Transboundary geothermal system at the Lutzmannsburg-Zsira are of TRANSENERGY project

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Keywords: 3D modelling, geology, hydrogeology, thermal system, thermal water flow.

ABSTRACT

A coupled groundwater flow and heat transport model of the Lutzmannsburg-Zsira region was developed. The study area is located in the trans-boundary zone between Austria and Hungary.

The site contains several geothermal water utilisations on both sides of the border, which impact on natural groundwater conditions. The aim of the modelling study was to evaluate the natural state and production state groundwater conditions, and to make predictions on cross-boundary interferences.

A three-dimensional finite element type coupled geothermal model was constructed to provide a coherent quantitative representation of geothermal flow systems. The model described the hydraulic behaviour of the flow system, the interaction between different reservoirs, and the geothermal conditions.

The model results provide information on trans-boundary depressurisation of the geothermal reservoirs. Scenario modelling was undertaken to predict the effects of groundwater extractions. The applied model can be used as a tool for sustainable thermal water management.

1. INTRODUCTION

The management of trans-boundary geothermal resources is a complex task to achieve the sustainable and effective development of geothermal resources. The Lutzmannsburg-Zsira geothermal system is situated in trans-boundary position, where the objective of attaining a good qualitative and quantitative status of thermal groundwater bodies appears to be endangered by discrepancies between current legislation and actions of users. Even so the demand is increasing for thermal water utilization in the region.

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 to both 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.

Focusing on the above mentioned local transboundary problems detailed geothermal characteristics of these sites, pilot area models were constructed. A coupled groundwater flow and heat transport model was developed to analyse the effects of recent and future thermal water utilizations.

The aim of the presented model was 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.

2. GEOGRAPHICAL SETTINGS

The Lutzmannsburg-Zsira pilot area situated at the Western margin of the Pannonian Basin, within the trans-boundary zone of Austria and Hungary. Sopron-Ödenburger Mountains, the Rosalia Mountains, Bucklige Welt and the Kőszeg-Rehnitz (Rohonc) Mountains represent the boundaries of the model area in the West. These high elevated mountains surround the Oberpullendorf Basin, which continues in the southern part of the Little Hungarian Plain (Kisalföld) eastwards. The elevation of the mountains vary between 400-900 m and gradually lowering eastward on the lowland the lowest point is 119 m.

Marcal valley represents the eastern boundary. Northward the region continues toward the Danube Basin (northern part of the Kisalföld Lowland). The N-NE boundary of the region situated in the margin of this part of the Little Hungarian Plain, the so called Hanság, which was originally a wetland in natural conditions (Fig.1).

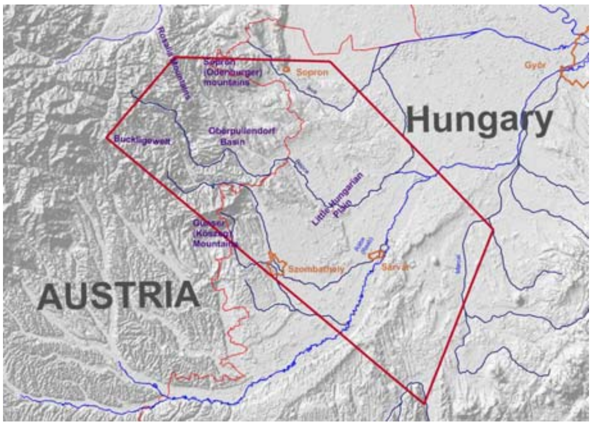

Figure 1. Geographical settings of the pilot area and the model region

3. GEOLOGICAL-, HYDROGEOLOGICAL- AND GEOTHERMAL CONDITIONS

2.1 Geology

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 (Fig.3). 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.

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 Penninic outcrops in the SW part of the region, in the Rechnitz tectonic window and continue eastward in the basement covering with Austro-Alpin nappes. The estimated thickness of the unit is more than 2000 m.

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. 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. 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). 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.

