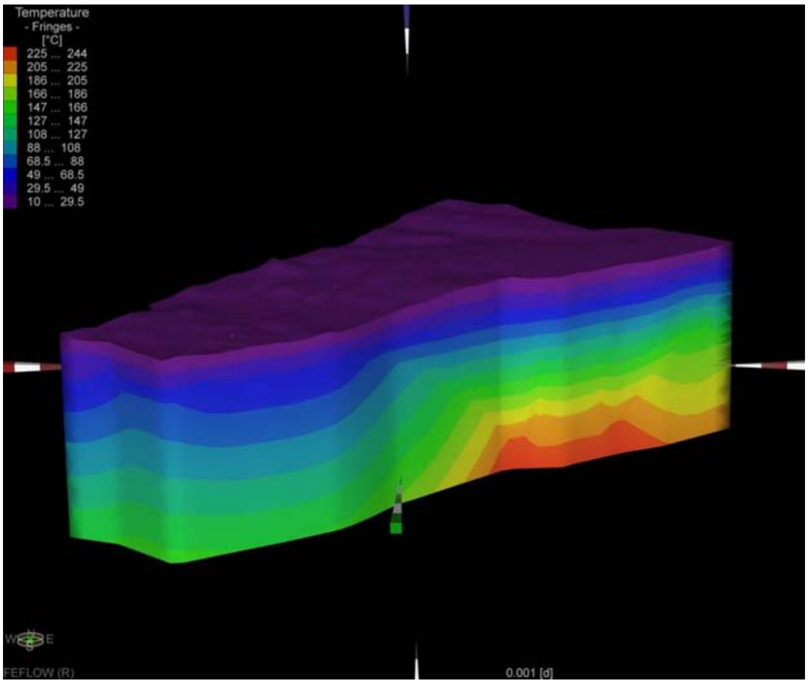


Figure 21: Temperature distribution in the Bad-Radkersburg model.

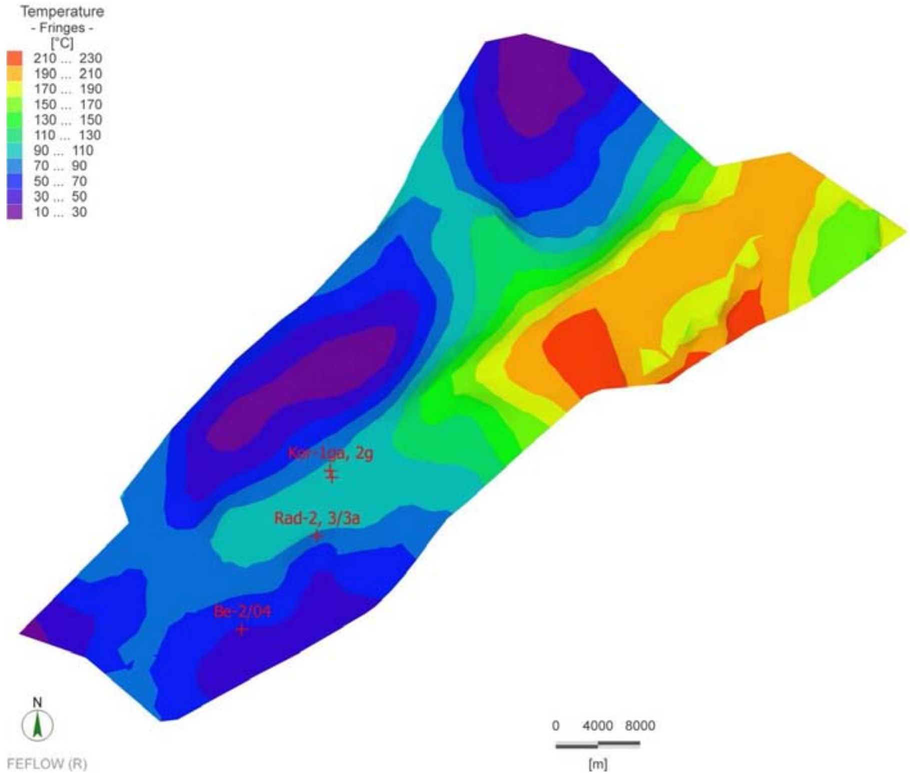


Figure 22: Temperature distribution in the base of Neogene (slice 8) of the Bad-Radkersburg model.

The largest discrepancy between computed and measured temperature is observed in the borehole Be-2/04 (Figure 23). It indicates geothermal anomaly in the Benedikt area which cannot be simulated with the model on a pilot area scale. In order to simulate local geothermal conditions different modelling approach was used.

3.2.3.5 The Benedikt local model

The local model area was defined in the SE part of the pilot area model, around the well Be-2/04 in Benedikt. It is a roughly square shaped and covers an area of 65 km^2 (Figure 23).

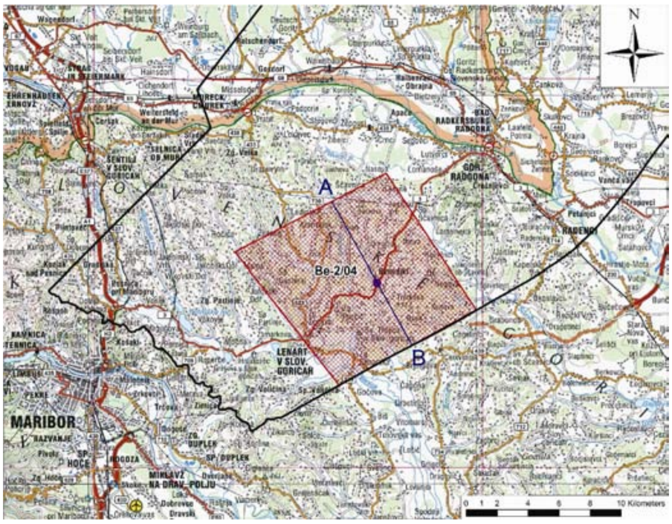


Figure 23: Benedict local model area - red square, the black line delineates the pilot area model area, dark blue line

The upper boundary is represented by the surface whereas the lower boundary is set at depth of 2 km in the Pre-Neogene basement rocks.

The upper slice of the model is represented by the surface, while the lower slice is set at the depth of 2 km (distance from the surface). There are two geological layers, namely Neogene rocks and Pre-Neogene basement. Those two are further subdivided into several numerical layers (Neogene into 9 layers, Pre-Neogene basement into 8 layers).

Comparing to the results of pilot areal model, the fit is much better in the case of local model. This result indicates that temperature distribution in Benedikt can result from vertical groundwater movement in the fracture zone of Raba fault (Figure 24 and Figure 25).

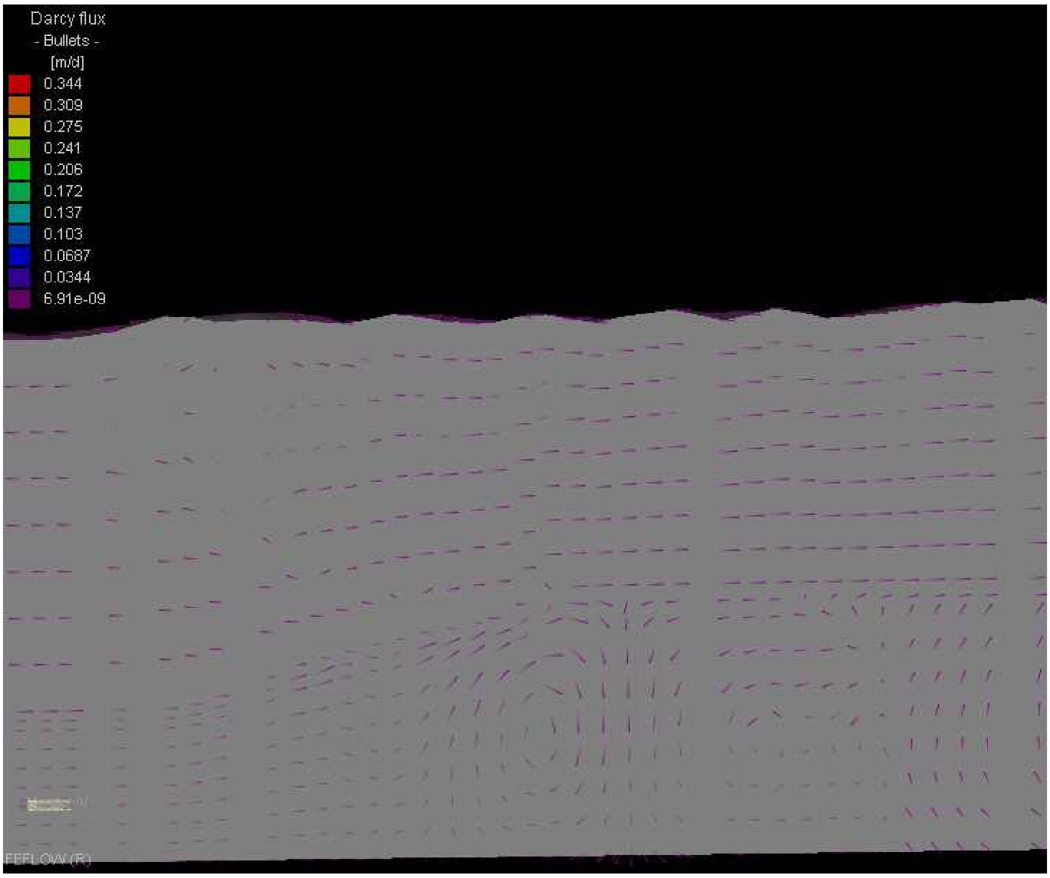


Figure 24: Groundwater flow in the northwest boundary of the Benedikt local model.

