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Report on the Zsira- Lutzmannsburg pilot area model

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5.2.3 Detailed hydrogeological modelling

5.2.5 Detailed geothermal modelling

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1 INTRODUCTION

Geothermal energy and its most important carrying medium, thermal groundwater is strongly linked to geological structures, regardless of political borders. Sustainable utilization of resources in transboundary geothermal systems requires common harmonized geothermal energy and thermal water management in the effected countries.

During the everyday management of thermal water systems, a tool is needed to provide the decision makers with information about the future responses of the system given to the effects of various interactions, as well as about available hydrogeothermal resources. This tool can be based on the results of different geoscientific models (geological, hydrogeological and thermal models).

This report presents the results of the steady state hydrogeological model of the Zsira-Lutzmannsburg pilot area of the TRANSENERGY project.

2 GENERAL BACKGROUND

The geothermal systems of the western part of the Pannonian Basin located in transboundary position. 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 (ROTAR-SZALKAI 2012). The identified geothermal reservoirs extend toboth countries. Several famous spas are operated in the region within a relatively short distance from 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) and the recharge and thermal conditions require further clarification.

To provide an overview on the large-scale hydrogeological processes of geothermal systems and the connection among the main groundwater bodies, supra-regional hydrogeological model was developed.

Focusing on local transboundary problems, and the detailed geothermal characteristics of these sites,pilot area models were constructed. The supra-regional model supplied the boundary conditions of the pilot models.

3 MODEL OBJECTIVES

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.

4 CONCEPTUAL MODEL

4.1 Geographical settings

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 1) extends along the national border between Hungary and Austria. The Sopron-Ödenburger Mountains, the Rosalia Mountains, Bucklige Welt and the Kőszeg-Rehnitz (Rohonc) Mountains represent the boundaries of the model area in the West. The elevation of the mountains vary between 400-900 m. The highest point of the model region is 897 m. These high elevated mountains surround the Oberpullendorf (Felsőpulya) Basin, which continues in the southern part of the Little Hungarian Plain (Kisalföld) eastwards. The terrain is gradually lowering eastward, and the elevation of the lowland is slowly decreasing toward EN, the lowest point is 119 m. The Marcal valley represents the eastern boundary. Northward the region continues toward the Danube Basin (northern part of the Kisalföld Lowland). This part of the Little Hungarian Plain (Kisalföld) is called Hanság, which was originally a wetland in natural conditions.

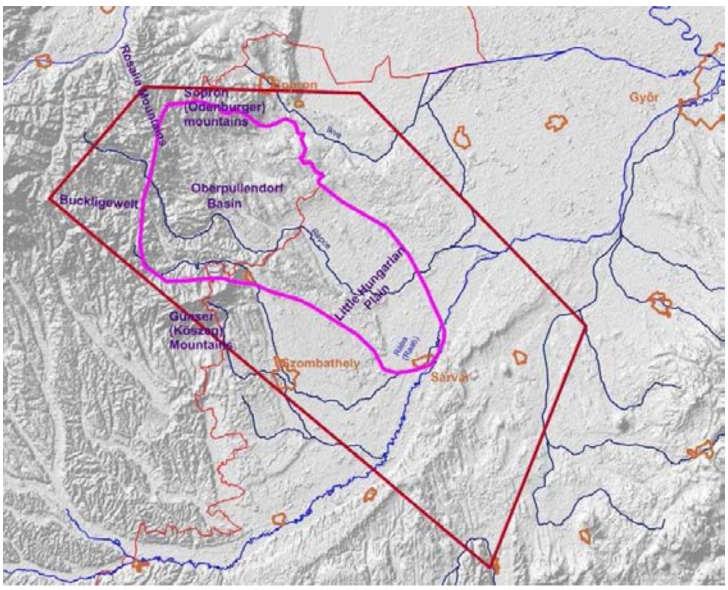


Figure 1. Geographical settings of the pilot area and the model region

There are many smaller creeks derived in the mountains. The main rivers of the region, Rába (Raab) and Répce and Ikva collect the water of smaller creeks, and drive towards the Danube River. Marcal has small watershed in the model region, but important because it represents the eastern model boundary. The rivers follow the main tectonic lines.

Several wetland areas are situated in the pilot area (along the Répce river and Hanság region) in natural conditions. However, inundation continuously endangered the human settlements and ploughlands. Since the beginning of the 19th century, several attempts were made to drain the Hanság. Currently, a dense channel network drains the water from the region towards the Danube.

4.2 Climate

The region belongs to the cool and humid climate. The annual mean temperature varies between 7.5-10 ºC; in the vegetation period it varies between 14.5-16.5 ºC.

The annual amount of precipitation varies between 590-800 mm. Its value is higher in the mountain region and it is decreasing eastwards in the lowland (Figure 2).

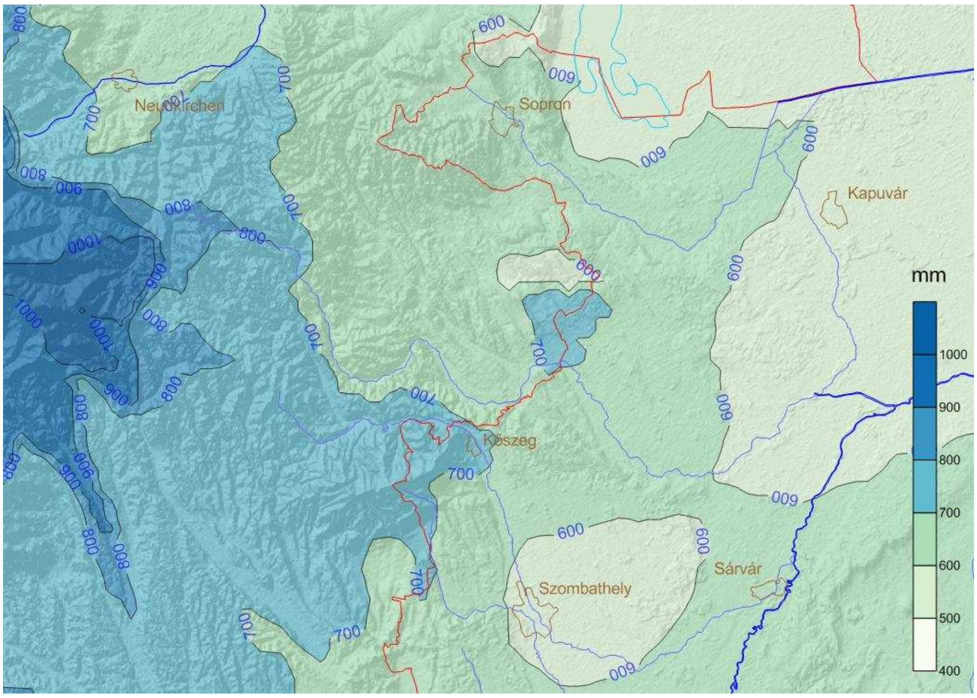


Figure 2. Distribution of annual amount of precipitation

4.3 Geological settings

The Lutzmannsburg – Zsira area has no natural, geological borders. The basement consists mainly of metamorphosed crystalline rocks of the Austroalpin (Semmering- Wechsel System) and the Penninic (Rechnitz window) units. These units form different nappe systems thrusted on each other. The tectonic movements and the deep structural position results different grade metamorphosis of the rocks. The basement is covered with Neogene succession.

Based on the constructed geological map surfaces a 3D geological model was developed (Figure 3). The details of the geological model can be found in separate report (Maros et al 2012). In the following the summary of the geological settings is described.

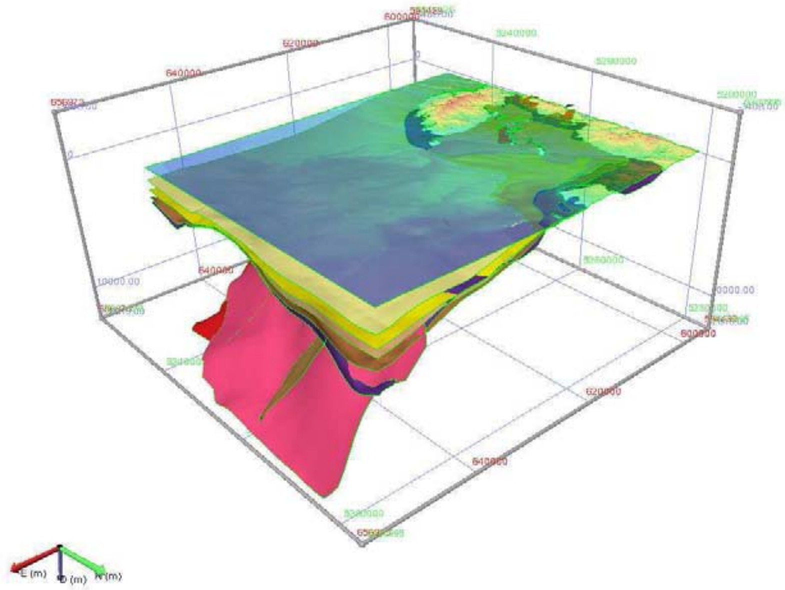


Figure 3. 3D geological model of the Zsira- Lutzmannsburg pilot area from the NE.

4.3.1 *Basement formations*

The Penninicum which consists of an ophiolite massif (serpentinised ultramafic, metagabbro, greenschist and blueschist) and metasediment rock complex (calcareous phyllite, quartzphyllite, metaconglomerate) represents the deepest structural unit. The protolites are Jurassic oceanic crust formations and pelagic sediments which were rich in marly pelites derived from the opening basement of the Penninic Ocean. The unit is strongly folded, and consists of several internal nappes. The Penninicum outcrops in the SW part of the region, in the Rechnitz tectonic window and continue eastward in the basement covering with Austro-Alpin nappes (Figure 4). The estimated thickness of the unit is more than 2000 m.

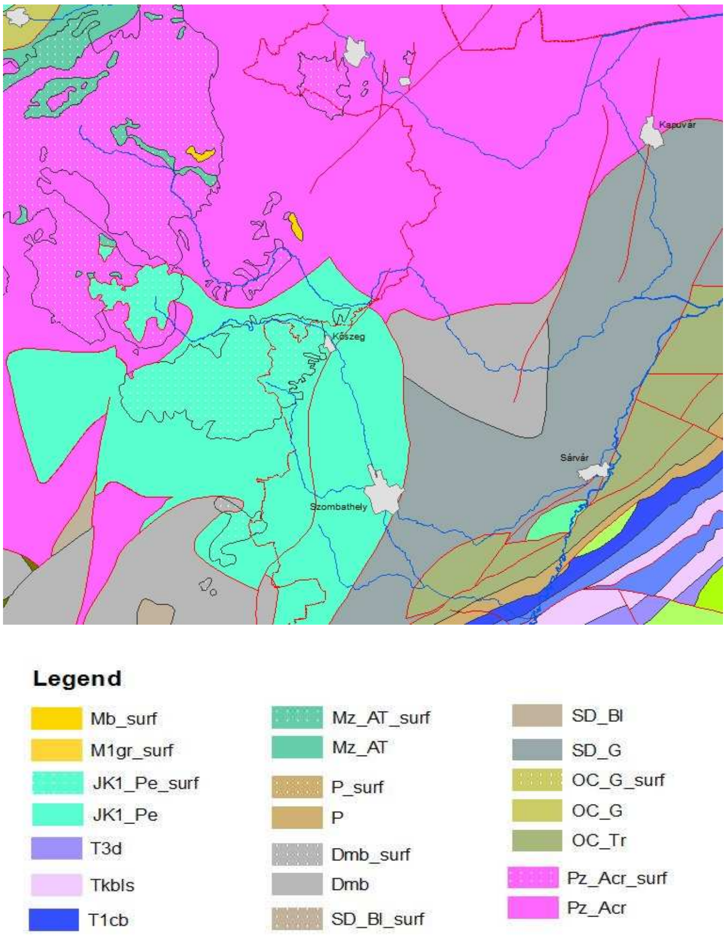


Figure 4. Location of the basement units (Maros et al. 2012)

The tectonically connected Lower Austro-Alpine nappe unit can be found on the surface at the NW part of the area in tectonic windows of Sopron-Mountains and Wechsel. This unit composes the basement on the North in 1000–2000 m depth, covered by neogen sediments (Figure 4). It consists of polymetamorphic gneiss and mica-schist of Wechsel series.

The Upper Austro-Alpin nappe system forms the basement a SW-NE zone W of the Raab (Raba) fault system. South from the model region it can be found in greater extent in the Steyer Basin (Figure 4). The tectonical located unit built up from the rock complex of Graz Paleozooic in Austria and the correlated Rábamente Metamorphic Complex in Hungary. The low-grade (Szentgotthard Phyllite, Mihály Phyllite, Bük Dolomite, Ölbö Carbonatephyllite) and very low-grade (Nemeskolta Sandstoneschist, Sótony Metabasalt) metamorphic formations was interpreted as the result of an Early Paleozoic sedimentary cycle by Fülöp (1990) who considered the Nemeskolta Sandstone as the basal unit of the cycle, then different phyllites (Mihályi Phyllite) would follow with volcanic intercalations (Sótony Metavolcanite) and Devonian carbonate (Bük Dolomite) closes the sequence. The main basement formation of the area is the Bük Dolomite, which was exposed in numerous boreholes around the SE part of the pilot arae (Bük, Ölbö, Rábasömjén, Nemeskolta, Ikervár). The maximal thickness of Bük Dolomite Formation is 280 m. The Devonian formations occur in two patches in the area. The boundary of the Devonian formations in the northwestern patch are the thrust front between Upper and Lower Austroalpine Units on the northwestern, and younger normal fault on the southeastern part. The boundaries of the southeastern patch are stratigraphical on the southern and the eastern part, and structural (younger normal faults) on the northwestern part.

Eastward from the Raba tectonic zone carbonate Mesozoic unit form the basement, which supposed to belong to the Upper Austro-Alpin nappe series. These formations constitute the unit of the Transdanubian Range. According to the interpretation of deep seismic profiles the deeper parts of the Upper Austro-Alpin complex can be found below the carbonate series.

4.3.2 Neogene sediments

The Lower Miocene siliciclastic and debris sediments have been deposited in the morphological lowlands on the tectonically preformed surface of the crystalline units. The Miocen- Pannonian porous sediment series has growing thickness toward E-SE. The maximum thickness is 2000 m at the eastern part of the region.