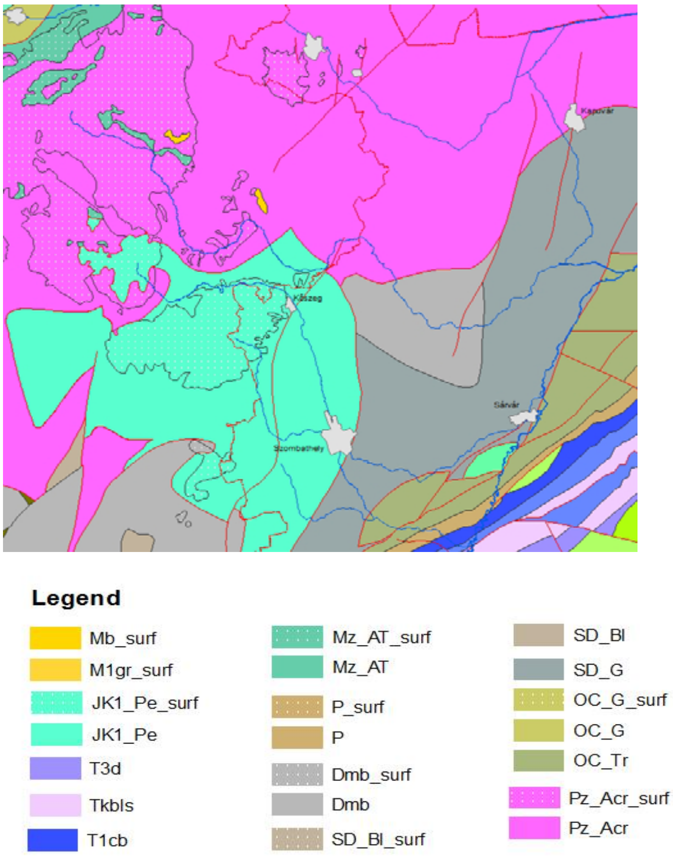

Figure 2. Location of the basement units (Maros et al. 2012)

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.

The Neogene sediments deposited in the morphological lowlands on the tectonically preformed surface of the crystalline units. The Miocene-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. 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).

2.2 Hydrogeology

The following ***hydrostratigraphical units*** (composite units which encompass different geological formations with the same hydrogeological properties) 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 little informationis available about their characteristics and the locations of basement resevoirs.

The Devonian Dolomite 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 physically 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.

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.

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. Currently, there are only small patches of wetlands, but the dense artifical drainage channel network receives considerable groundwater discharge.

The hydraulic conditions of 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 (**Fehler! Verweisquelle konnte nicht gefunden werden.**). 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. 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.

Several monitoring wells register the hydraulic potential changes in the Pannonian aquifers. After several decades of observation only little (no more than 1-2 m) potential decline occurred. However, significant groundwater depressurisation exist in the Miocene layers due to groundwater extractions (Figure 9). The head drop exceeds 14 m during the 20 years monitoring period (Fig. 3).

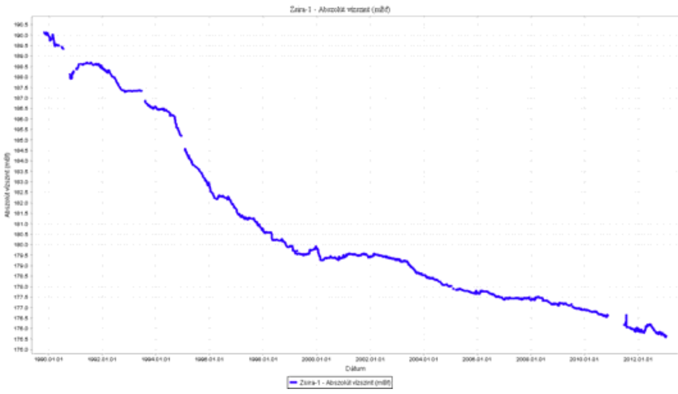

Figure 3. Changes in groundwater heads in Zsira monitoring well

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.

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.

Extensive groundwater extractions exist in 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.

4. MODEL DEVELOPMENT

The first step in model developing was to create a 3D geological model. This was the basis of the groundwater flow and heat transport model.