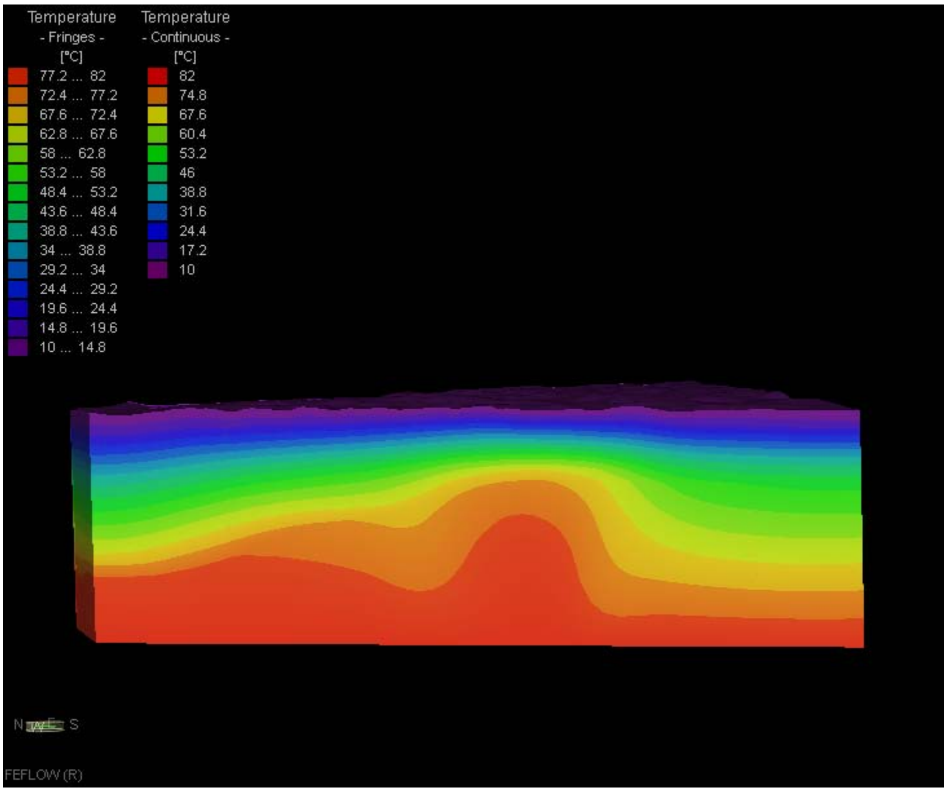


Figure 25: Temperature distribution in the cross section across borehole Be-2/04 in the N-S direction

3.2.4 Danube Basin model area

3.2.4.1 Model objectives

The model of the Danube basin pilot area of the Transenergy project focused on Upper Pannonian aquifer, partly on adjacent thermal karst aquifers.

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

The aim of the numerical modeling was to simulate the hydrogeological and geothermal conditions in the in the geothermal water body of pre-Neogene and Neogene fill of the Danube Basin. The goal of modeling that comprises 3D groundwater flow and heat transport simulations was to provide information for better understanding of the hydrogeological and geothermal conditions in the pilot area. 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. 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 detailed description of the model can be found in Annex VI. “Report on steady state hydraulic model of the Danube basin pilot area” (Svasta et al. 2013.).

3.2.4.2 Geographical settings and model domain

The pilot area of Danube basin evaluated in TRANSENERGY project is situated in Slovakia, Hungary and partly at Austria. The Danube basin pilot area covers around 12 170 km^2 (Figure 26).

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 Danube Basin has finger like extensions, basins of the river tributaries 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.

3.2.4.3 Geographical settings and model domain

The model area is outlined in accordance with the TRANSENERGY project pilot area. From top the model is limited by the topographical surface, adopted from the digital elevation model SRTM. To the depth the model extends down to -10,000 m a.s.l.

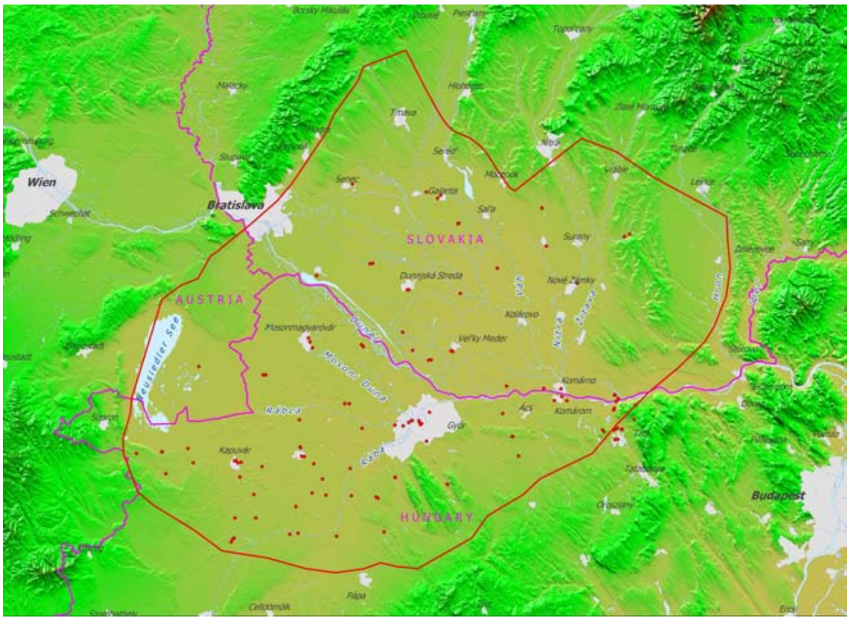


Figure 26: Delineation of Danube Basin pilot model area with the production wells.

3.2.4.4 Model layerig

The model adopted a geological model consisting of 8 hydrostratigraphic units, that were delineated based on geological model (Figure 27):

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

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

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

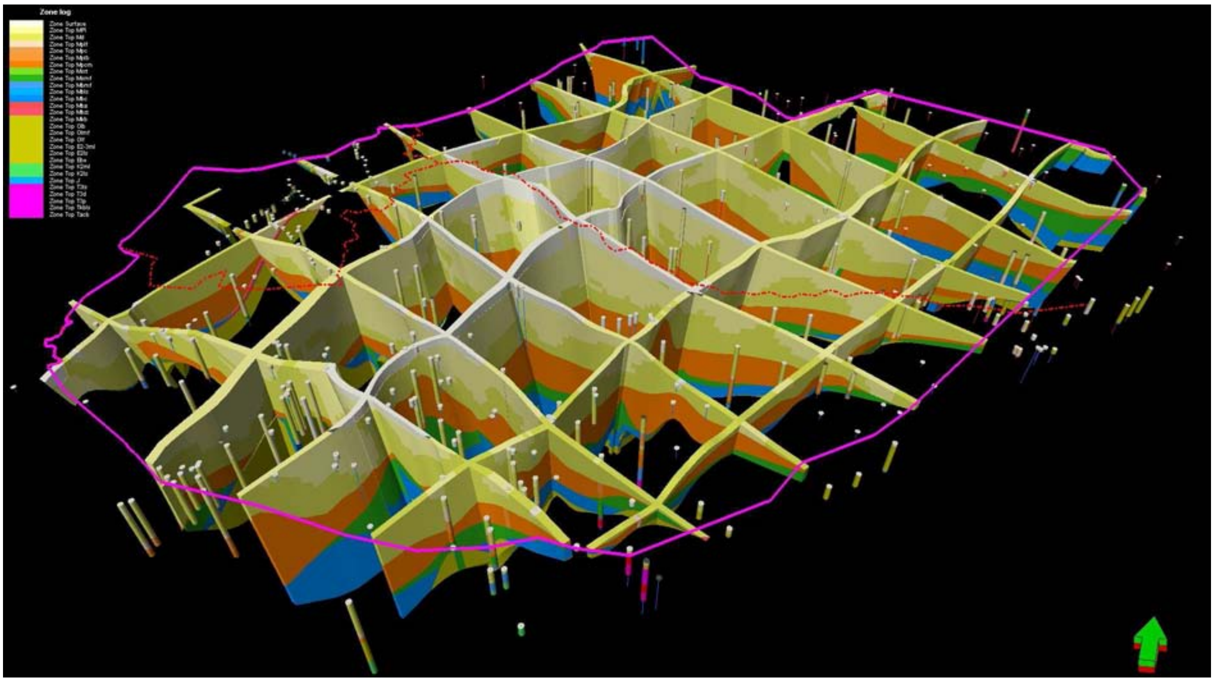


Figure 27: Fence diagram of Danube Basin geological model.