During the Eggenburgian and Ottnangian the study area was characterized by continental sedimentation on the erosional surface of the paleo-mezozoic rocks. It unconformably overlies the tectonically pre-, and synformed Mesozoic basement, and is unconformably overlain by the Szilágyi, Kozárdi, Lajta or younger 'Pannonian' formations. In the middle (HU) and the northern (A) region (in foreland of Kőszeg Mts.) limnic, marsh or deep paludal succession with lignite seams and with unsorted clastic basal beds were deposited (Brennberg Formation). It is assigned to the Ottnangian only on the basis of its overlying succession of Karpatian-lower Badenian age (Ligeterdő Gravel Formation, "Auwaldschotter"), which is made up mainly of fluvial, subordinately brackish water gravel, conglomerate, sand and marl. The lower part of the lower Badenian is missing all over the area due to early Badenian tectonic movements and erosion. Badenian successions start with the upper part of the lower Badenian with abrasional basal breccia and conglomerate, locally with calcareous matrix (Pusztamiske Formation). In marginal, shallow marine facies it is overlain by corallinacean limestone ("Leithakalk", Lajta Formation). Nearshore facies are characterized by grey, greenish-grey sand-sandstone (Pusztamiske Formation). Offshore deep-basin (shallow bathyal) facies are represented by fine siliciclastic sediments: sandy silt, silty clay marl with sandstone intercalations Tekeres Formation), and sandy-silty claymarl. In the Upper Badenian siliciclastic sediments were deposited (Szilágy Clay Marl Formation) due to the renewed flooding. In shallow marine environments deposition of the „Leithakalk" went on.

With the onset of the Sarmatian a significant change occurred, which was triggered by the restriction of the open sea connections of the Central Paratethys. Biogenic calcareous sediments (mollusc-bearing limestone, and oolithic limestone, Cerithium limestone) of shoreline facies (Tinnye Formation) and fine-siliciclastic sediments (grey, greenish-grey clay marl, sand, silty clay marl) of shallow-marine facies (Kozárd Formation) were deposited.

The Pannonian sequence in the study area is a shelf-slope system prograded chiefly from northwest to southeast. During the Upper Miocene (Pannonian) a more or less uniform Pannonian Basin developed, the formation of which may have been started in the late Sarmatian. Predominantly fine-siliciclastic sequences of different facies accumulated in the Csapod-trough along the synsedimentary normal fault to the basin on the southeastern part of the area (Endrőd Fm.). The overwhelming part of the successions of the deeper basin facies (Endrőd Formation) is made up homogeneous pelitic deposits; distal turbidites are represented by separate sand bodies (Szolnok Formation). Underwater slope (delta slope and basin slope) sediments are represented predominantly by dark grey clay marl as coarser sediments were carried further basinwards to be deposited as turbidites (Algyő Formation). Sand bodies occurring along the fluvial delta fronts belong to the Újfalu Formation on the northwestern part of area. Deposits of the alluvial plain are represented by the frequent alternation of fluvial and lacustrine fine grained sand, silt, clay and clay marl beds locally with lignite strips (Zagyva Formation). By the end of the Late Miocene, rivers running down from the neighbouring mountains filled up the basin, and a continental terrain came into being in the area of the former basin).

4.3.3 Tectonics

There are two main thrust planes constructed by Alpine tectogenetical cycle. The Alpine thrust planes are located on the margin of Rechnitz-window between Penninic and Upper Austroalpine Units in the middle of the area. Furthermore, another thrust plane is located between the Upper and Lower Austroalpine Units on the northern part of the area. The thrust planes, formed in the Middle and Upper Cretaceous were separated by normal faults in the Paleogene (Balogh & Dunkl 2005) and Early Miocene (prerift phase of the Pannonian Basin). This normal fault tectonics was connected to the basement exhumation structure of the Rechnitz-window core-complex (Tari 1994). The third main structural element of the pilot area is a younger normal fault which formed in the synrift phase of the Pannonian Basin. The repeatedly reactivated normal fault is located in the southeastern part of the pilot area (in Hungary). The NE-SW strike normal fault is detected in the boreholes of Bük to the southeast and northwest of Ölbő boreholes, cutting across the Lower Pannonian basement, the Miocene formations and faulted the formations of the Upper Austroalpine Units including the Bük Dolomite Formation and the thrust plane between the Upper and Lower Austroalpine Units (out of pilot area). This significant fault was called „Répce-fault" by Tari (1994). The main structural elements of the pilot area are shown in Figure 5.

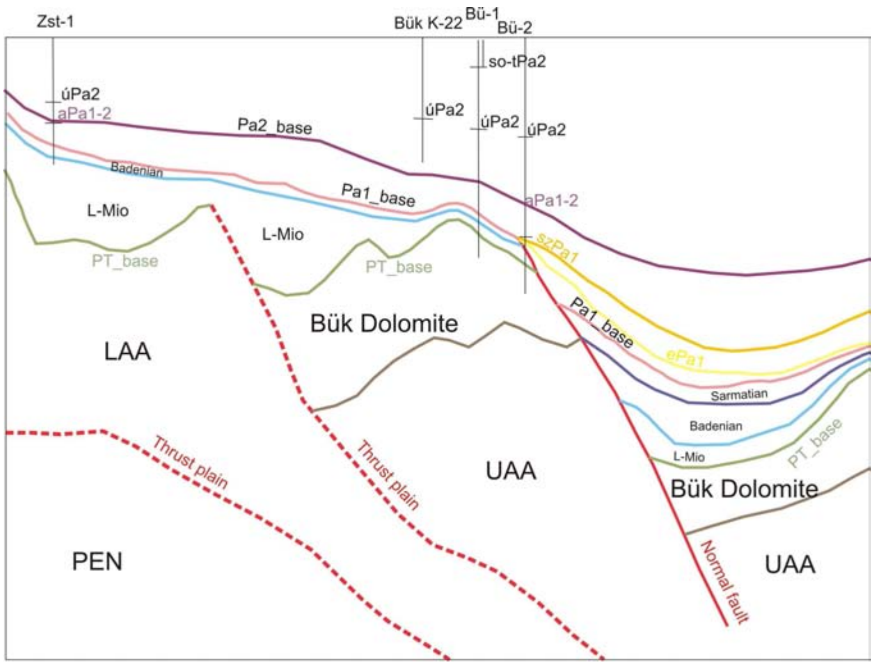


Figure 5. Main structural elements in the seismic section at the eastern part of the Zsira- Lutzmannsburg pilot area (Hungary).

UAA – Upper Austroalpine Unit, LAA – Lower Austroalpine Unit, PEN – Penninic Unit

4.4 Hydrogeological settings

The hydrogeological settings is reviewed on the basis of earlier studies and models, and field data obtained during well installation and monitoring. In the following the most important processes influencing the hydraulic conditions and the hydrogeological characteristics of the main hydrostratigraphical units will be described.

4.4.1 Hydrostratigraphical units

The following hydrostratigraphical units were determined in the Lutzmannsburg-Zsira pilot area:

- Crystalline Basement Formations
- Devon Dolomit Formation
- Miocene Formations
- Lower Pannonian Formations
- Upper Pannonian Formations
- Quarternary Formations

The Crystalline Basement Formations represent fractured aquifers, usually with low permeability. Nevertheless, in structural zones and the upper wheathered zone their permeability can be higher, and can act as reservoirs. Due to deep basinal position littleinformationis available about their caharacteristics and the locations of basement resevoirs.

The Devonian Dolomit Formation is a special type of basement reservoirs. It can be characterized as a fractured aquifer, with high permeability. The permeability originates from multiple tectonic stresses, the reactivation of structural elements, and possible karstification during exposed periods.

The Miocene layers have different hydrogeological characteristics. The Lower Miocene, siliciclastic shallow water sediments are good porous aquifers. The shallow marine deposited biogen limestones and siliciclastic limestones have double porosity and usually have high permeability too. The other deep basin deposited Miocene sediments are usually aquitards. The thin permeable layers are usually surrounded with low permeability marl and clay layers, which results restricted recharge of the aquifers. The low grade of groundwater flow results extremely high TDS values. The Miocene layers have hydrogeological importance only in basin marginal position, or where they are deposited directly on the basement where they represent connected reservoirs with basement rocks.

The Lower Pannonian series were deposited in delta slope environment. They mostly comprise clay and marl, and act as regional aquitards. The isolated permeable sand bodies derived from turbidites has no connections with other aquifer layers. This formation phisically separates the upper thermal waters from the lower geothermal systems.

The Upper Pannonian sandy layers represent one of the most important aquifers. Alternating with silty layers their permeability varies within a wide range. They have important role both as a cold drinking water supply and as a thermal water resource.

The Quarternary sediments are important only in river alluvial formations. Usually their thickness does not exceed 100 m in this region.

4.4.2 Recharge

Recharge of groundwater originates mainly from regional infiltration. The main recharge area is represented in the high elevation mountain region, which is mainly situated in Austria. Here, the crystalline basement formations are exposed in a large extent. Through the upper wheathered zones and main fractures the infiltrated water can leak toward the basement of the basin. The outcropping Miocene and Pannonian layers can receive direct recharge along the gradually deepening layers.

Besides the amount of precipitation, the hydraulic characteristic of the surface geological formations can influence the recharge process. On the basis of the surface geological map different recharge categories were determined (Figure 6).

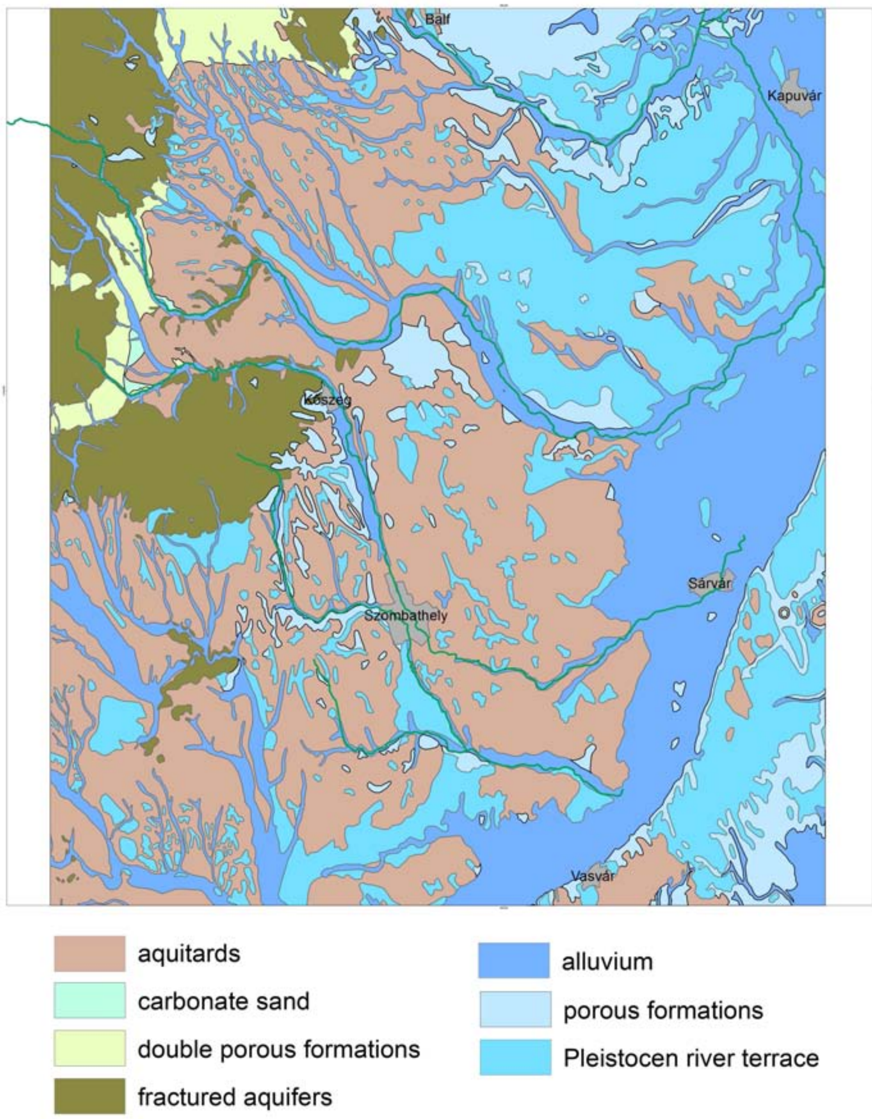


Figure 6. Recharge chategories in the modell area

4.4.3 Natural discharge

Natural discharge of groundwater can occur atsprings, direct leakageinto rivers or creaks, or at regions with high groundwater table (wetlands).

The main groundwater discharge areas of the model domain are the rivers and river alluvial valleys. The Rába river collects the water of the shallower flow system. The regional disharge area of the deep groundwater flow system and the thermal waters is the Marcal river.

In natural conditions several wetlands, especially Hanság had important role of groundwater discharge. RCurrently, there are only small patches of wetlands, but the dense artifical drainage channel network receives considerable groundwater discharge.

4.4.4 Hydraulic conditions

The groundwater flow system can be characterised with the position of the groundwater table, distribution of hydraulic potencials and their changes in time.

The groundwater table is known from the earlier regional groundwater models, especially the Supra-regional model of the TRANSENERGY project (Figure 7). Continuous groundwater table evolved only in the porous sediments of the basin. The groundwater table is situated mainly in Pleistocene sediments, or in the outcropping Pannonian or Miocen formations. The seasonal changes of groundwater table can be observed everywhere, but no long-term trends can be identidfied.