4.1 Geological Model

The 3D geological model was based on harmonized formations and harmonized borehole database (Fig. 4). The model was done by the software Jewel. The model contains different surfaces of the main hydrostratigraphical units and most important tectonic elements, faults and thrusts of the region. The model grids were refined based on the evaluations of 2D seismic section series and gravitational, magnetotelluric modelling.

4.2 Groundwater flow model

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:

A three-dimensional (3D) model was developed using the finite element model software FEFLOW 6.1.

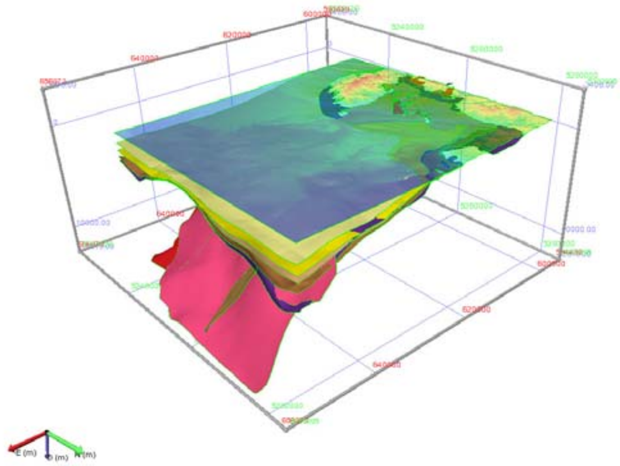

Figure 4. 3D model of the Lutzmannsburg-Zsira pilot area from the NE

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 (Fig.5).

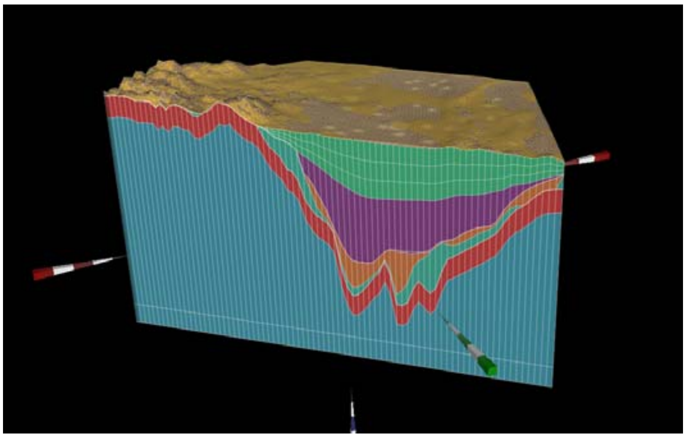

Figure 5. Model layering

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 (Tóth et al. 2012) groundwater model (created in earlier phase of the project) to define boundaries of deeper systems.

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.

Model calibration was performed by means of automated calibration using PEST. The observed vs. simulated hydraulic heads (scatter plot) at observation points is indicated in Fig.6.

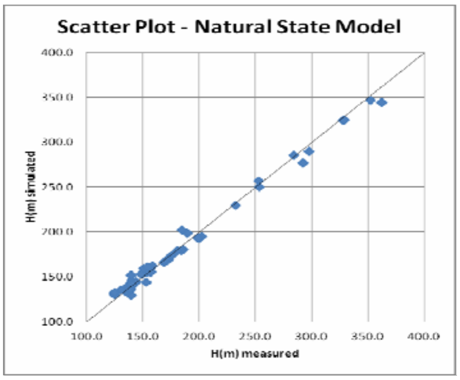

Figure 6. Scatter plot, natural state model

4.3 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.

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 Tóth et al. (2011). The thermal properties applied in the model are listed in Table 2.

The calibration was based on a selection of borehole temperature data available for the study area. The most complete and continuous temperature profiles were obtained. The temperature profile of the Bük-1 borehole is shown on Fig.7.