3.2.4.5 Results of the model

Hydraulic head distribution

Distribution of hydraulic heads in the model depends primarily on boundary conditions and spatial distribution of hydraulic conductivities (Figure 28). In upper parts hydraulic potentials are reflecting hydraulic heads set as constants in Quaternary, in deeper horizons hydraulic pressures are equilibrated, resulting in lower head differences.

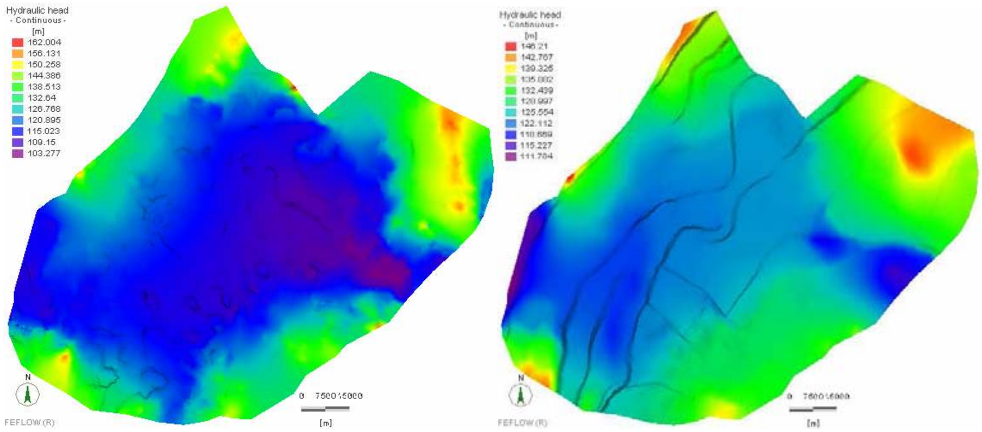


Figure 28: Distribution of computed hydraulic heads at the base of Upper Pannonian (left) and base of Cenozoic (right), pre-utilization state.

Pictures show values on whole model layer, while respective hydrostratigraphic units cover only central part of the area. The same principle applies for all similar maps in this report.

Evaluating effects of thermal wells utilization

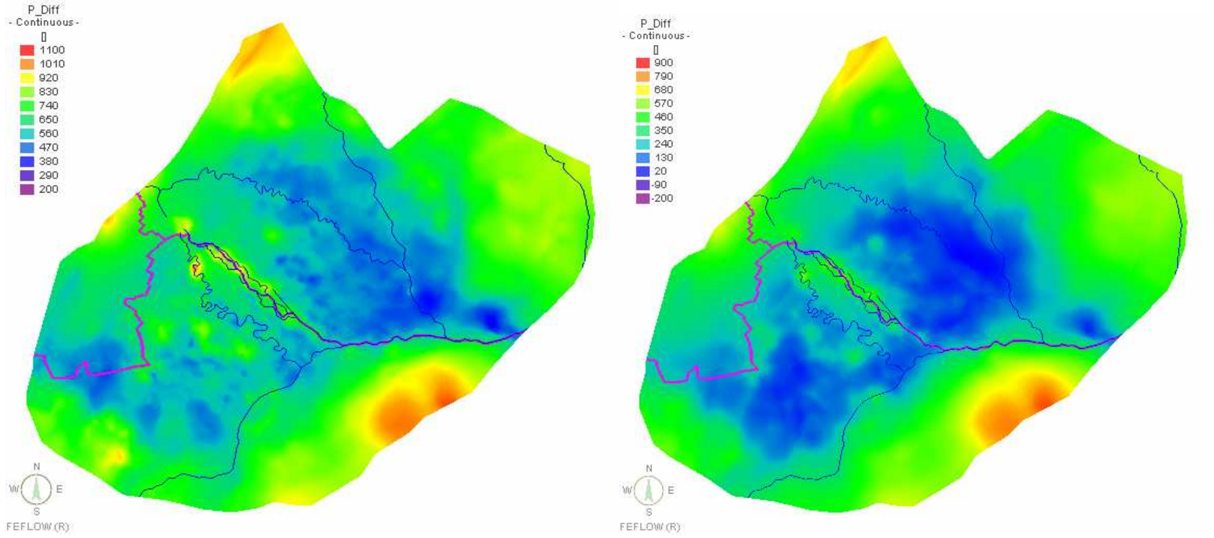
Simulation of theoretical infinite pumping of all existing operating geothermal wells was performed to predict future evolution of pressure and thermal field in the area and to help identifying potential adverse impacts of extensive and unsustainable thermal water over-utilization. Pumping thermal water 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 (Figure 29a – d).

Temperature distribution

In Pre-Quaternary rock formations conduction is the main mechanism for heat transport. Due to relatively intensive water interchange between recharge and discharge zones in Quaternary sediments, convection is of high importance. Convection driven heat transport is also dominating in karstified Mesozoic carbonate formations in Gerecse and Pilis Mts. and Komárno elevated block. Recharge of precipitation is causing a considerable cooling of the whole carbonate massive in Komarno elevated block in the south-eastern part of the model.

The influence of the cooled water intrusion into the geothermal aquifer is visible in both modeling scenarios and in all visualized levels. Though the temperatures in geothermal aquifer, proven by drilling especially on Slovak part, show (north part adjacent to Sturovo) much further influence of the cooled water front. This might be caused by excluding the infiltration area in Gerecse and Pilis Mts. that would add higher recharge rate and thus have stronger effect on cooling further northern parts of the structure. Notable is also cooling effect of thick quaternary gravels and sands along the central part of Danube river. Owing to large depth (up to 713 m) and high permeability of these sediments, rapid circulation of 10˚C cold groundwaters across the whole thickness, coming from almost infinite source – river Danube, excavates heat from underlying Neogene sediments. This cooling propagates to large depths over 3 km (Figure 30 a, b).

a) -1000 m a.s.l b) -2000 m a.s.l



c) -3000 m a.s.l d) -5000 m a.s.l

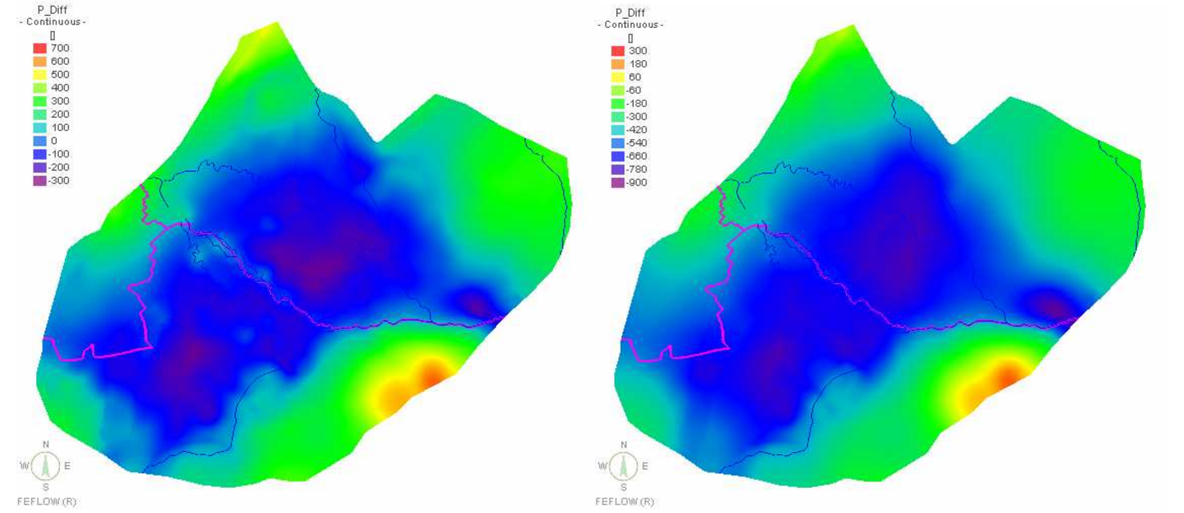
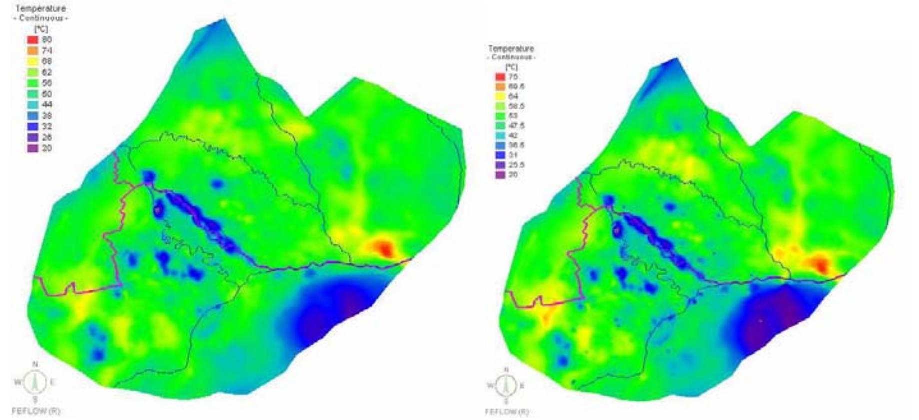


Figure 29: Pressure differences (Pa) caused by steady pumping at different depth levels.