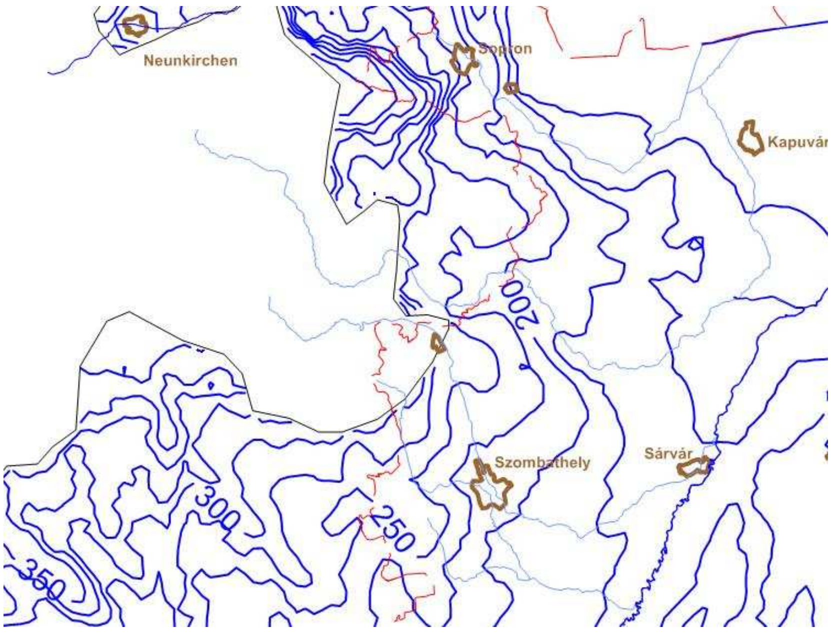
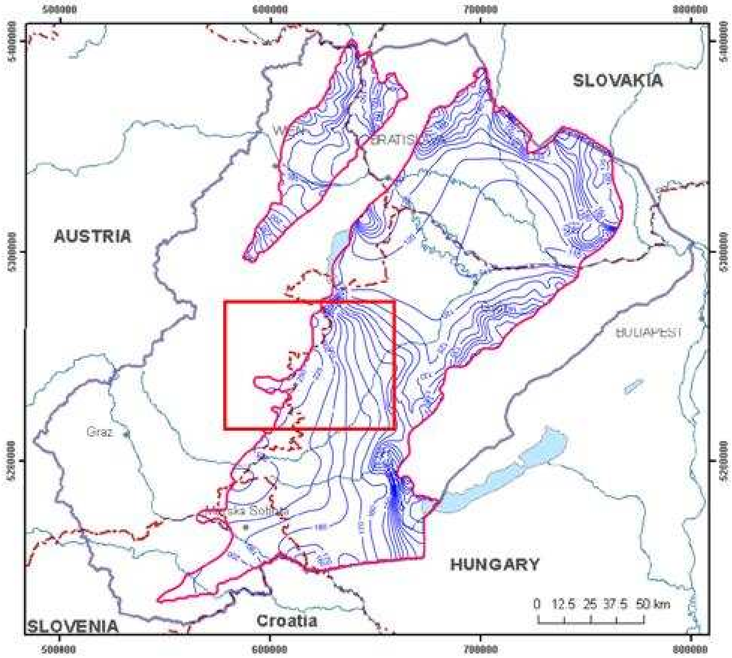


Figure 7. Calculated groundwater table in sura-egional model of TRANSENERGY project

The natural hydraulic potential values are known from well construction records and from calculated values of hydrogeological models. The results of the supra-regional model of TRANSENERGY project are shown in Figure 8. According to the existing information, the direction of groundwater flow in the Pannonian sediments is W-E in the elevated western regions,then groundwater partly flows towards the Marcal river or turn to N-NE towards the direction of the Hanság region. The NE flow direction is significant in the deepest layers.



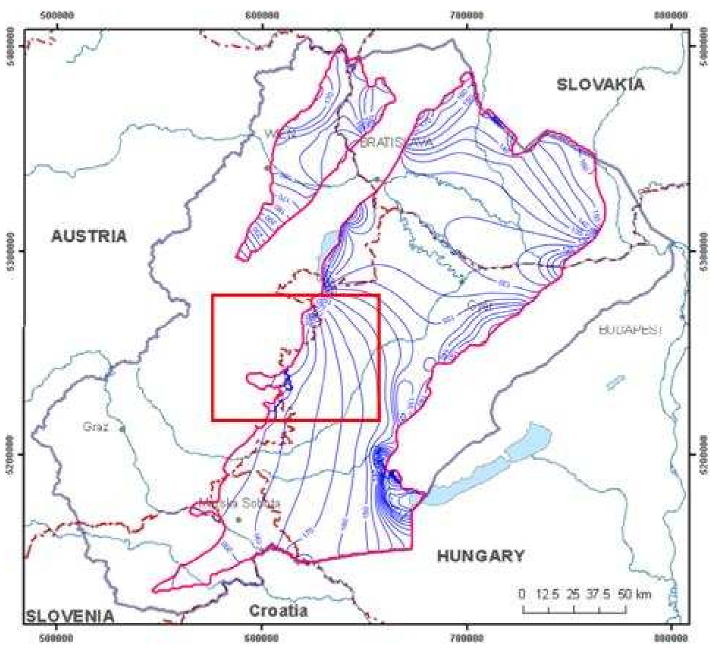


Figure 8. Calculated hydraulic potentials in the Upper Pannonian cold water (upper figure) and thermal water (lower figure) layers oft he Supra-Regional model

Several monitoring wells register the hydraulic potential changes in the Pannonian aquifers (Ólmod K-2, Bük K-15, Csepreg K-13). After several decades of observation only little (no more than 1-2 m) potential decline occured. However, significant groundwater depressuristaion exist in the Miocen layers due to groundwater extractions (Figure 9). The head dropexceeds 14 m during the 20 years monitoring period.

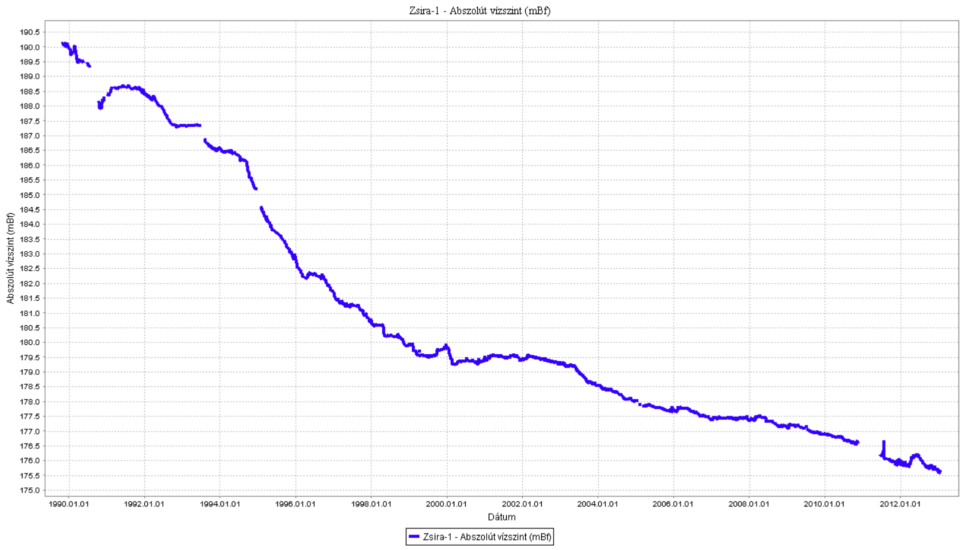


Figure 9. Changes in groundwater hydraulic potential in Zsira monitoring well

4.5 Geothermal conditions

The deepening basement and the potential thermal water reservoirs ensure favourable geothermal conditions both in the basin filling porous sediments and in the basement itself. The geothermal gradient (determined according the measurements of wells and drillings) in most cases exceeds the European average. The higher values are related to basement highs which mean the significance of conductive heat flow. Convection has only cooling effect near the mountain regions where descending cold water occurs.

The available maximum temperature is increasing eastward parallel with the basement depth. It starts to decrease at the SE margin of the area, where the basement is rising again toward the outcropping Transdanubian Midmountains. The temperature varies between 80-110 °C at 2500 m depth. Higher anomalies occur in the region of Szombathely-Sárvár and Csorna-Kapuvár.

The deepest temperature measurement was obtained in the crystalline basement at Egyházasrádóc (Rád-1) at the depth of 3401.5 m, where the temperature reached 115.8 °C. The Rad-2 borehole reached 112°C at 2950 m depth.

In the Devonian Dolomite basement reservoir at Bük. Thermal water at 61-68 °C temperature was discovered between 1000-1282 m depth. At the same place at 756 m depth, in the Upper Pannonian formation, 46,7 °C was measured. The Devonian basement temperature at Ölbő region is observed between 81-89 °C at the depth of 1965.5 m. In the Sárvár region 101 °C was measured at the depth of 2003 m, while in the Upper Pannonian layer 53.5°C was observed at a depth of 1296 m in Sárvár region. Similar to the Sárvár area, the Szombathely-II bore produced water at 103,5 °C from 2014 m depth within the deep crystalline basement. The same borehole produced water of 59 °C from the the Upper Pannonian layers at 948 m depth.in. In the region of Celdömölk, where the basement is built up from Mesozoic formation of the Transdanubian Range, the basement temperature is significantly lower (68 °C at 2656 m depth). Similar trend can be observed at Mesteri.

4.6 Groundwater extractions

Extensive groundwater extractions existing the region for several decades, both from the cold and the thermal water aquifers.

More than 200 wells are supplying drinking water in the region (Figure 10The depth of the wells in Austria does not exceed 100 m, except for the Neckenmarkt (Sopronnyék) and Kobersdorf (Kabold) bores. The aquifers are represented by different Upper Pannonian, Miocene and crystalline Basement formations.

The Hungarian drinking water supplying wells mostly target Upper Pannonian, sometimes Quaternary aquifers. The depth of the wells usually does not exceed 200 m. The biggest drinking water supplying system is the Szombathely-Kőszeg regional waterwork (VASIVÍZ Zrt). It supplies drinking water to 36 settlements. Concentrated withdrawals characterize the regions of Sárvár, Kapuvár, Celldömölk, Fertőd, Répcelak, Pecöl, Bük.

The most important places of thermal water extractions are Lutzmannsburg (Locsmánd) in Austria, and Bük, Szeleste, Sárvár, Szombathely, Szentgotthárd, Celldömölk, Balf, Kapuvár, Petőháza and Hegykő, Petőháza. The map of groundwater extraction wells are shown in Figure 10.

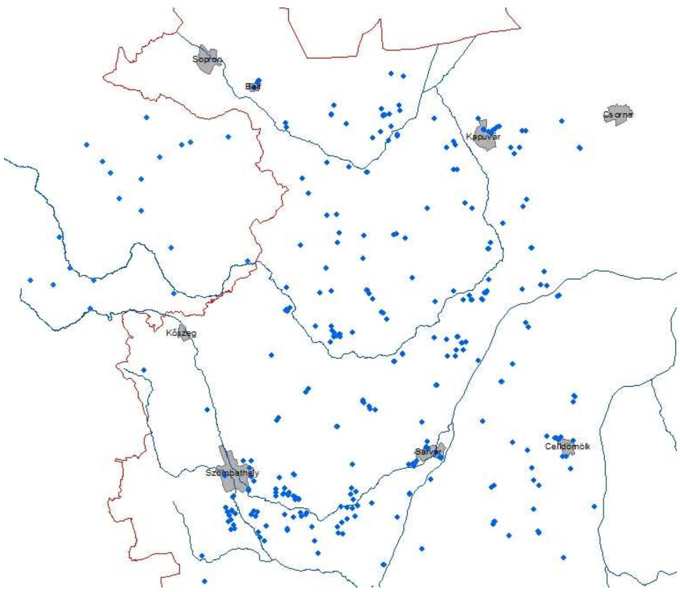


Figure 10. Location of groundwater extraction wells

5 NUMERICAL MODEL

The aim of the numerical modelling exercise was to investigate the natural flow field and temperature distribution in the study area both horizontally and vertically. The present report describes the results of the natural state modelling, which represents the first stage of the modelling study. The results and calibrated parameter fields obtained through natural state modelling will be used for investigating the effects of groundwater extractions (scenario modelling) on the flow conditions and heat distribution in the study area.

5.1 Modelling methodology

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.

The present stage of the modelling study doesn't include the simulation of groundwater extractions or predictive model runs. These will be described in a following report.

5.2 Applied software

A three-dimensional (3D) model was developed using FEFLOW 6.1 (Diersch, 2006). FEFLOW (Finite Element subsurface FLOW system) is a sophisticated 3D finite element software package for the modelling of flow, reactive mass and heat transport processes in porous media under saturated and unsaturated conditions. The FEFLOW package includes interactive graphics, a GIS interface, tools for interpolation and visualisation of data, and powerful numeric techniques for solving the equations of groundwater flow and solute transport.

FEFLOW uses a Galerkin-based finite element approach with a selection of numerical solvers and tools for controlling and optimising the solution process. For the simulation of groundwater flow at the site, flow simulations were undertaken using saturated steady state models.

5.3 Hydraulic model

5.3.1 Model geometry

5.3.1.1 Model domain

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 1. Coordinates of model corners.

model domain corner	UTM X	6 UTM Y
1	582000	5262000
2	599000	5281000
3	635000	5280000
4	674000	5241000
5	657000	5200000

The approximate extent of the model domain is 95x47 km. The model domain is shown in Figure 11.

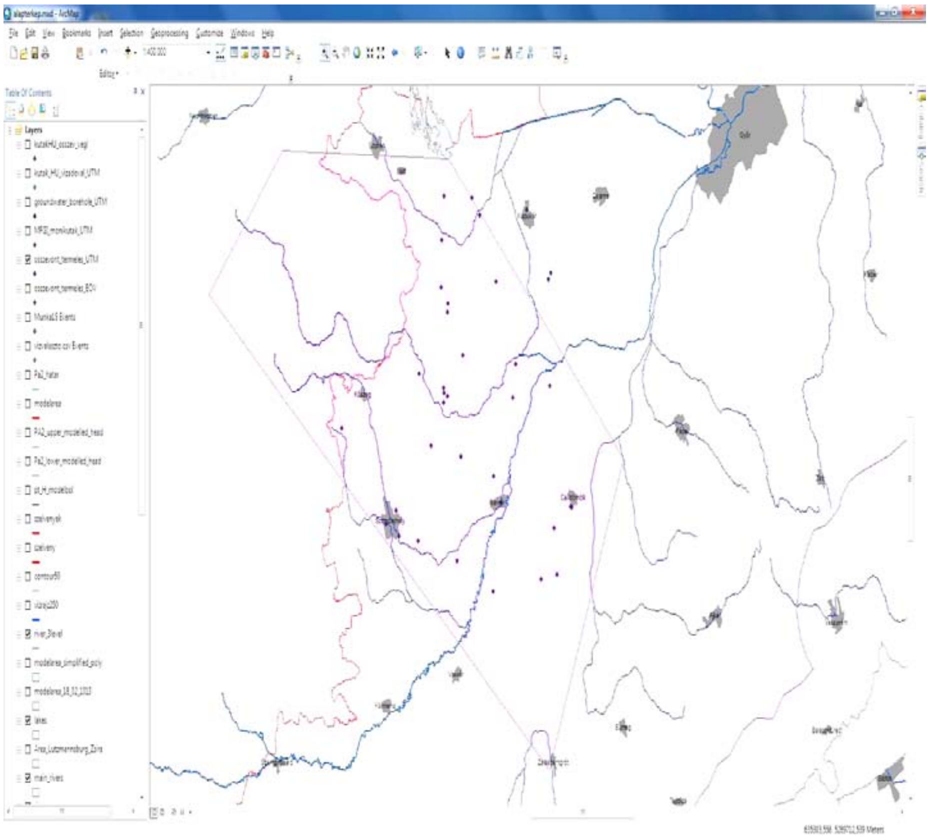


Figure 11. Model domain. Blue dots indicate extraction wells, red line indicates national borders, blue lines indicate surface streams.