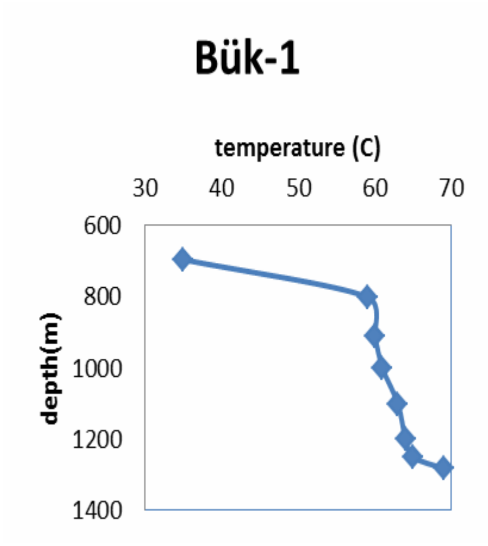

Figure 7. Temperature profile of the Bük-1 borehole

4.4 Results of the integrated models

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

- Hydraulic head distribution (Fig.8)
- Groundwater fluxes
- Temperature distribution (Fig. 9)

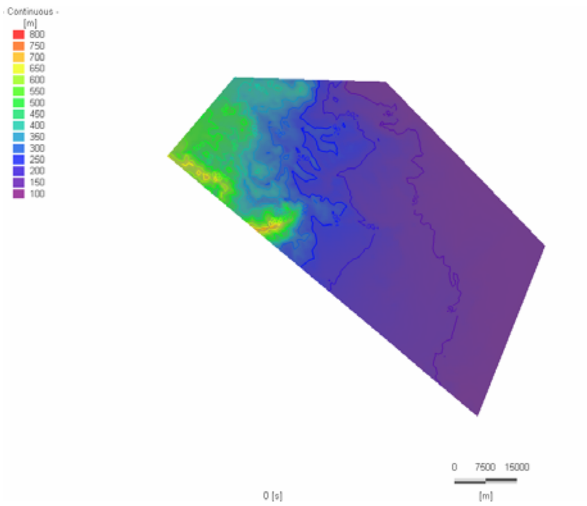

Figure 8. Simulated water table elevation.

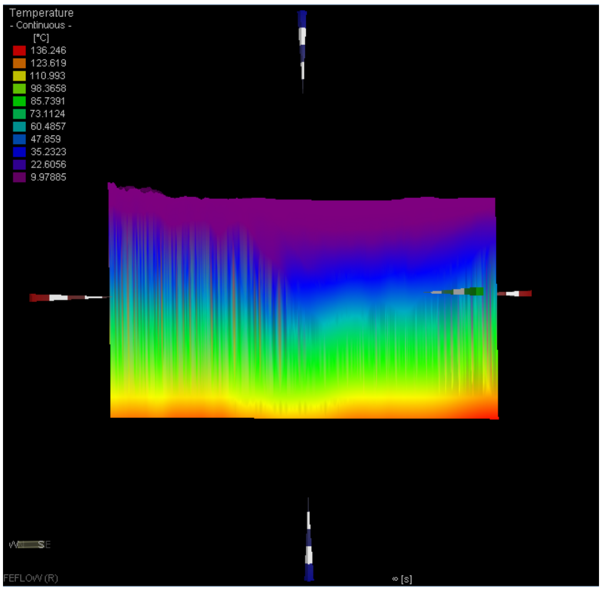

Figure 9. Simulated NW-SE temperature profile

The groundwater flow model confirmed out preliminary assumption, that the recharge area is in the higher elevated Austrian part of the region, while natural discharge occur in the lowland area in Hungary. The main groundwater flow direction is E-NE in every layer.

The results of the geothermal models showed that conductive heat transport is the significant process in the geothermal field. 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.

3. CONCLUSIONS

A coupled groundwater flow and heat transport model of the Lutzmannsburg-Zsira area was developed. The model described the system both in natural state and considering current water withdrawals.

Long term withdrawals cause depressurisation of the groundwater flow system. Effects of pumping occur on both sides of the national boundaries.

The scenario model predicts depressurisation at different rates of pumping. The developed model can serve as a tool for sustainable thermal water management of the region.

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