Pre-utilization Steady pumping

a) -1000 m a.s.l



b) -2000 m a.s.l

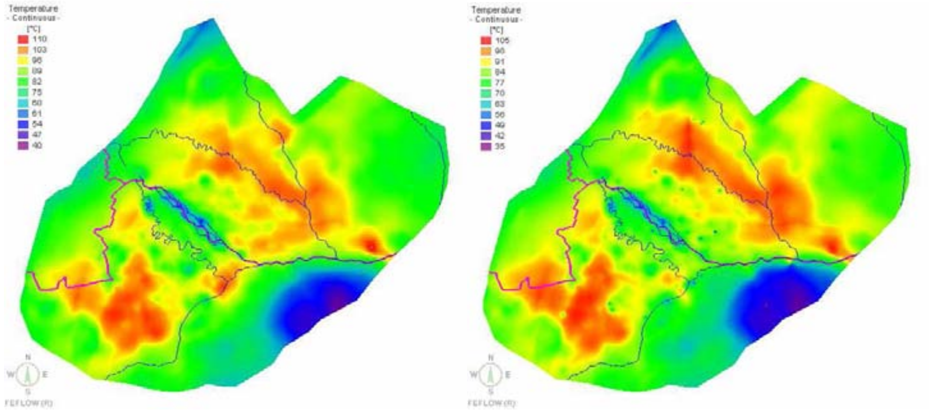


Figure 30: Temperature distribution at different depth levels. Compared are both state scenarios: pre-utilization and steady pumping. Mind the different color scales.

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.

The Figure 31hows 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 Transdanubian Midmountains 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.

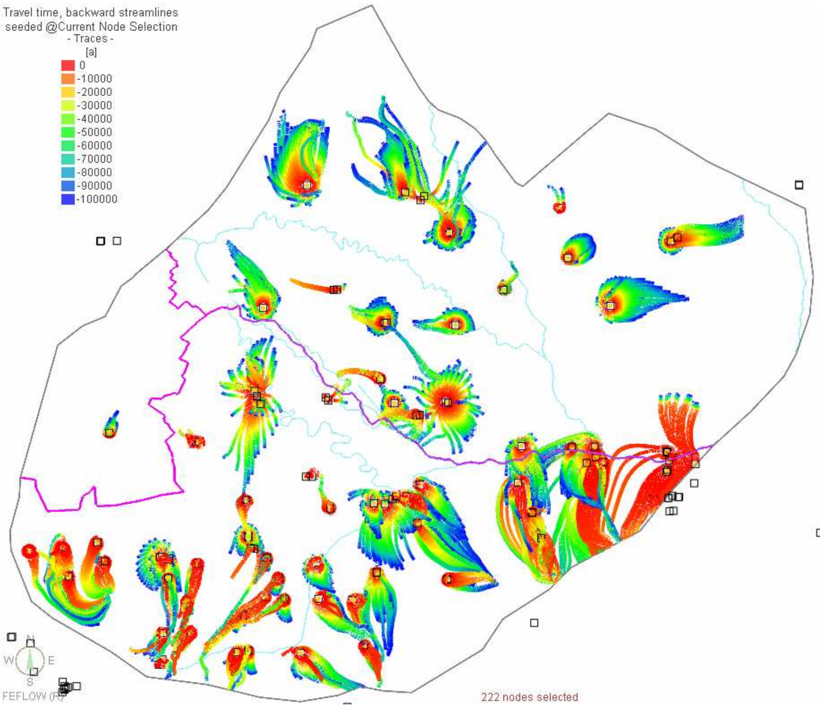


Figure 31: Vertical projection of 3D flow paths towards thermal wells with travel time [years].

Amounts of groundwater flowing across national boundaries were quantified by calculating flow budget for different model domains. Results are summarized in Figure 32 and Figure 33

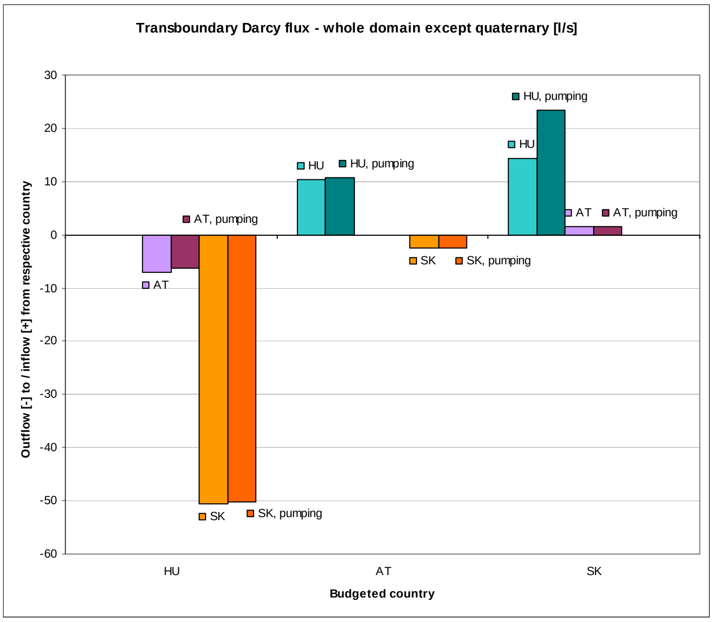


Figure 32: Transboundary flow within Pre-Quaternary rock formations between Hungary, Slovakia and Austria quantified for two model scenarios.

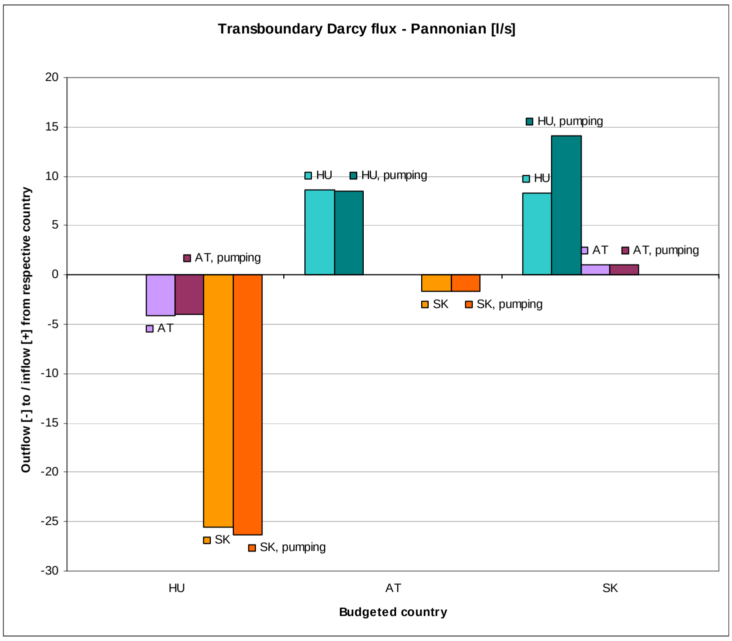


Figure 33: Transboundary flow within Upper Pannonian sediments between Hungary, Slovakia and Austria quantified for two model scenarios.

Energy balance

Geothermal modeling is a useful tool for calculating thermal energy associated with different parts of studied area. Separate calculations were made to evaluate thermal power (MWt) for all 3 involved countries (Figure **34**).