6.1.1.1 Finite Element Mesh

The applied finite element mesh consisted of 11370 linear triangular finite elements in each model layer and 5793 finite element nodes in each model slice. The total number of finite elements is 136440. The average size of finite elements is 1000 m. The mesh was refined around extraction bore locations to an average element size of 100 m for supporting a better accuracy of scenario models. The applied finite element mesh is indicated in Figure 12.

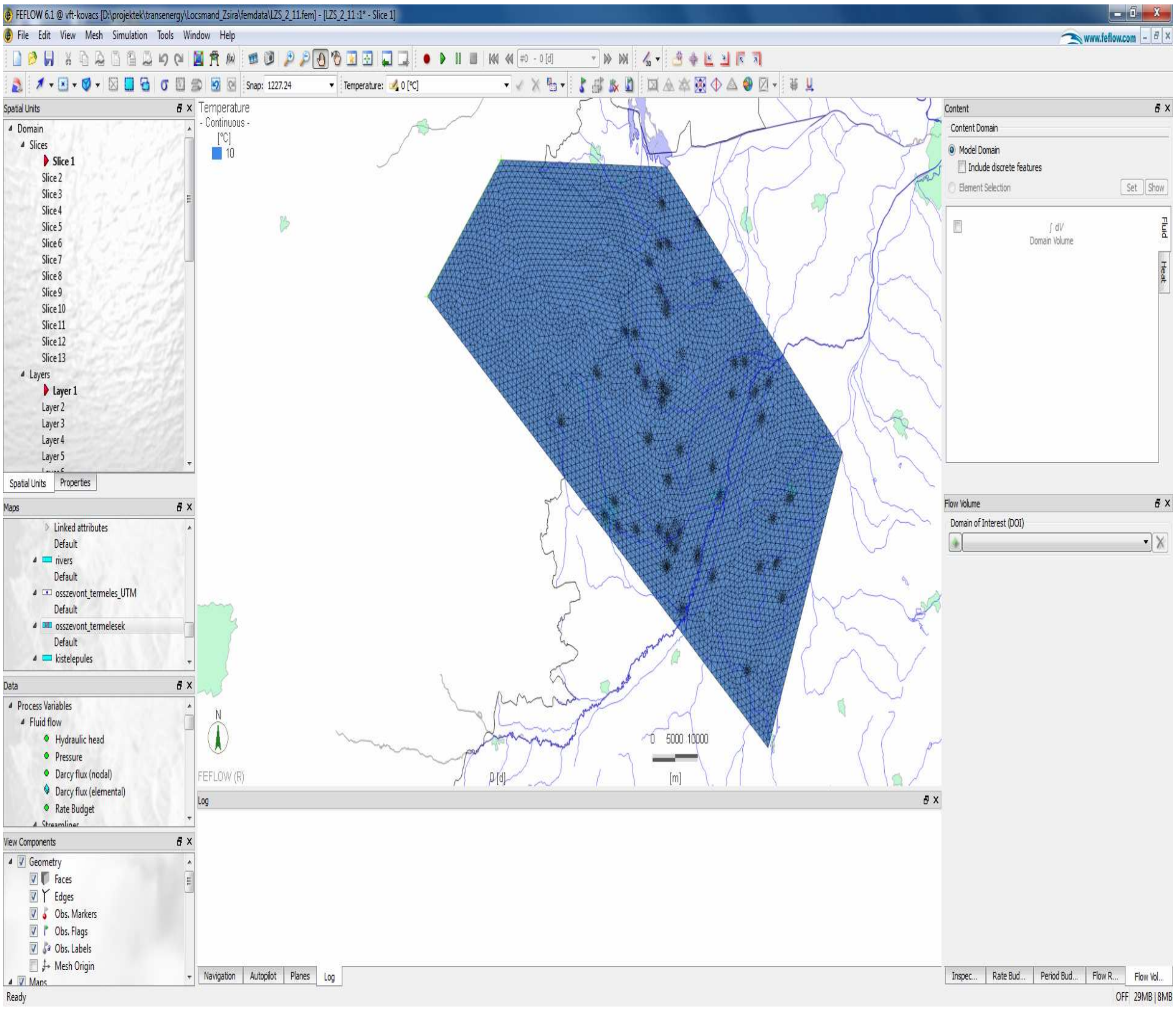


Figure 12. Finite element mesh.

6.1.1.2 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 vertical discretisation applied in natural state modelling will be further refined in the scenario modelling stage if deemed necessary. The applied model layering is described in Table 2.

Table 2. Applied model layering.

Unit	Geological code	Lithology	7 Hydro-stratigraphy	8 Model layers
Quaternary	Q	sand, silt, clay, gravel	AF1	9 1
Late Pannonian	Md	clay-marl, silt, sand	AF2	10 2-4
Early Pannonian	Mplf, Mptb, Mpcm	clay, silt, marl	AC1	11 5
Sarmatian	Msmf	clay, marls, sand, sandstone	AC2	12 6
Badenian	Mbls	limestone, conglomerate	AC3	13 7
Early Miocene	M1fc	conglomerate, sand, marl	AF3	8
Devonian	Dmb	marble	AF4	9
Basement upper	JK1_Pe, Pz_Acr, Pz_met, Pzs	phyllite, schist, gneiss	AF5	10
Basement lower	JK1_Pe, Pz_Acr, Pz_met, Pzs	phyllite, schist, gneiss	AC4	11-12

A block model of the finite element mesh is provided in **Figure 13Hiba! A hivatkozási forrás nem található.**

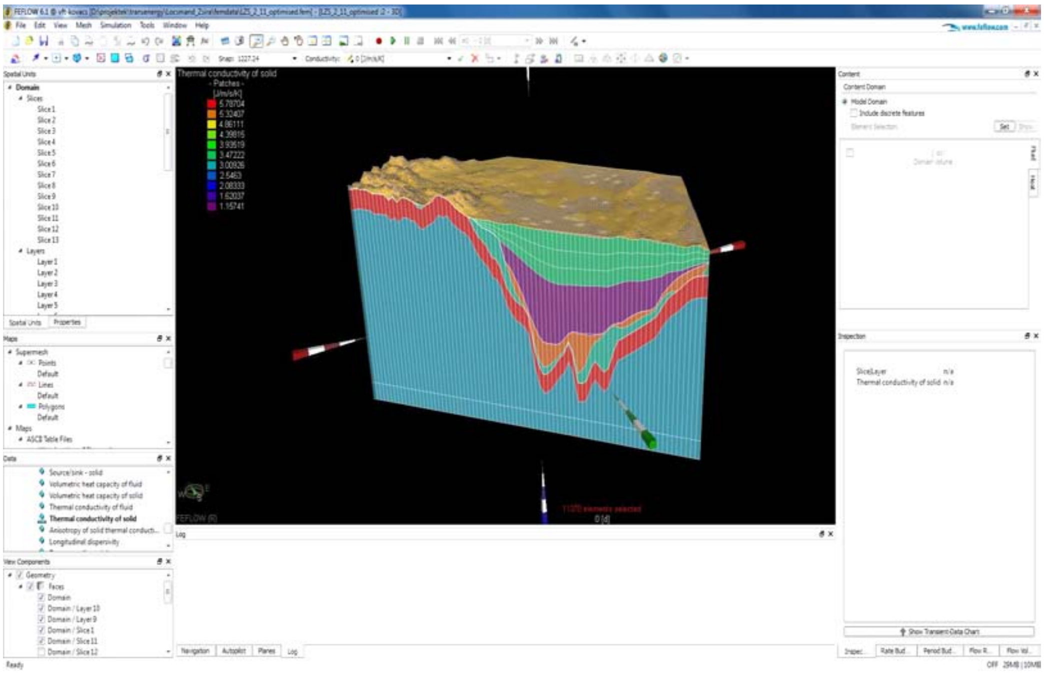


Figure 13. Model layering.

The topography of layer surfaces was determined from the pilot-scale geological model. In areas extending beyond the pilot-scale geological model, the pilot-scale and supra-scale geological information were combined.

13.1.1 Boundary conditions

Boundary conditions were determined to support both the shallow (upper-Pannonian) and deep (pre-Neogene) flow systems. While natural surface water manifestations and regional water divides can be applied as flow boundaries in case of the upper-Pannonian – Quaternary aquifer systems, boundary conditions had to be extracted from the supra-scale groundwater model to define boundaries of deeper systems. The following boundary conditions were applied (Figure 14 and Figure 15):

- Prescribed head boundary of H=130 mASL was applied along the eastern model boundary on slice 1. This zone is the regional discharge area where groundwater upflow is expected along the Marcal-Zala valley.
- Prescribed head boundary of H=130 mASL was applied along the north-eastern model boundary on every slice. This is the main outflow area of the model where groundwater cross-flow is expected as indicated by the supra-scale groundwater model.
- Prescribed head boundary of H=600-400 mASL was applied along the north-western model boundary on slices 6-10. Hydraulic heads were linearly interpolates between domain corners. This model boundary represents regional groundwater inflow in the upper zone of the crystalline basement and overlying sediments.

- Constrained head boundary condition was applied along the Rába river on slice 1. The Rába represents an outflow zone. Flux constrain of q≤0 was applied to avoid unrealistic recharge into the aquifer along the riverbed. Hydraulic head values follow surface topography.
- Prescribed flux (q=0) boundary condition was applied along the south-western and northern model boundaries. Based on surface topography, catchment delineation and the results of the supra-scale model these sides are parallel with the dominant flow directions.

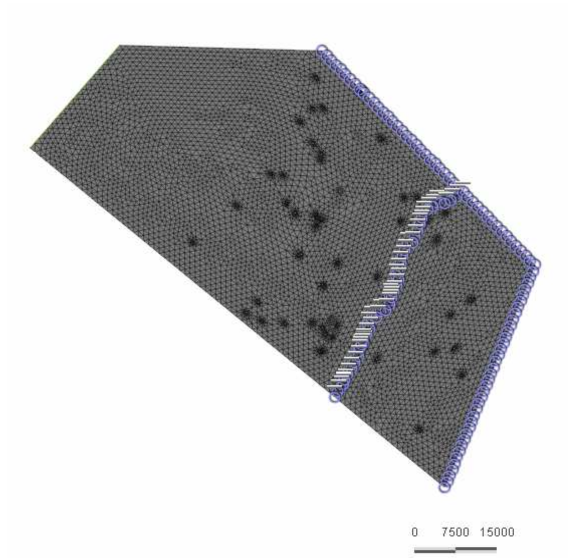


Figure 14. Boundary conditions, slice 1.

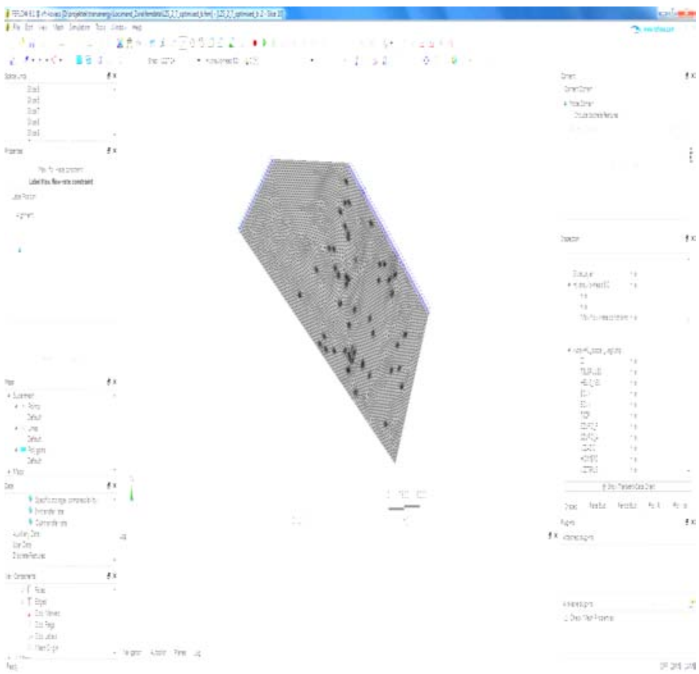


Figure 15. Boundary conditions, slice 10.

A uniform value of 70 mm/y surface recharge was applied on slice 1 representing surface infiltration.

13.1.2 Model parameterisation

The hydrogeological parameter fields applied in groundwater flow models are usually based on field measurements. The applied parameter distribution is either homogeneous within prescribed model zones, or obtained by interpolation between discrete observations. Initial hydrogeological parameters in this study were based on field measurements, literature data and model parameters applied in modelling studies targeting the study area (Tóth et al. 2012, Csepregi et al. 2006). Because of the limited information on site specific field parameters, homogeneous parameter distributions were applied for each hydrostratigraphic unit.

The calibrated hydraulic parameters applied in the natural state model are indicated in Table 3.

Table 3. Optimised hydraulic conductivities.

14 Unit	15 Kxy(m/s)	16 Kz(m/s)
17 Quaternary	18 1,40E-03	19 1,95E-04
20 Late Pannonian	21 1,46E-05	22 5,00E-06
23 Early Pannonian	24 1,00E-08	25 1,00E-09
26 Sarmatian	27 1,00E-07	28 1,00E-08
29 Badenian	30 1,00E-07	31 1,00E-08
32 Miocene	33 1,00E-07	34 1,00E-08
35 Devonian	36 5,00E-06	37 1,00E-07
38 Basement upper	39 1,00E-08	40 1,00E-09
41 Basement lower	42 3,40E-09	43 4,00E-10

43.1.1 Model calibration

Model calibration was performed by means of automated calibration using FEPEST. FEPEST is an interface developed by DHI-WASY that allows for configuring and running PEST in estimation mode. The input parameters and parameter limits are configured in FEPEST, while observations are imported from the FEFLOW fem file. FEPEST generates a PEST control file, template file and instruction file and launches the PEST executable. The output generated by pest.exe displayed in the FePEST interface including the complete output, diagram of the objective function, and optimised parameters.

PEST (WNC, 2004) 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.

PEST calibration requires the following steps:

- Selecting adjustable parameters: Hydraulic conductivities in all hydrostratigraphic units were selected for PEST calibration.

- Defining initial guesses and allowable minimum and maximum values for the selected parameters: Initial guesses were derived from literature values. Constraints were defined so that PEST had sufficient freedom to achieve the best parameter values within a reasonable range of parameter values. In general, one order of magnitude difference from the initial values was allowed for each parameter in both directions.