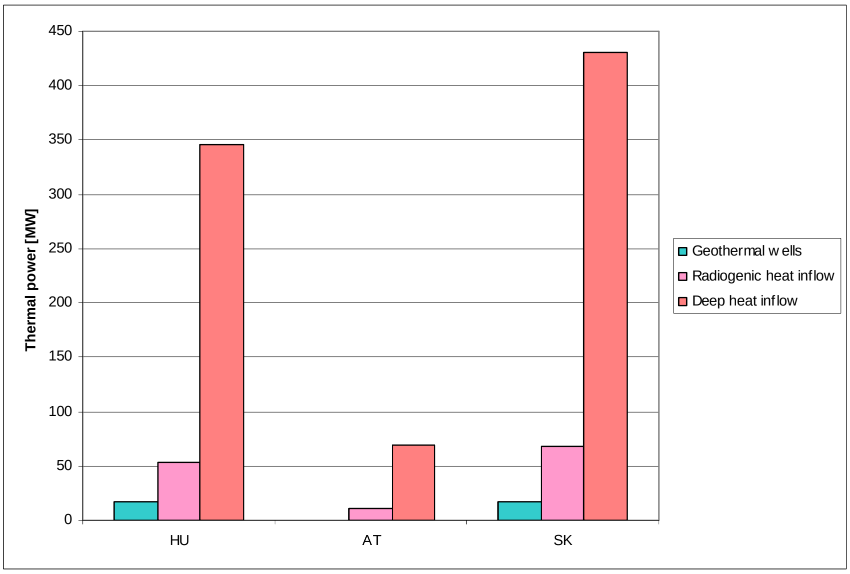


Figure 34: Thermal power of wells, radiogenic heat generation and basal heat inflow for Hungary, Slovakia and Austria.

3.2.5 Komárno – Štúrovo model area

3.2.5.1 Model objectives

The actuality of the modelling is the recovering karst system throughout the Transdanubian Range. From the beginning of the 1900's the karst system is affected by bauxite and coal mining, which became more intense in the 1950s: intense karst water abstractions started in the whole area (eg. Fenyőfő, Dudar, Kincsesbánya, Tatabánya, Mány, Dorog etc.). These water abstractions seriously impaired the natural karst flow system and caused regional, transboundary depressions in the Transdanubian Range. Several lukewarm (15-30°C) springs had dried up due to this activity.

After the mine closures the karst flow system started to regenerate and the beginning of the 2000's the hydraulic heads continuously rising (e.g. Tata, Tatabánya, Patince, etc.) and some of the springs reactivated (e.g. Dunaalmás, Tata, etc.). Under these conditions the historic spa utilizations took place in Tata, Esztergom, Štúrovo, Patince pretend larger production yields for the operation of the spas. Some old/new utilizations in the NW part of the pilot area also exist and used the thermal water for spa or agricultural targets. The main question is how the spa and agricultural utilizations can coordinate their operations and claims in a sustainable manner in this changing system.

The goal of modelling that comprises 3D groundwater flow and coupled heat transport simulations was to provide information for better understanding of the hydrogeological and geothermal conditions in the Komárno – Štúrovo pilot area. It is the first step in modelling process and gives the basis for scenario analysis for sustainable utilisation of the regional groundwater and geothermal resources.

Presented approach is the first attempt of the conceptual and numerical presentation of studied karst flow and geothermal system of the NE part of the Transdanubian Range in Hungary and its forelands in Slovakia. The modelling is based on current state of knowledge and data of the natural conditions of the karst flow system, which all have certain limitations.

The main questions and the objectives of the modelling are the following:

- simulate and examine the effect of the mine water-abstraction on the karst flow system,
- investigate the recovering of the karst system after the mine closure,
- examine the behaviour of the natural „thermal" springs (Tata, Esztergom)during and after the mine water abstractions,
- study the sustainable operation of the cold and thermal drinking water, spa- (Esztergom, Komárom, Sturovo, Patince) and agricultural utilizations,
- the possibility of further geothermal utilizations on the area.

In this first step of the modelling a steady state three dimensional groundwater and heat flow model was constructed, calibrated and used to describe and understand better the natural conditions of regional flow of the pilot area before the mining.

The aim of the numerical modelling was to simulate the hydrogeological and geothermal conditions in the cold and geothermal water body of Mesozoic carbonate rocks near the surface in the Transdanubian Range and in the deep towards the Danube basin. One of the main goals was to reconstruct the pre-abstraction state of the system before the bauxite and coal mining. On the other hand by the help of the 3D groundwater flow and heat transport model we tried understand better of the hydrogeological and geothermal conditions in the pilot area. ***In this phase a steady flow and steady heat transport was constructed. In the second phase a transient flow model will be built take into account the mine water-abstractions in the region to predict the effects of the decreasing production after the mine closures.***

3.2.5.2 Geographical settings and model domain

The Komarno-Šturovo (Komárom-Párkány) Pilot Area of the Transenergy Project is situated in the north-eastern part of the Transdanubian Range in Hungary and its basinal part in Slovakia. The groundwater bodies are divided by national boundaries and are in focus of International Commission for the Protection of the Danube River (ICPDR).

The borders of the pilot area fit the presence of the Triassic carbonate basement and the watershed of the carbonate aquifer. The south-eastern and eastern borders are the same as the south-eastern and eastern border of the Supra-regional model pilot area, then towards west, the northern border set along geological structure between the Mesozoic and metamorphic formations of the Veporic unit in Slovakia. In north-west the border is the boundary of the Triassic formations. Only the south-western part of the model boundary – between settlements of Ugod and Eplény – is artificial (

Figure **35**).

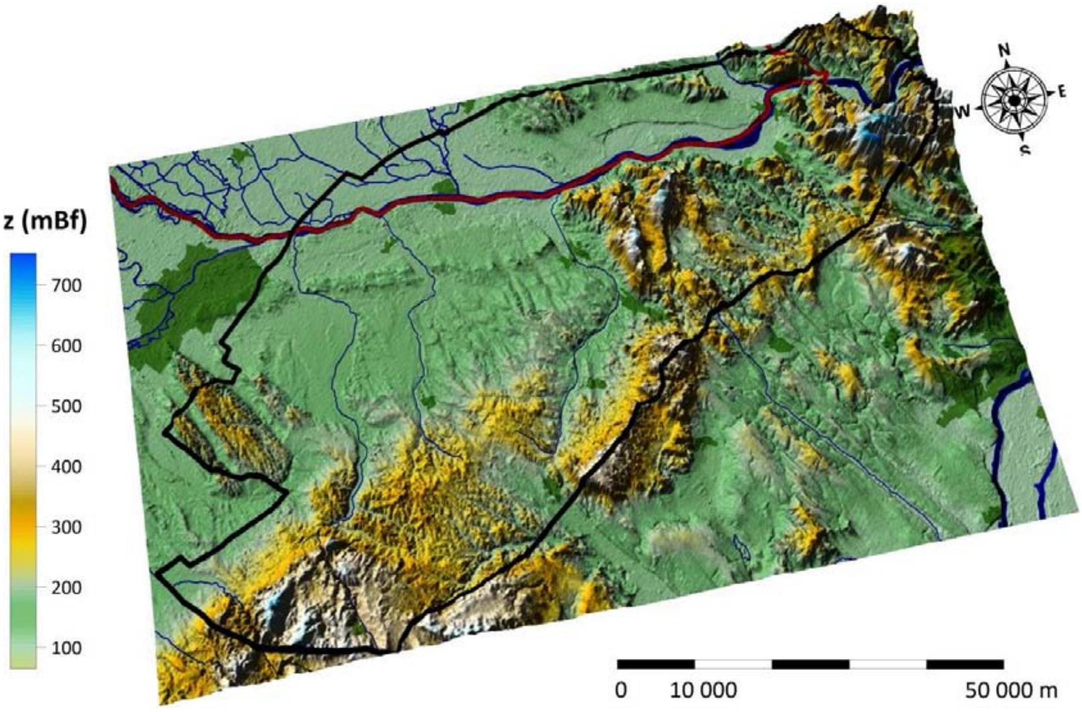


Figure 35: The area of the Komarno-Sturovo pilot model

The model area is outlined in accordance with the TE project pilot area, however it was enlarged to ensure natural boundary conditions.

The upper boundary of the model is the topographical surface, while the depth of the model is set at -5000 mASL. This depth is large enough for the undisturbed heat boundary condition for the next modelling phase, and at the same time deeper the inferred deepest part of the flow system.

During the horizontal outlining and mesh design the following aspects were taken into consideration: the geological framework with the main tectonic structures, the watersheds, the groundwater bodies, the main rivers, the recharge areas and the main discharge areas.

3.2.5.3 Model layerig

The geometry of the lithostratigraphic units, location of the covered and uncovered karst and the hydrogeological units of the area were taken into consideration. The model layers follow the geological settings: the pinched out layers exists towards E, SE. This pinching out were built in the model by parameter change in the same layer. Six main hydrostratigraphic units were defined this way in twelve numerical layers:

- Quaternary
- Upper Pannonian
- Lower Pannonian
- Miocene
- Paleogene
- Triassic basement

The Upper Pannonian and the Triassic units were divided into four and three, the Lower Pannonian was divided into two numerical layers. In this phase the fifth layer was represent the Upper Pannonian thermal water aquifer, the tenth layer is the uppermost 100 meters of the cavernous Triassic carbonate unit (Figure **36**).