- Defining observations and weights: PEST minimises the weighted sum of squared differences between model predictions at the locations of observations and real observed data. The sum of weighted squared model-to-measurement differences is known as the "objective function". As no other information was available, standing water level data from a selected set of monitoring bores were used as observations. Each observation was assigned a weight of 1.

- Preparing PEST files: PEST uses four types of files including (1) a model batch file; (2) model input template files; (3) model output reading instruction files; and (4) PEST control file. These files were prepared automatically by FEPEST.

- Running PEST: At each iteration of a PEST run, the PEST optimisation algorithm adjusts the values of model parameters with the goal of reducing the value of the objective function. The new model parameter values are written to model input files using input template files. If the model runs successfully, the model generates a set of output files.

- Utilising PEST outputs: The PEST calibration process is finished, when its stopping criterion is met. The results of the final calibration iteration are written in an output file, and the groundwater model is run with the best achieved parameter values. The results of the last PEST iteration was considered to be the best possible steady state solution for groundwater flow. The optimised parameters were used in heat transport simulations models, and will be used as initial conditions in transient model runs.

The observation dataset together with observed and simulated values is indicated in Table 4.

Table 4. Calibration dataset.

44 Name	45 Locality	46 Code	47 Measured	48 Modelled	49 Residual
50 hea-1	51 Stoob	52	53 200,3	54 192,9	55 -7,4
56 hea-2	57 Lackendorf	58	59 202,6	60 194,8	61 -7,8
62 hea-3	63 Markt St.Martin	64	65 124,8	66 130,1	67 5,3
68 hea-4	69 Neutal	70	71 185,9	72 180,7	73 -5,2
74 hea-5	75 Unterfrauenhaid	76	77 153,7	78 154,9	79 1,2
80 hea-7	81 Unterrabnitz	82	83 150,2	84 154,0	85 3,8
86 hea-8	87 Lockenhaus	88	89 189,8	90 198,4	91 8,7
92 hea-9	93 Oberrabnitz	94	95 139,4	96 129,4	97 -10,0
98 hea-12	99 Répcelak	100 Répceleki Sajtgyár 4 sz kut tartalek	101 184,1	179,0	-5,1
hea-13	Szombathely	Sárdéri Vizmű IV.sz kút B-21	138,5	134,9	-3,6
hea-14	Szombathely	Sárdéri Vizmű III.sz kút B-17	140,3	145,7	5,4
hea-15	Babót	Közkút /Béke u./	136,0	138,4	2,4

hea-16	Acsád	Acsád B-1	148,6	153,3	4,7
hea-17	Táplánszentkereszt	Sárdéri Vizmű XVII.sz kút B-3	157,4	155,7	-1,7
hea-19	Táplánszentkereszt	Sárdéri Vizmű XVI.sz kút B-1	143,5	144,6	1,1
hea-20	Szombathely	Déli Vizmű VIII.sz kút B-36	180,8	179,4	-1,4
hea-21	Táplánszentkereszt	Sárdéri Vizmű XII.sz kut B-7	136,4	133,2	-3,2
hea-22	Szombathely	Déli Vizmű X.sz kút B-31	158,2	162,2	4,0
hea-23	Vép	Sárdéri Vizmű XVIII.sz kút K-3	168,8	166,1	-2,7
hea-24	Petőháza	Magyar Cukor Rt., Cukorgyár	170,1	167,9	-2,2
hea-26	Táplánszentkereszt	Sárdéri Vizmű XIV.sz kút B-2	152,9	144,2	-8,6
hea-27	Táplánszentkereszt	Sárdéri Vizmű XV.sz kút B-4	156,6	156,2	-0,4
hea-28	Újkér	Kokas major /sertéstelep/	172,6	168,8	-3,8
hea-30	Sárvár	Baromfifeld. Váll. B-17 kút	140,2	139,8	-0,4
hea-31	Csepreg	Vizmű II.sz kut K-8	143,5	144,0	0,5
hea-32	Simaság	Rehabilitációs Int. B-2 kat. sz. kút	156,4	155,3	-1,1
hea-33	Csepreg	Csepreg K-7	169,7	167,3	-2,4
hea-34	Szombathely	Sárdéri Vizmű XX.sz kút K-42	198,8	193,0	-5,8
hea-35	Ostffyasszonyfa	VASIVIZ RT Vizmü I.számú kút	125,0	132,2	7,2
hea-36	Szombathely	Sárdéri Vizmű XX/a.kút K-43	198,9	193,4	-5,6
hea-37	Sárvár	Vizmű I.sz kút K-19/a	185,0	202,5	17,5
hea-39	Sárvár	Vizmű IV.sz kút K-21	134,3	133,7	-0,6
hea-40	Tömörd	Vizmű K-3 kat.számú kút	139,0	136,1	-2,9
hea-41	Kenyeri	Kenyeri K61 megfigyelőkút	175,6	173,7	-1,9
hea-42	Répcelak	VASIVIZ Zrt I sz. K-6/a	181,0	179,1	-1,9
hea-43	Csepreg	K-11 kat. számú kút	135,5	138,4	2,9
hea-44	Szombathely	Termálfürdő II.sz kút B-46	150,9	159,3	8,4
hea-45	Lövő	Lővő főmajor (urge major)	138,4	136,7	-1,7

hea-46	Rum	Vizmű I.sz kut K-3	139,6	151,8	12,3
hea-47	Bük	Vizmű F3.jelu kút K-6/a.	140,4	141,7	1,2
hea-48	Bük	Vizmű F4.jelu kút K-7	154,1	161,0	6,9
hea-49	Táplánszentkereszt	Sárdéri Vizmű XII/b.kút K-12	130,9	135,6	4,7
hea-52	Cirák	Főmajor	232,6	229,6	-3,0
hea-53	Répcelak	Répceleki Sajtgyár 2.sz.kút	252,7	257,3	4,6
hea-54	Röjtökmuzsaj	Röjtökmuzsaj Vizmü	253,4	250,2	-3,2
hea-55	Újkér	Dózsa Népe Mg.Sz./központi major	283,8	285,5	1,6
hea-56	Nagycenk	MgTSz Tarsulas Baromfitelep	292,4	277,3	-15,1
hea-57	Vép	Mezgazd. Intézet K-5 kat.kút	297,5	289,9	-7,6
hea-58	Veszkény	Főmajor tehenészet	328,2	324,5	-3,7
hea-59	Mihályi	Mihályi Agrár Rt., főmajor	328,8	324,8	-4,0
hea-60	Mesteri	Vizmű 1.sz kut K-4/a.	352,4	346,9	-5,5
hea-61	Nemesker	Serteskombinat	362,4	344,5	-17,9

The observed vs. simulated hydra**ulic** heads (scatter plot) at observation points is indicated in Figure 16.

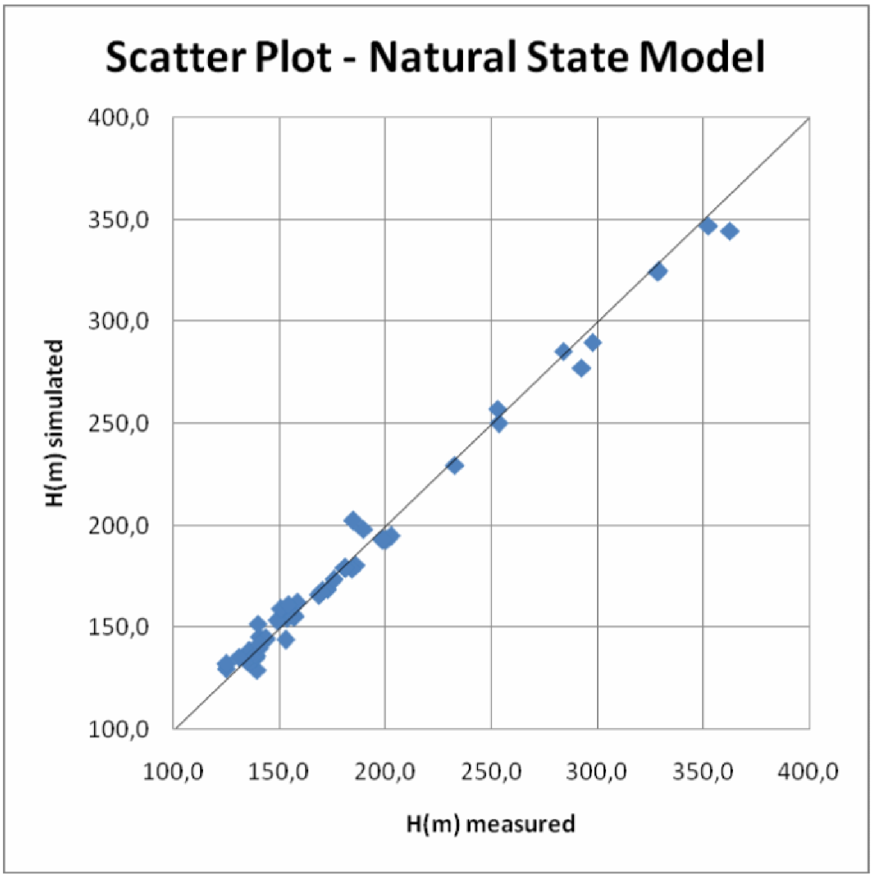


Figure 16. Scatter plot, natural state model.

The primary method for quantitatively assessing the goodness of fit of calculated data is through calculation of the Scaled Root Mean Square Error (RMS). The RMS error (or standard deviation) is the square root of the average of the squared differences in measured and simulated heads, expressed as (Eq. 1):

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}(x_{calc} - x_{obs})^2}{n}} \qquad \text{(Eq. 1)}$$

where n is the number of measurements. The Scaled Root Mean Square Error (SRMS) is the RMS divided by the range of observed values, or (Eq. 2):

$$SRMS = \frac{RMS}{(X_{obs})_{\max} - (x_{obs})_{\min}} \qquad \text{(Eq. 2)}$$

where X_{obs} is the measured head, and X_{calc} is the calculated head.

The calibration statistics of the natural state model are given in Table 5.

Table 5. Calibration statistics.

Root Mean Square Error (RMS)	6.28
Scaled Root Mean Square Error (SRMS)	0.03
Number of residuals with non-zero weight	52
Mean value of non-zero weighted residuals	2.2
Maximum weighted residual	8.4
Minimum weighted residual	-17.9
Variance of weighted residuals	102 6.3
Standard error of weighted residuals	103 6.3

According to international standards, the required calibration accuracy is generally set in accordance with the model complexity. For a medium complexity regional model such as this, an RMS error of approximately 6.28 % is considered to be a good calibration.

103.1 Geothermal model

The geothermal model of the study area was based on the calibrated hydraulic model. Heat transport component was coupled with the hydraulic model to simulate convective and conductive heat transfer.

103.1.1 Boundary conditions

The simulation of heat transport requires the definition of heat boundary conditions in addition to hydraulic boundaries already defined during the hydraulic modelling stage. The following heat boundary conditions were applied:

- Constant temperature boundary condition of t=10 C was applied at the top slice. This boundary represents an average atmospheric temperature at the ground surface.
- Heat flux boundary condition was applied at the model base (-5000 mASL). The spatially varying heat flux distribution was obtained from the supra-regional conductive model of Lenkey et al. (2012). The applied values vary between 55-90 mW/m^2.
- Constant temperature boundary condition of t=10-30 C was applied on slices 6-11 along the western model boundary. This boundary condition represents the temperature of groundwater inflow from the west.

103.1.2 Model parameterisation

Uniform parameter distributions were used in the main hydrostratigraphic units. The same parameter zones were applied for thermal properties as for hydraulic properties. Initial parameter values were obtained from laboratory measurements undertaken within the frameworks of the TE project. Additional data was obtained from Toth et al. (2011). The thermal properties applied in the model are listed in Table 6.

Table 6. Thermal properties.

104 Unit	105 Model layers	106 Porosity	107 Thermal conductivity (W/mK)	108 Longitudinal dispersivity (m)	109 Transverse dispersivity (m)
110 Quaternary	111 1	112 0.3	113 3	114 5	115 0.5
116 Late Pannonian	117 2-4	118 0.2	119 3	120 5	121 0.5
122 Early Pannonian	123 5	124 0.2	125 3	126 5	127 0.5
128 Sarmatian	129 6	130 0.2	131 3	132 5	133 0.5
134 Badenian	135 7	136 0.1	137 3	138 5	139 0.5
140 Miocene	141 8	142 0.1	143 3	144 5	145 0.5
146 Devonian	147 9	148 0.1	149 3	150 5	151 0.5
152 Basement upper	153 10	154 0.05	155 3	156 5	157 0.5
158 Basement lower	159 11-12	160 0.05	161 3	162 5	163 0.5

163.1.1 Model calibration

During the first stage of modelling an approximate model calibration was achieved by means of the gradual modification of key model parameters (manual calibration). A more accurate calibration using automated calibration techniques will be undertaken in the subsequent stage of the modelling works including the simulation of groundwater extractions.

The calibration dataset included a selection of borehole temperature data available for the study area. The most complete and continuous temperature profiles were obtained from the following bores (Table 7):

Table 7. Temperature profile dataset

164 Location	165 code	166 data interval (depth, m)
167 Bük	168 1	169 695-1282
170 Bük	171 K15	172 50-500
173 Celldömölk	174 ENY1	175 1726-3000
176 Csapod	177 1	178 1605-4100
179 Mihályi	180 12	181 1017-1360
182 Mihályi	183 37	184 61-1566
185 Szombathely	186 Fürdo1	187 50-750
188 Szombathely	189 Fürdo3	190 50-650
191 Szombathely	192 2	193 100-2140

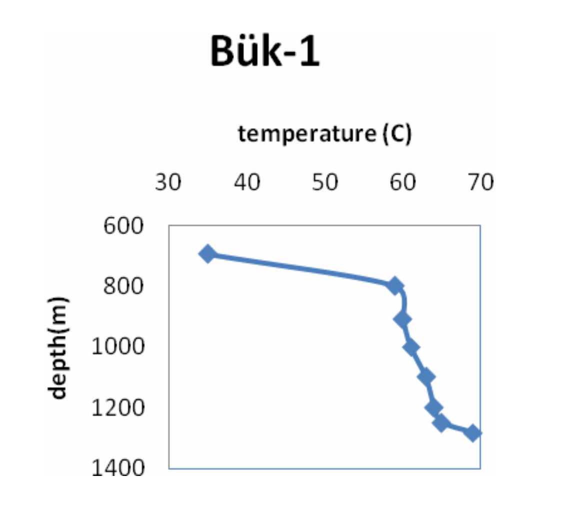
The temperature profiles of the above bores are shown in Figure 17. The investigated profiles indicate a continuous temperature gradient throughout most of the bore profiles indicating little influence of convective mixing of groundwater. Drops or reversals of the temperature gradient can be seen on the following profiles:

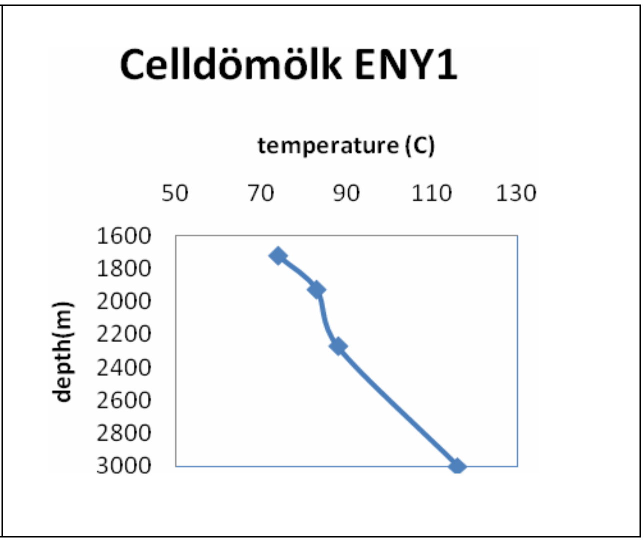
- A significant drop of the temperature gradient is evident on the profile of the Bük 1 bore, indicating groundwater mixing and the presence of a geothermal reservoir between the 800-1280 m depth. This horizon belongs to the Devonian dolomite aquifer, which is the main target of our investigations.

- A shorter interval of decreased thermal gradient can be seen on the profile of the Celldömölk ÉNY1 bore between 1930-2270 m, indicating increased permeability and groundwater mixing at the base of the lower-Pannonian layers. Similarly, intervals of thermal inversion can be seen on the profiles of Csapod 1 (between 2700-2800 m), Mihályi 12 (between 1290-1320 m) and Mihályi 37 (between 1330-1390 m) temperature profiles. These sections also belong to the base of the lower-Pannonian strata and assumed to indicate high permeability zones with increased groundwater movement.

- A relatively short interval with decreased thermal gradient can be seen on the profile of the Szombathely Fürdő 3 bore between the 550-600 m depths within the upper-Pannonian sequence. This drop in the thermal gradient might indicate a zone of intense groundwater circulation and the mixing of waters with different temperatures.

It is important to note, that although the upper-Pannonian aquifer system is considered to be the main aquifer system in the area, there is no indication of convective mixing on the temperature profiles. This is assumed to be the consequence of strong anisotropy which might block the vertical component of flow between the different aquifer horizons.





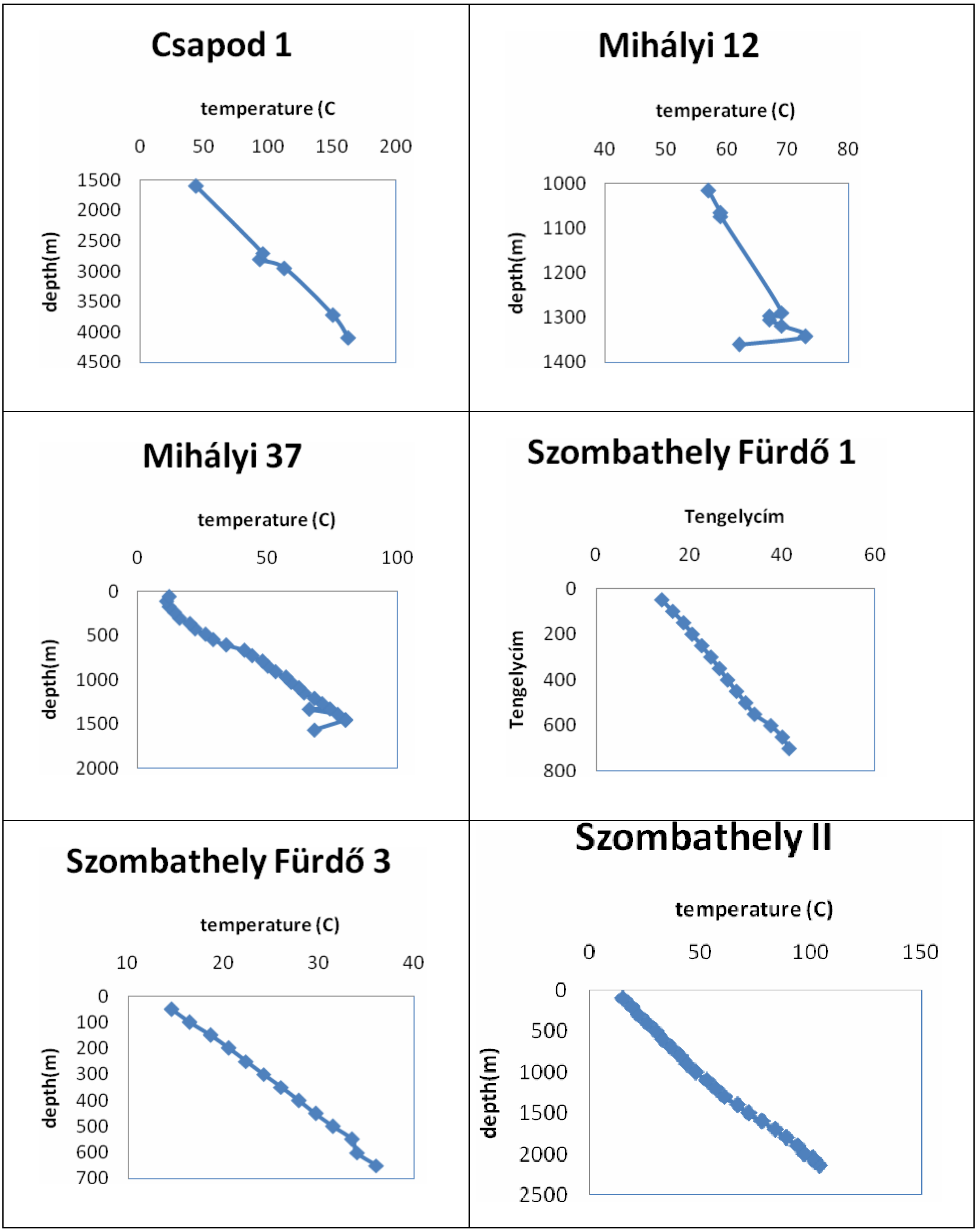


Figure 17. Temperature profiles of reference bores.

194RESULTS

The coupled groundwater flow and heat transport model provided three-dimensional information on the following:

- Hydraulic head distribution
- Groundwater fluxes
- Temperature distribution

The simulated groundwater table contours and potentiometric plots are shown in figures **Figure 18** to Figure 22.

Groundwater flux vectors at the water table are shown in Figure 23. Hydraulic heads and darcy velocity distribution along a NW-SE cross section are shown in Figure 24 and Figure 25.

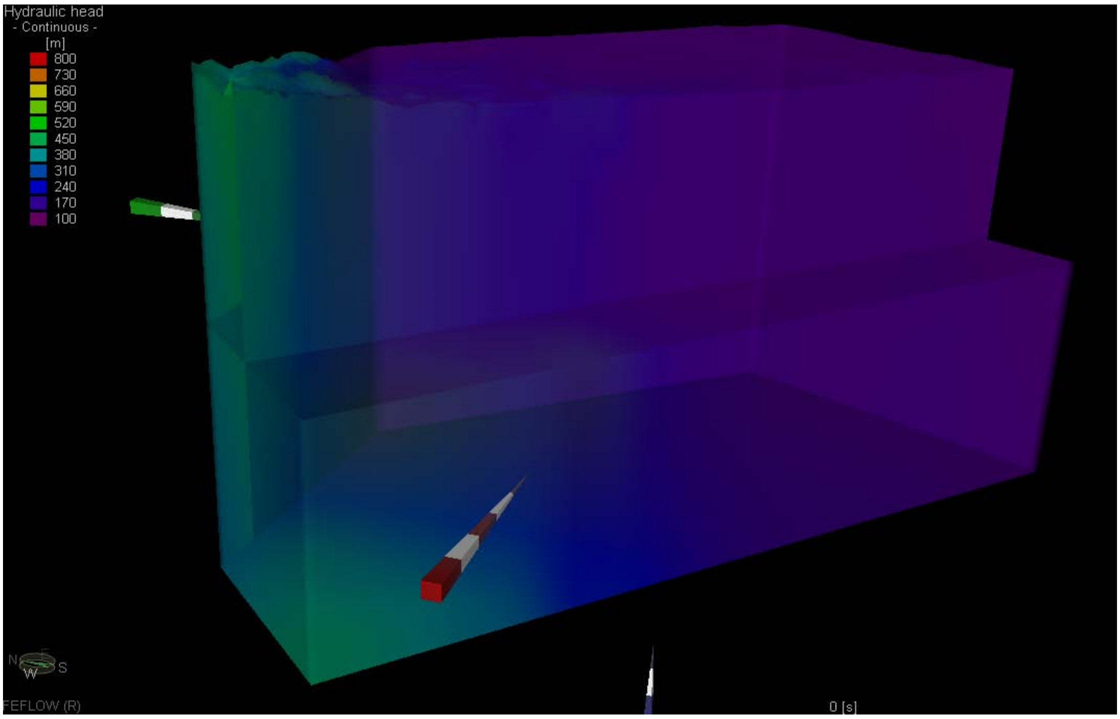


Figure 18. Simulated hydraulic head distribution across 3D block model.

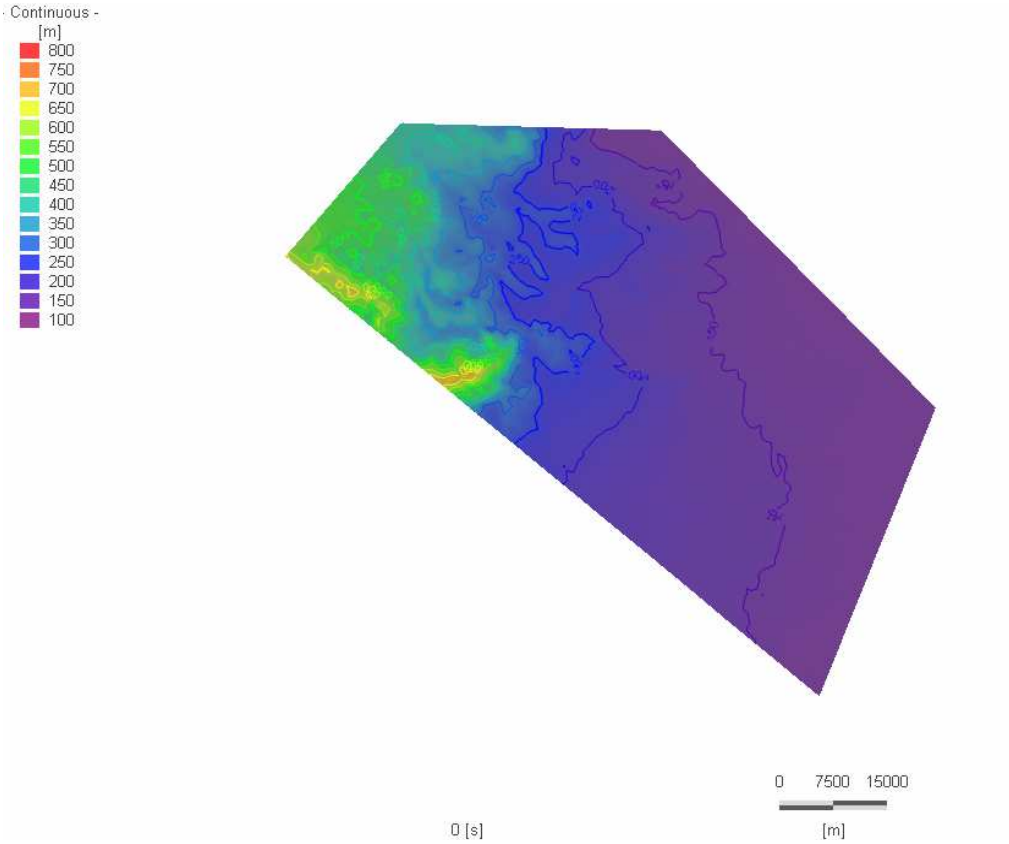


Figure 19. Simulated water table elevation.

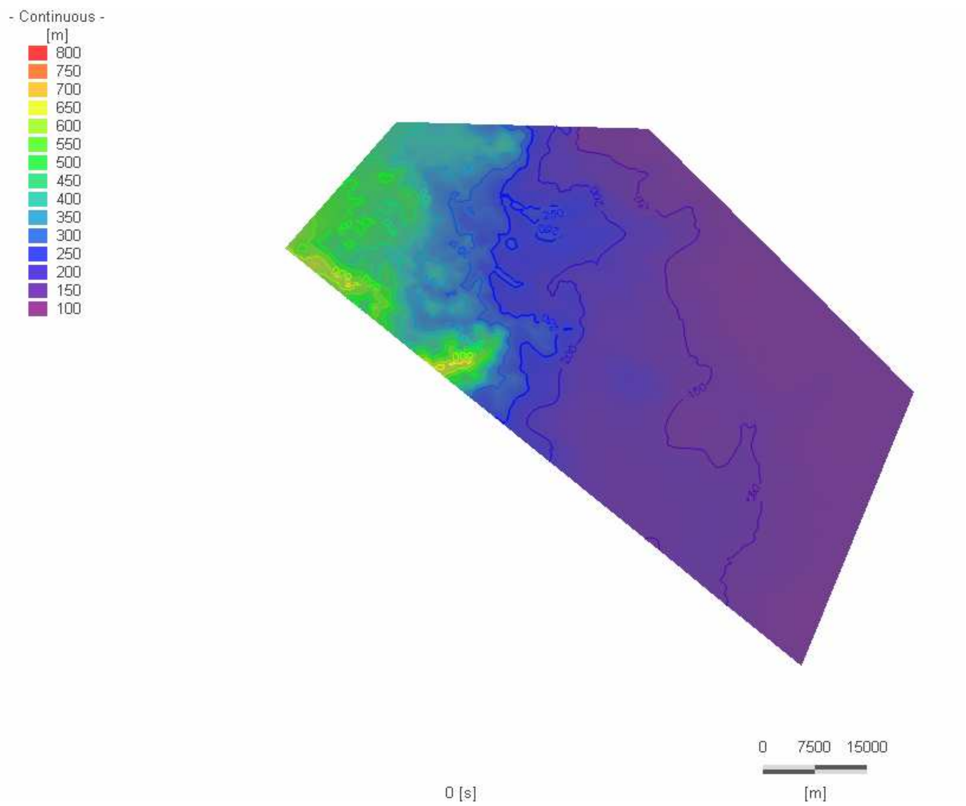


Figure 20. Simulated hydraulic head distribution at the base of the upper-Pannonian aquifer (slice 5).