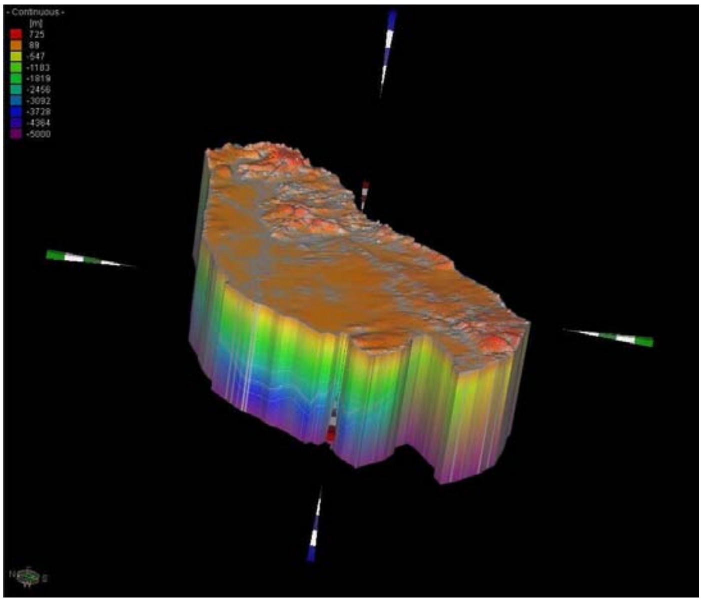


Figure 36: Geometry of the pilot area model

3.2.5.4 Results of the model

The open karst system is basically sensible for the climate parameters (direct relation between the surface and the deep subsurface region through the outcrops on the surface). Consequently the boundary conditions and the diffuse recharge on the top of the aquifer were the most sensitive parameters during the modelling of the hydraulic head distribution. (The head is less sensitive to the spatial distributions of hydraulic conductivity of the Mesozoic rocks due to the thick unified flow system.)

The recharge area of the deep karst system in Slovakia is situated in the area of outcropping carbonates in the Hungarian part of the modelled area. Subsurface water and heat flow has no limit along national borders. The simulated results are well reproduces this situation.

The modelled hydraulic heads are in a good agreement with the calculated ones around Tata and the NE part of the model, but unfortunately some under calibrated heads modelled in the SW part of the model area.

The Figure **37** presents the simulated hydraulic head distribution of the karst aquifer.

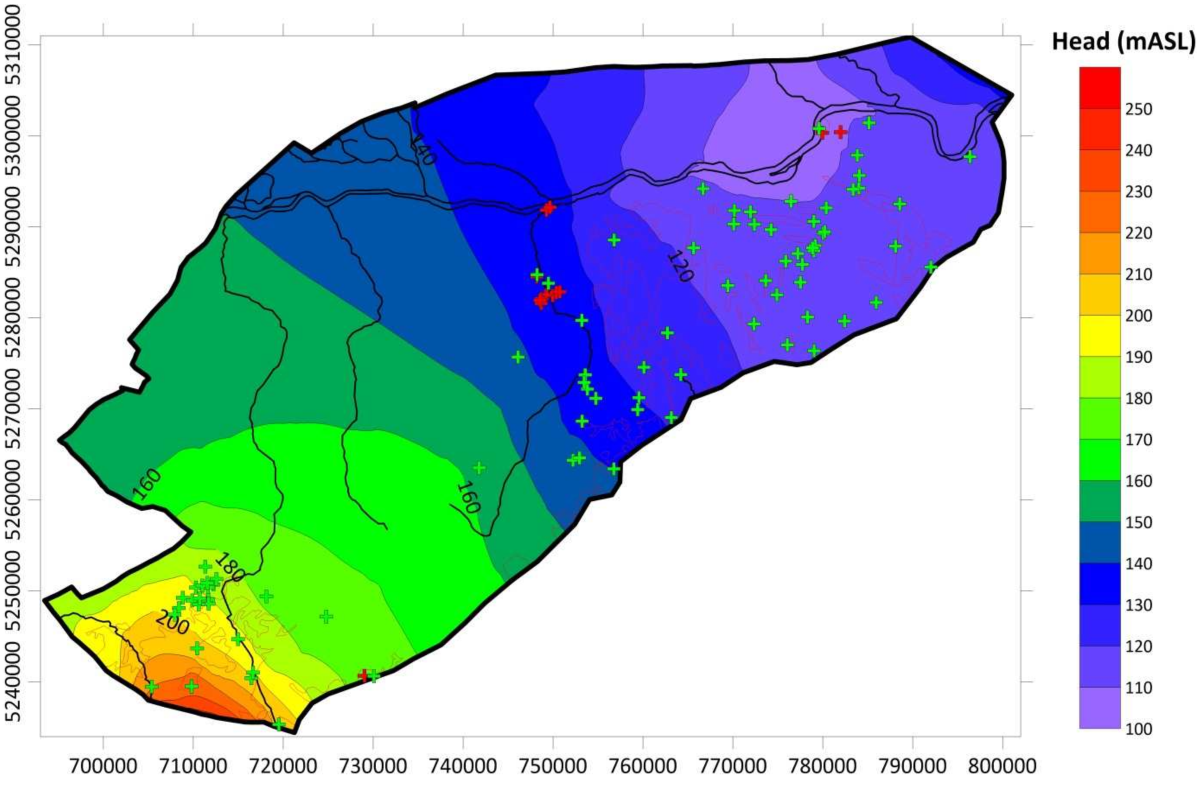


Figure 37: Modelled hydraulic head on the model layer '10', represented the Mezozoic karst aquifer

The temperature distribution of the Transdanubian karst flow system is mainly affected by forced heat convection. In the karstified dolomite and limestones the water can flow deep down the surface without any barrier: the recharged precipitation water cool down the system even at high depths. Due to the intensive flow system, this cooling effect can observed also far from the recharge areas (Figure **38**).

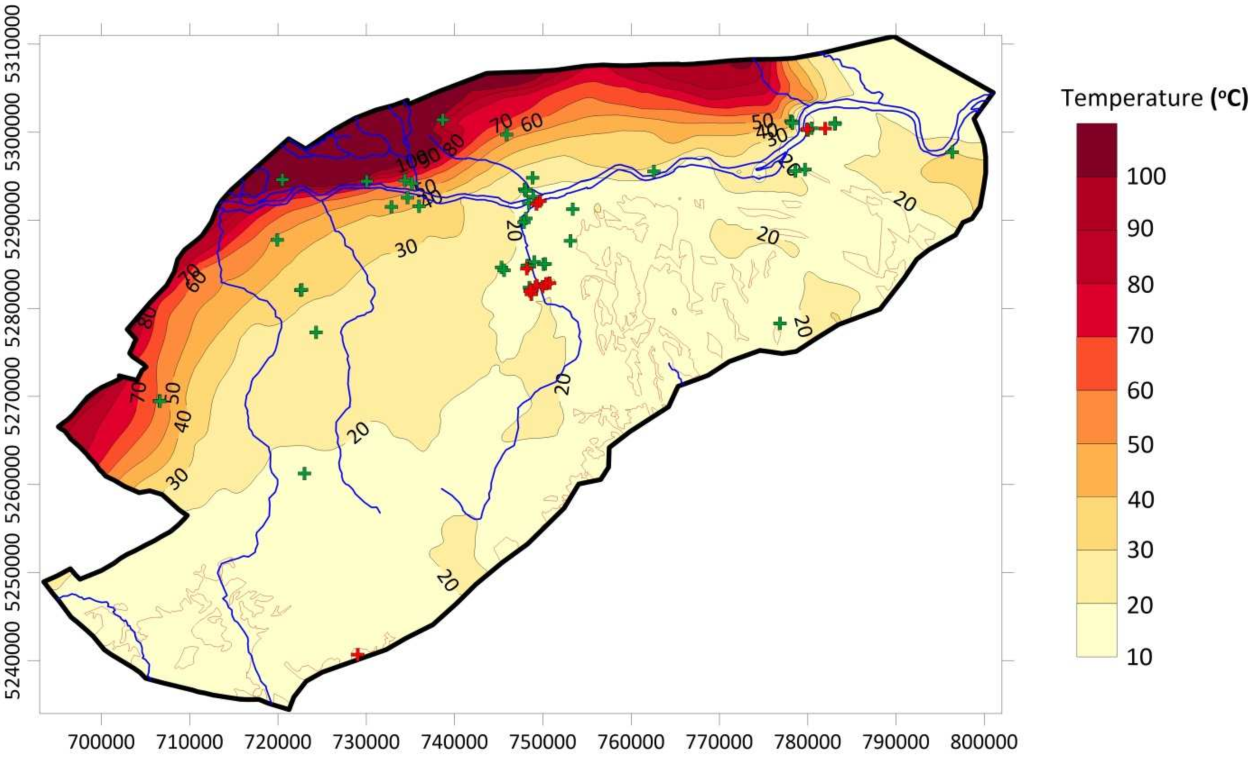


Figure 38: Modelled temperature distribution in layer ‘10’ (top of Mesozoic basement)

As described above the heat distribution affected by the flow system, thus the heat is very sensible for the hydraulic features of the aquifer. During the calibration of the head and heat distribution we had to manage together these two parameters, which took more difficult the modelling and the calibration.