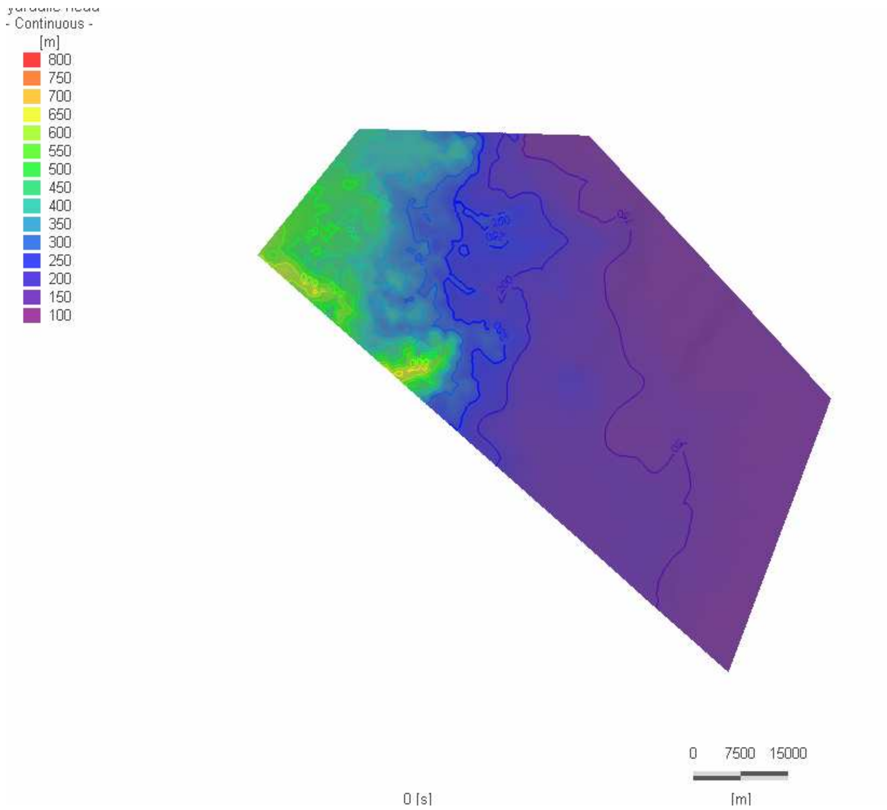


Figure 21. Simulated hydraulic head distribution at the base of the lower-Pannonian aquifer (slice 6).

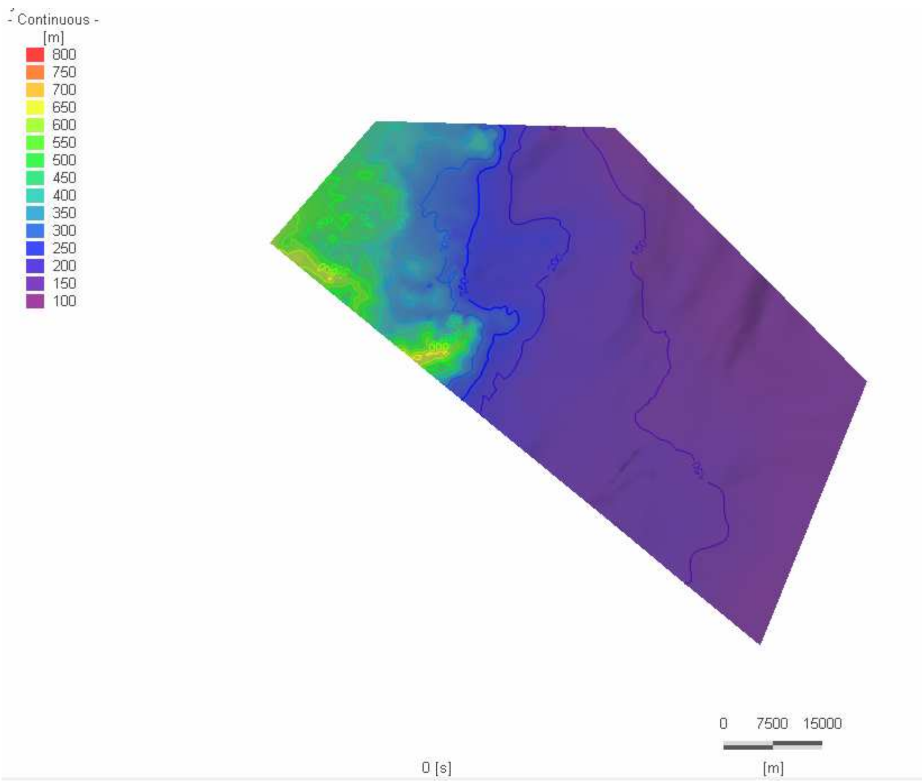


Figure 22. Simulated hydraulic head distribution at the base of the Tertiary layers (slice 9).

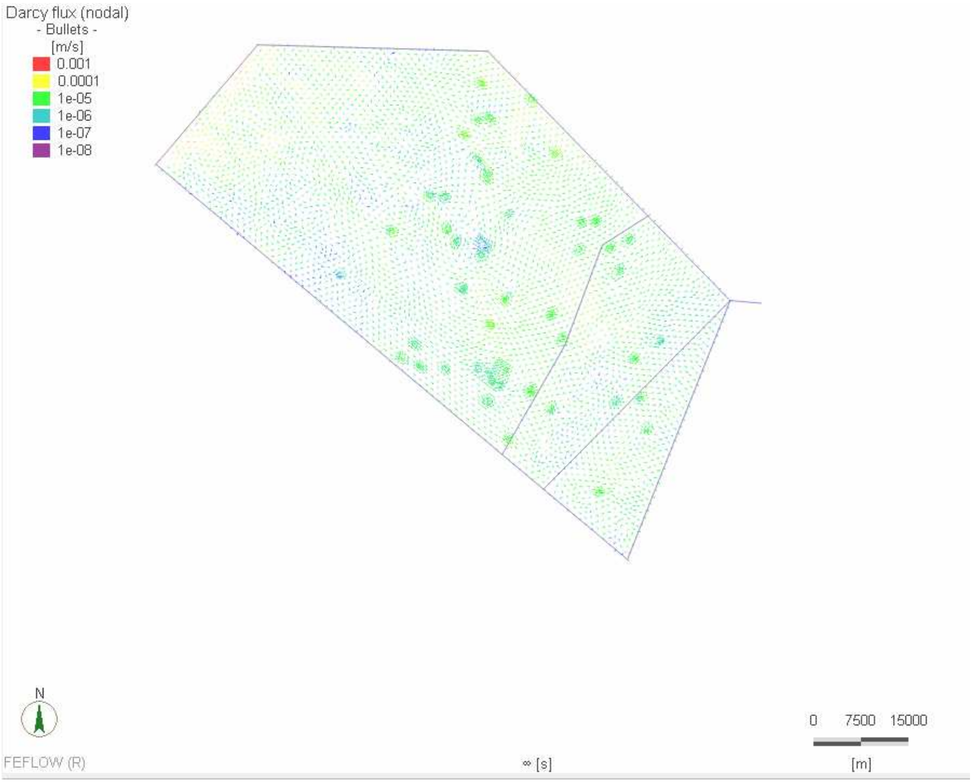


Figure 23. Simulated flux vectors at the water table (slice 1).

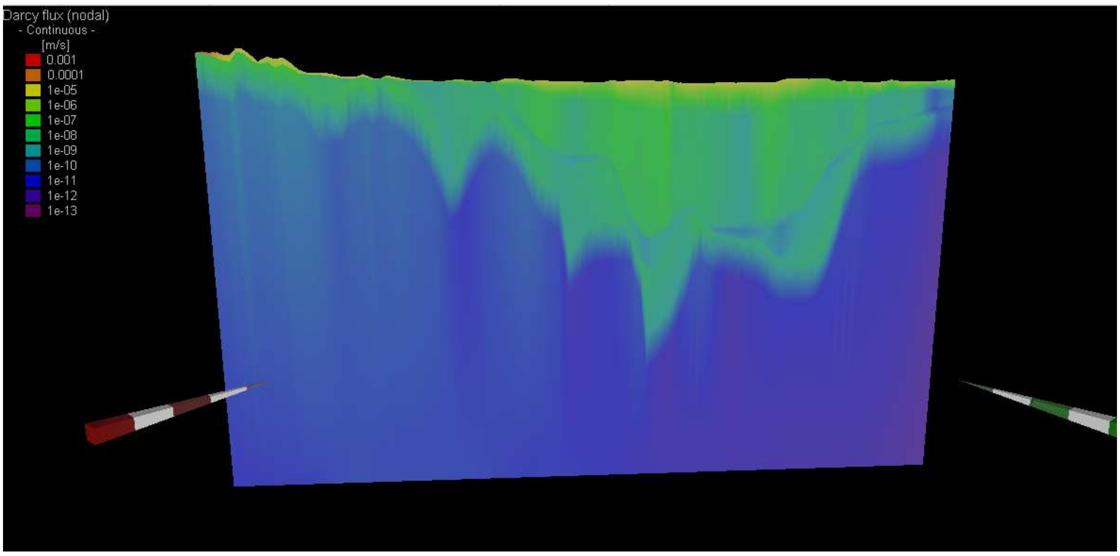


Figure 24. Simulated flux values along a NW-SE section.

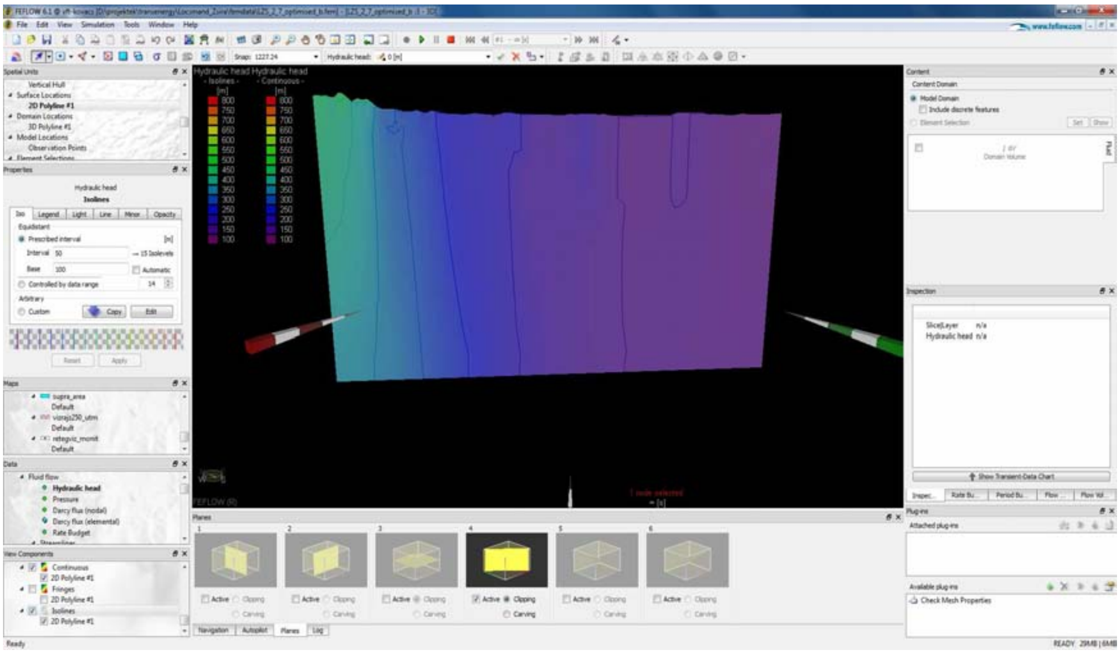


Figure 25. Simulated hydraulic head distribution along a NW-SE section.

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. The flow field follows a semi-radial pattern. The main inflow area is along the western model boundary, where the regional flow system feeds the modelled domain. Outflow occurs along the south-eastern (Marcal Valley) and north-eastern model boundaries. The Marcal Valley represents the regional discharge area, while the north-eastern side of the model is a cross-flow area. Surface infiltration represents approximately 40% of groundwater recharge, while the rest arrives as groundwater inflow from the west. The water budget of the area is indicated in Table 8.

Table 8. Simulated water budget.

Boundary	In (m^3/d)	195 Out (m^3/d)
Prescribed head	1.29e+6	2.02e+6
Infiltration	7.24e+5	N/A

The simulated temperature distribution at different depths is shown in Figure 26 and Figure 27. A vertical NW-SE profile of simulated temperatures is shown in Figure 28.

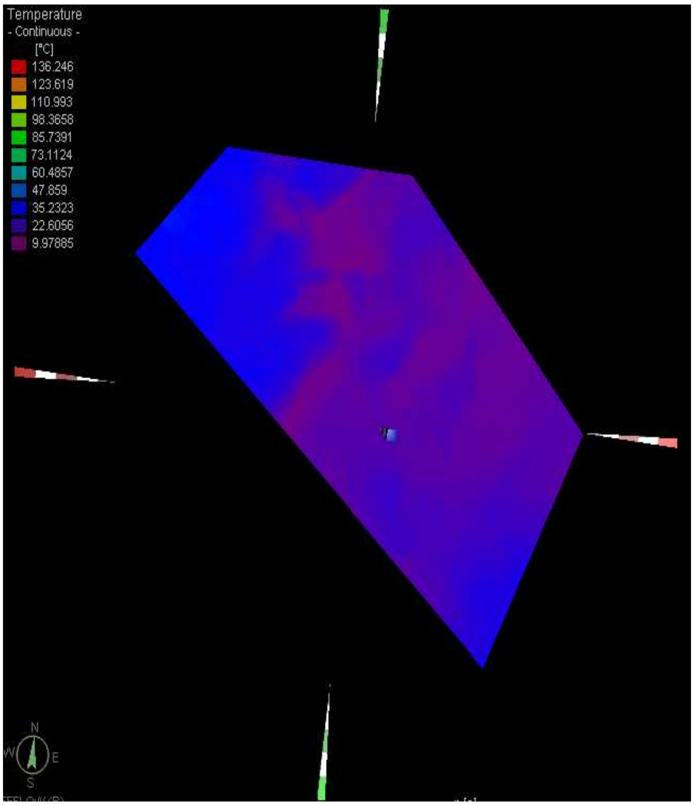


Figure 26. Simulated temperature distribution at -1000 mASL.

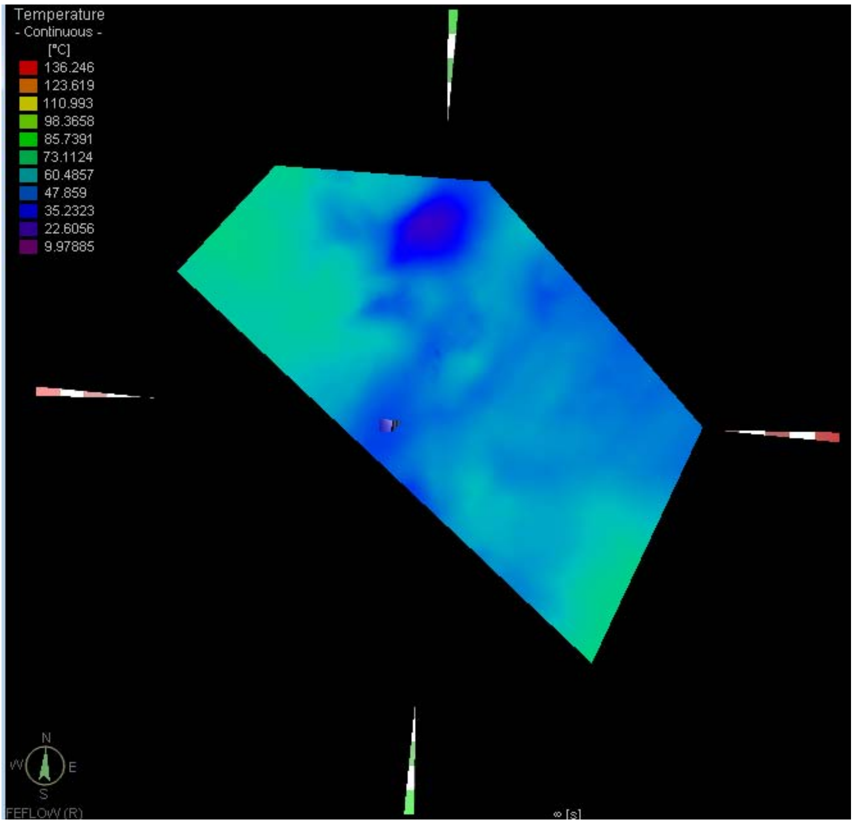


Figure 27. Simulated temperature distribution at -2500 mASL.

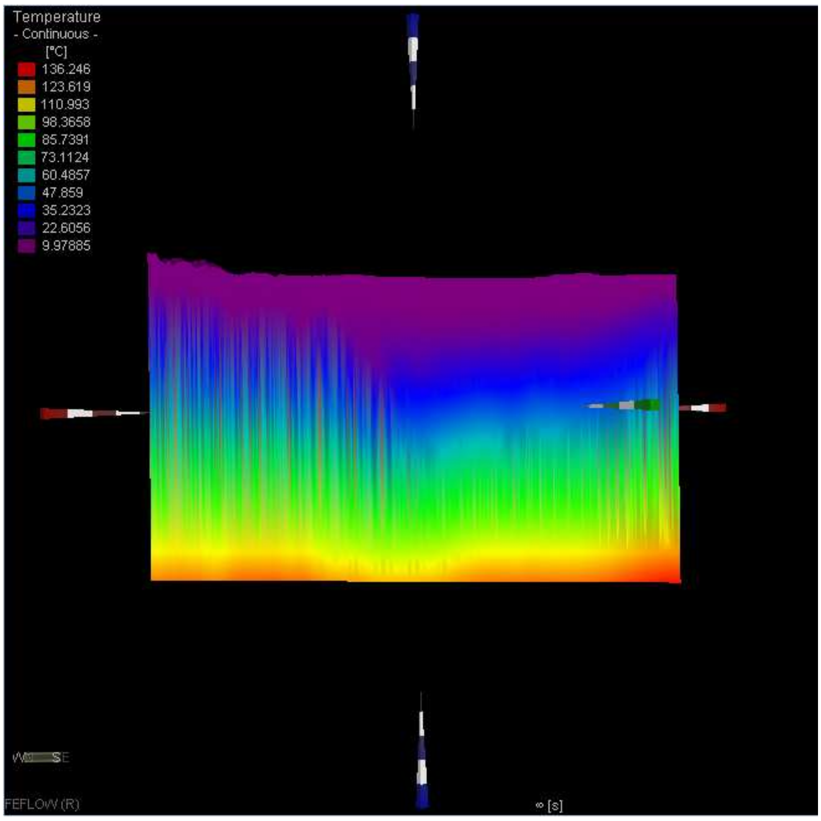


Figure 28. Simulated NW-SE temperature profile.

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.

. A better accuracy of temperature modelling can be achieved by the application of automated calibration techiquesto be applied in the next stage of modelling.

196 SUMMARY AND CONCLUSIONS

The geothermal system of the Zsira-Lutzmannsburg pilot area in the western part of the Pannonian Basin is located in a transboundary 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 Zsira-Lutzmannsburgpilot 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 temperature distribution indicates little vertical variations of temperature within the upper pannonian sediments, and gradually increasing temperatures within older sediments and the fractured basement.

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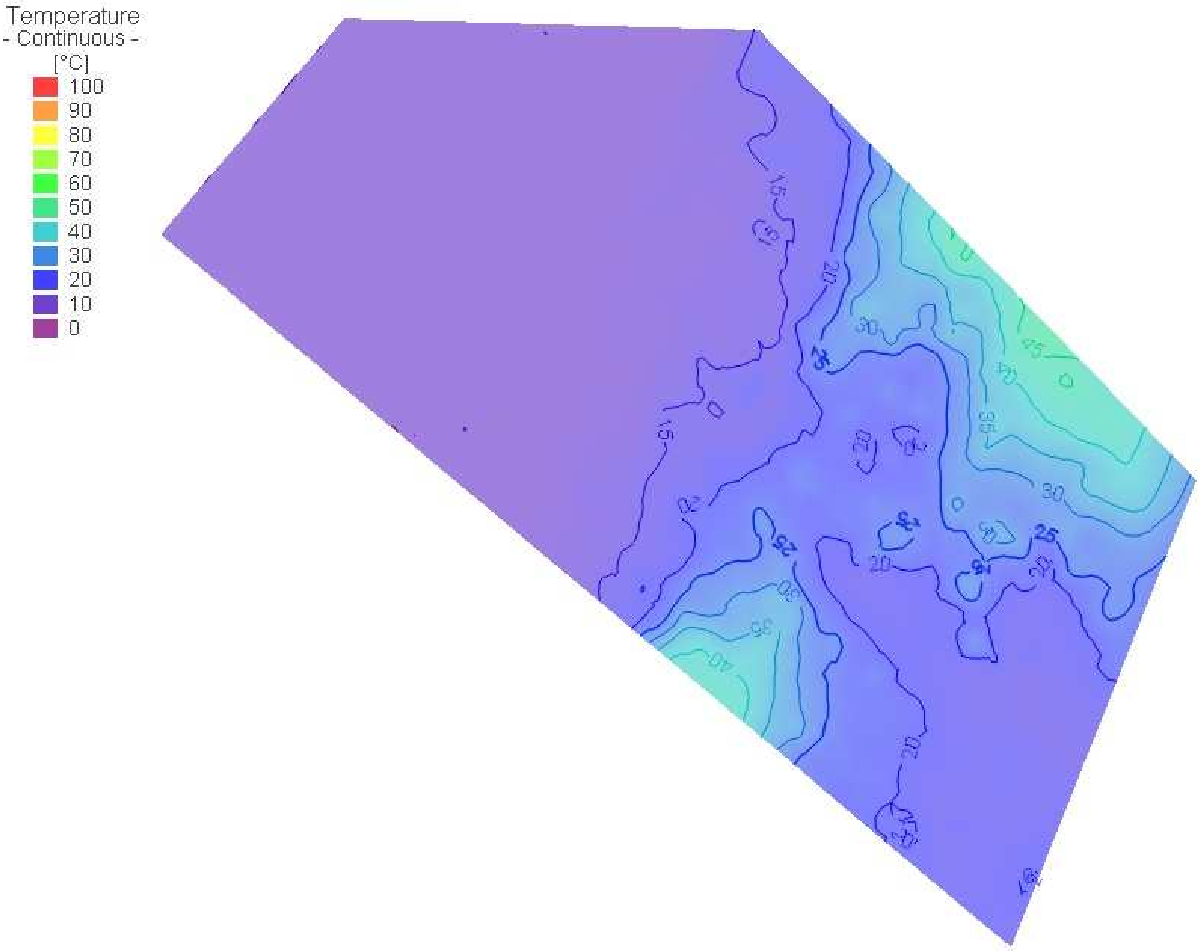
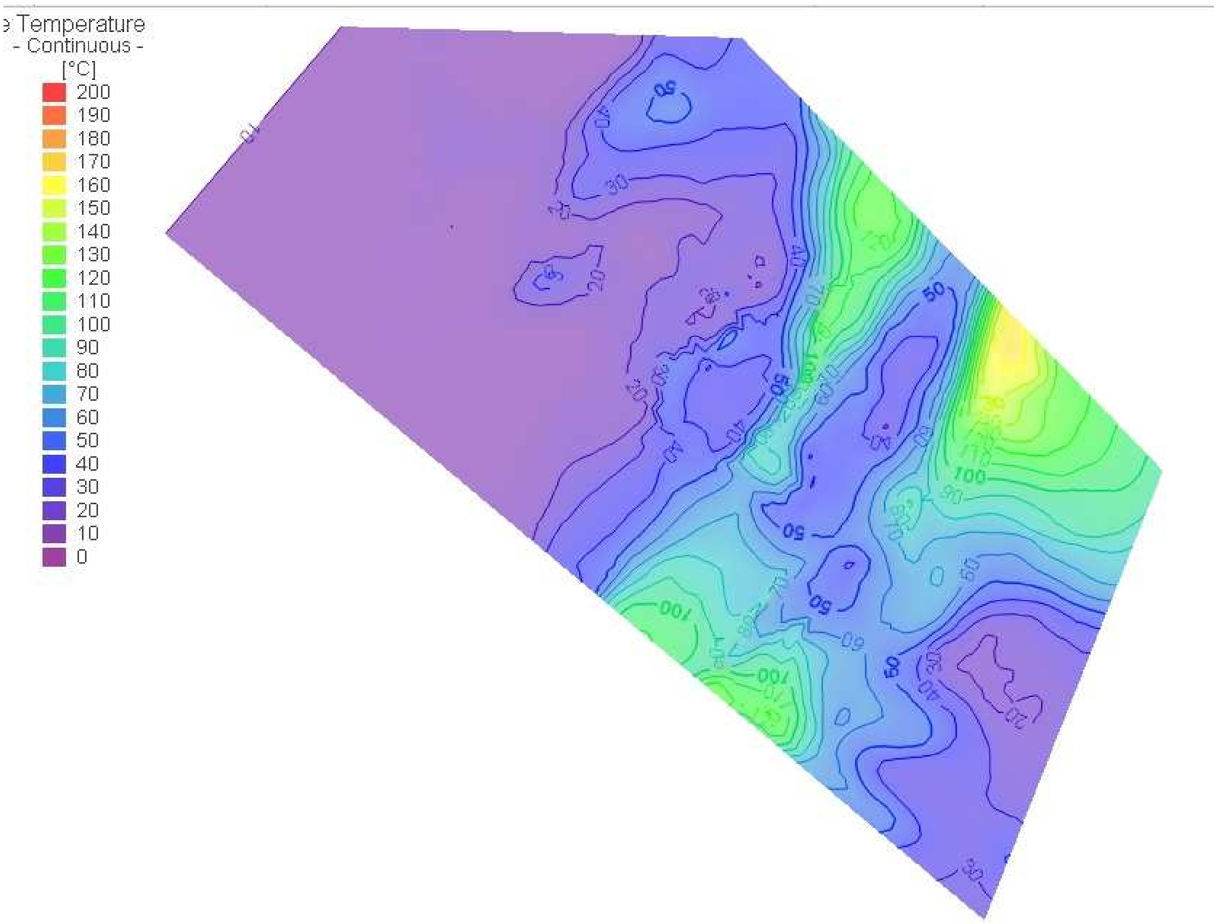
Annex I

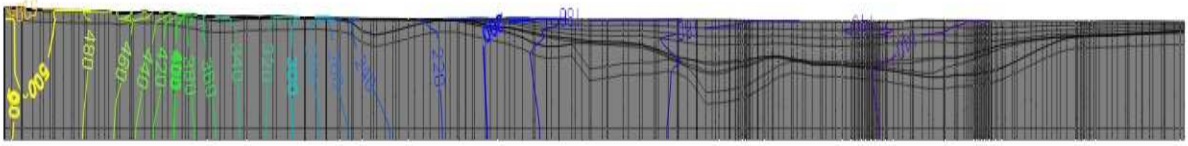
Temperature distribution at the base of Upper-Pannonian Formation



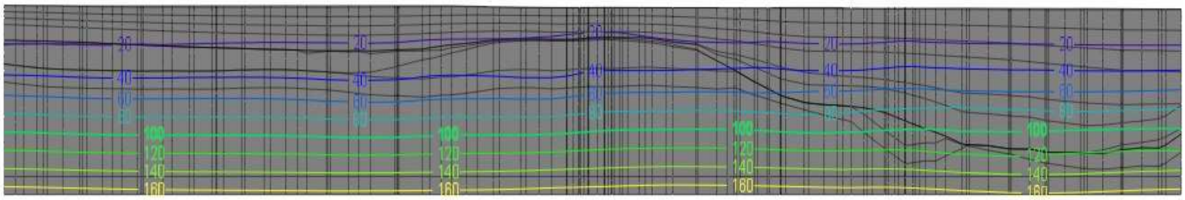
Temperature distribution at the top of the Basement Formation



Temperature distribution in the NW-SE cross-section



Temperature distribution in the NE-SW cross-section



Annex II

Water budget of the flow system

Q m3/d	Natural state	Current Production
In @ BC's	4180	4724
Out @ BC's	181054	140803
Recharge	176873	176873
Wells	0	40795

Water budget of Bük Dolomit Formation

Q m3/d	Natural state	Current Production
In	940	2390
Out	940	755
Wells	0	1635