The detailed description of the model can be found in Annex VII. “Report on Komárno - Štúrovo pilot area model” (Gáspár and Tóth 2013).

3.2.6 Vienna Basin model area

3.2.6.1 Model objectives

The overall aims and scientific questions tackle the estimation of hydrogeothermal potentials and resources in the Vienna Basin. Until the publishing of this report no hydrogeothermal utilization for energetic purposes has been realized, although there is a considerable potential to be expected in this region. In this context a sustainable future geothermal development has to found on a harmonized bilateral evaluation of the existing resources and their quantification in terms of geometrical and numerical models. As the Vienna Basin was in the past and is still intensively used for hydrocarbon exploitation, possible conflicts to the hydrocarbon industry have to be considered.

The modelling comprises the following different approaches:

i. A regional scale 3D heat transport modelling covering the entire pilot area.
ii. A local to regional scale 2D raster calculation approach in order to estimate the available Heat in Place and expectable Heat Recovery Factors at selected hydrogeothermal plays.
iii. An experimental estimation of the Heat Recovery Factor based on 3D parameter modelling.

In this context approach (i) delivers crucial data input and boundary conditions for approach (ii) and (iv) in terms of temperature conditions. Approach (iii) in turn delivers empiric functions, which allow the derivation of Heat Recover Factors from hydraulic rock properties in a first approach.

As there are currently no geothermal installation for energy supply in the investigated hydrogeothermal plays and as the main relevant geothermal aquifers are supposed to represent connate, closed systems (no free or forced convection expected), pure conductive modelling will meet the requirements. Therefore a static hydraulic model has been neglected.

The presented report is clearly focussing on the achieved regional scale 3D heat transport model (i).

The aim of the modelling in the Vienna Basin was to calculate the overall geothermal conditions at the Vienna Basin in order to allocate thermal boundary conditions and input data for (i) the evaluation of hydrogeothermal potentials at the identified geothermal plays and (ii) for the subsequent scenario modelling at the Schoenfeld – Láb area. Temperature data from more than 160 hydrocarbon wells was used for validation of the results. Furthermore, the output of this model will deliver crucial input like boundary and initial conditions for a smaller and more detailed scenario model. In the central and northern Vienna Basin no major thermal water systems are expected, therefore pure conductive modelling was applied.

The detailed description of the model can be found in Annex VIII. “Report on the numerical modelling at the Vienna Basin pilot area model” (Goetzl et al. 2013).

3.2.6.2 Geographical settings and model domain

The Vienna Basin pilot area covers the central and north-eastern parts of the Vienna Basin. Crystalline outcrops, namely the Leithagebirge in Austria and the Little Carpathian Mountains in Slovakia define the eastern boarder of the model, the western boarder is defined by the boundary between the Flysch Zone and the Upper Austroalpine Bajuvaric nappe system. The southern boundary is defined by the Leopoldsdorf fault system. The maximum extension of the model area is about 150x75 km laterally and 15 km in depth (Figure **39**).

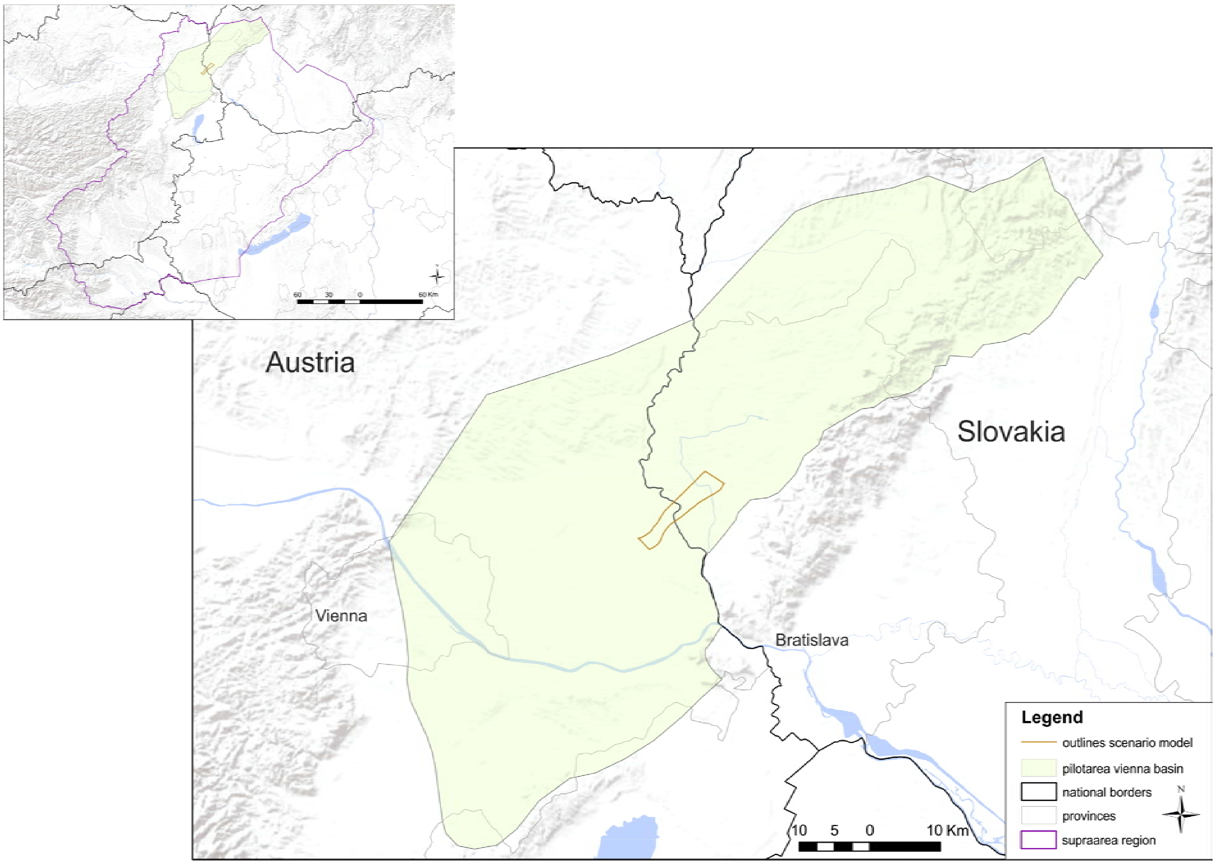


Figure 39: Delineation of pilot area and the scenario model “Schönfeld-Láb”.

The horizontal extend of the model is a 127x50 km2. The south-western boundary at the Leopoldsdorf fault has been adjusted in order to take the fault geometry into account. This was necessary to consider the thermal anomaly, caused by a major thermal water system located right beyond the fault.

The upper boundary is defined along the topography - surface, the lower boundary is set in a depth of 15 km below sea-level. This big vertical extend is needed to take all geological features of the Vienna Basin into account, as the lowest part of the pre-tertiary basement is situated in a depth of about 12 km below sea-level.

3.2.6.3 Model layerig

The following main geological units have been considered:

i. Crystalline basement; including Bohemian Massive, Tatric and Lower Alpine Units (aquiclude)
ii. Flysch units (aquiclude)
iii. Mesozoic Carbonates : Mesozoic cover of the Central Alpine and Tatric units (aquifer)
iv. Calcareous Alpine (Upper Alpine) Units (aquifer)
v. Neogene basin sediments (both aquifers and aquicliudes).

The Upper Alpine Units were subdivided on the basis of 3D interpolation of the material properties into the following nappe systems: Bajuvaric-, Tirolic-, Juvavic- nappe systems as well as Gosau Units and the Greywacke Zone.

3.2.6.4 Results of the model

The results of the regional scale thermal modelling deliver crucial data for further estimation of hydrogeothermal resources at the Vienna Basin pilot area and will be used for the subsequently following scenario modelling. The statistical evaluation of the results shows a good fit to the measured data. In total 775 DST temperature values from 235 wells were used for validation of the modelled subsurface temperatures. This evaluation shows that the applied simple 3D conductive thermal model was able to fit the observed subsurface temperatures in satisfying way although neglecting the effect of thermal convection. For the current study the measured temperatures are only used for validation of the model, detailed interpretation of these results is left open for further research (Figure **40**).

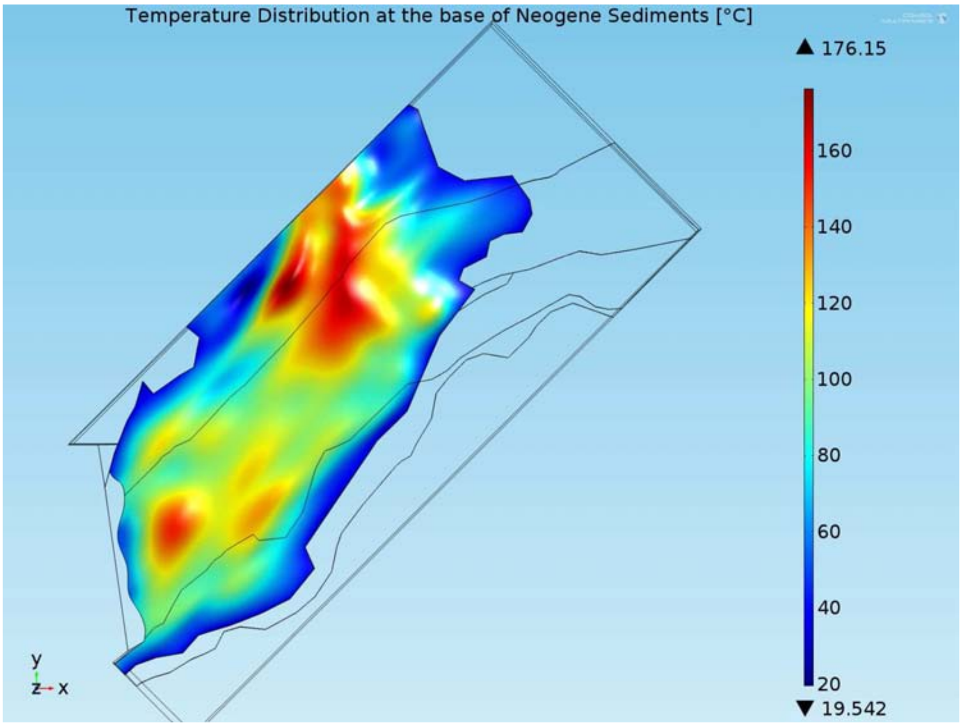
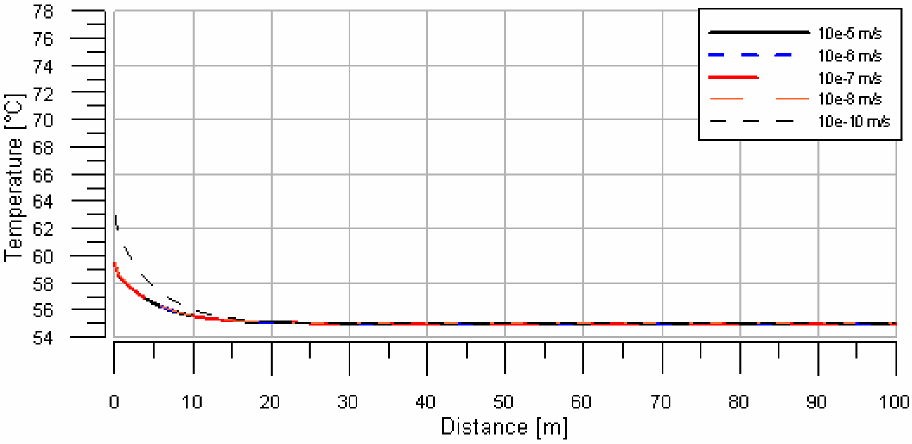


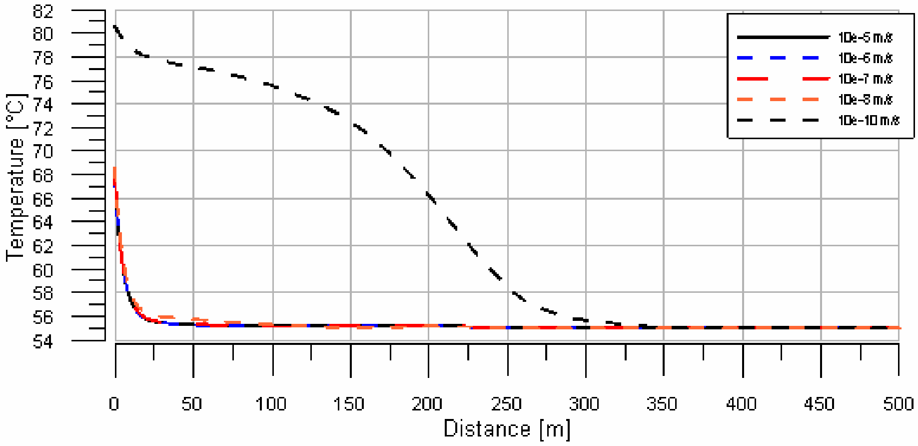
Figure 40: Temperature distribution at the Base of the Neogene sediments [°C].

The executed parameter study exhibits the dependence of the minimum required distances between the wells of a hydrogeothermal dublet as function of the aquifer thickness, the hydraulic conductivity and the yield. The distance between the wells of a dublet is in turn crucially influencing the so called Heat Recovery Factor (amount of technically extractable heat) of a geothermal reservoir. The influence of the aquifer thickness and the hydraulic conductivity shows a similar asymptotical behaviour passing critical values of (i) an aquifer thickness of more than 500 meters and (ii) a hydraulic conductivity of above 10-7 m/s. The yield of course shows of course a great influence on the minimum distance between the wells of a hydrogeothermal dublet. In order to consider the influence of the yield in a more general way further parameter studies will have to be executed assuming greater thicknesses of the aquifer as well as varying hydraulic conductivities (Figure41**Hiba! A hivatkozási forrás nem található.Hiba! A hivatkozási forrás nem található.**).

Temperature distribution in 2550 m.b.s. between production and injection well (100 m distance) after 50 years of operation



Temperature distribution in 2550 m.b.s. between production and injection well (500 m distance) after 50 years of operation



Temperature distribution in 2550 m.b.s. between production and injection well (1000 m distance) after 50 years of operation

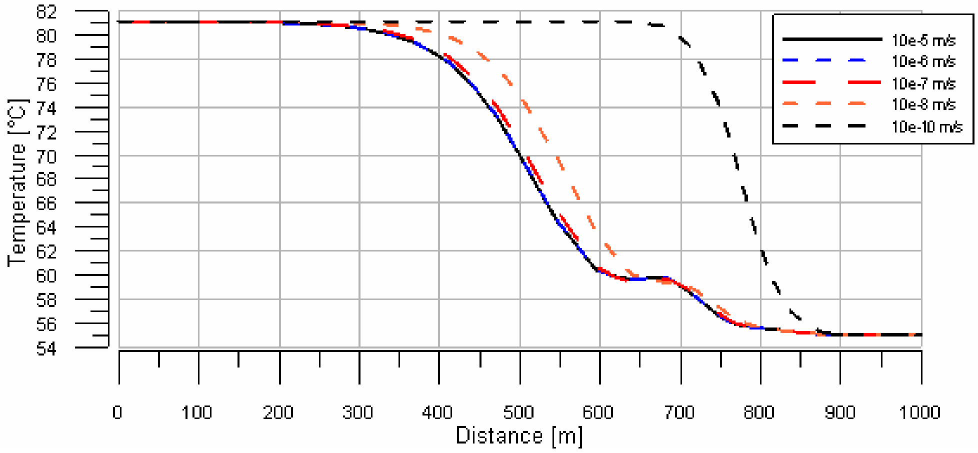


Figure41: Temperature distribution in a depth of 2550 m between the production (0 m) and the injection well
(well distance: 100 m, 500 m and 1000 m).

4 SUMMARY AND COCLUSION

To utilize the nature in sustainable way we have to understand the processes that rule the system. This way we can utilize the energy without the danger of depleting our resurces and we can care about the energy andresource policy of our neighbours. This is the idea behind the words „sustainable” and „transboundary”.

To help to undestand the processes in nature integrated models were created that descibe the water regime and circulation as well as the energy sources and resources, and balances. This was the mission of our uniqe partneship as we are the geological institutions. We gave by the models overall picture that can be studied in more details by more detailed studies. The models showed as well hypothetical scenarios in future (Komarno-Sturovo), explain the anomalies (Bad Radkensburg-Hodos, Danube basin), give oppinion on reasonbable reinjection and structures utilization (Vienna Basin).

The uniform system approach of Supra-regional models consisted of a series of conceptual and numerical models building on each other. Both in the supra regional and the local modelling areas these were the following:

- Geological models
- Hydrogeological (including hydrogeochemical-, flow-, and transport) models
- Geothermal models

The supra regional models included the entire project area. They handled this area in a uniform system approach. It had given an overview on the large-scale geological, hydrogeological and thermal characteristics of thermal water flow systems in the western part of the Pannonian Basin.

Pilot models focused on the local transboundary problems, and the detailed geothermal characteristics of these areas. The above discribed staeady state models of the pilot areas discribe the groundwater flow and geothermal system and serve as basis for the scenario models.

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