Report on the Zsira-Lutzmannsburg pilot area scenario modelling study

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5.2.3 Detailed hydrogeological modelling

5.2.5 Detailed geothermal modelling

5.3.1 Map series of the scenario model results

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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 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 groundwater flow and heat transport model of the Zsira-Lutzmannsburg pilot area of the TRANSENERGY project, with special emphasys on the functioning of the Zsira and Lutzmannsburg geothermal utilisations. The report contains the results of extraction scenarios and model predictions. The results of the natural-state model are presented in a previous report (Kovács and Rotár-Szalkai, 2013).

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 across both countries. Several thermal 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. The effects of groundwater extraction, the relation between the three identified reservoirs (Upper Pannonian, Miocene, and basement reservoirs) and the recharge and thermal conditions of these reservoirs required further clarification.

To provide an overview on the large-scale hydrogeological processes of geothermal systems and the connection among the main groundwater bodies, a 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 provided an overall characterisation of the flow system, and was used in the definition of boundary conditions of the pilot models.

3 MODEL OBJECTIVES

The aim of the present modelling work was to understand and characterise the natural hydro-geothermal system of the study area, to investigate the effects of existing geothermal water extractions, and to make predictions on different extraction scenarios. To achieve these goals, the modelling study included the following stages:

- Natural state modelling to understand the functioning of the natural geothermal system and to calibrate numerical model (Kovács and Rotár-Szalkai, 2013);
- Simulation of current groundwater extractions to understand reservoir response and hydraulic interference between extractions bores;
- Scenario modelling to investigate different extraction scenarios and to provide predictions of future reservoir conditions.

The conceptual model, the numerical model setup, and natural state model results are presented in Kovács and Rotár-Szalkai (2013). In order to provide background information to the subsequent scenario modelling study, a short extract of the natural state modelling is included in this report.

3.1 Geographical settings

Originally the pilot area was outlined according to 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.

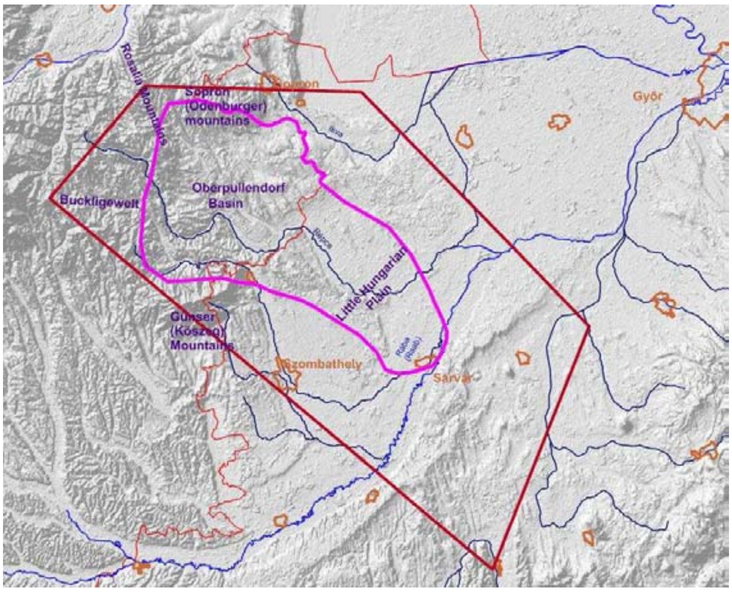

Figure 1. Geographical settings of the pilot area and the model region

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.

3.2 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).

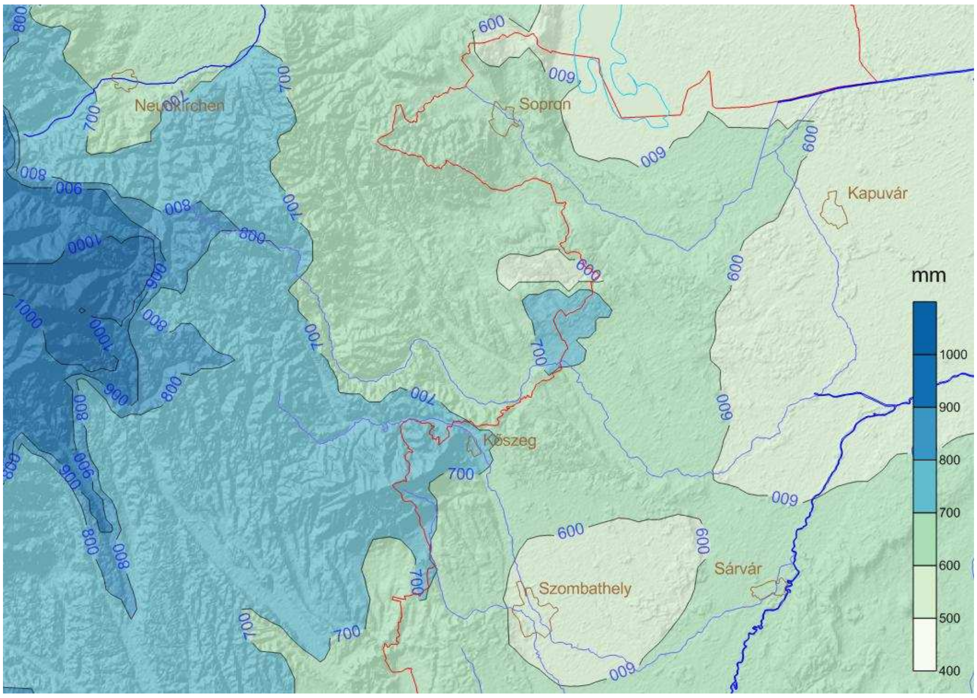

Figure 2. Distribution of annual amount of precipitation

3.3 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. The main structural elements of the pilot area are shown in Figure 3.

The details of the geological model can be found in Maros et al (2012). A detailed description of the geological formations included in the pilot model is provided in the natural state model report (Kovács and Rotár-Szalkai, 2013).

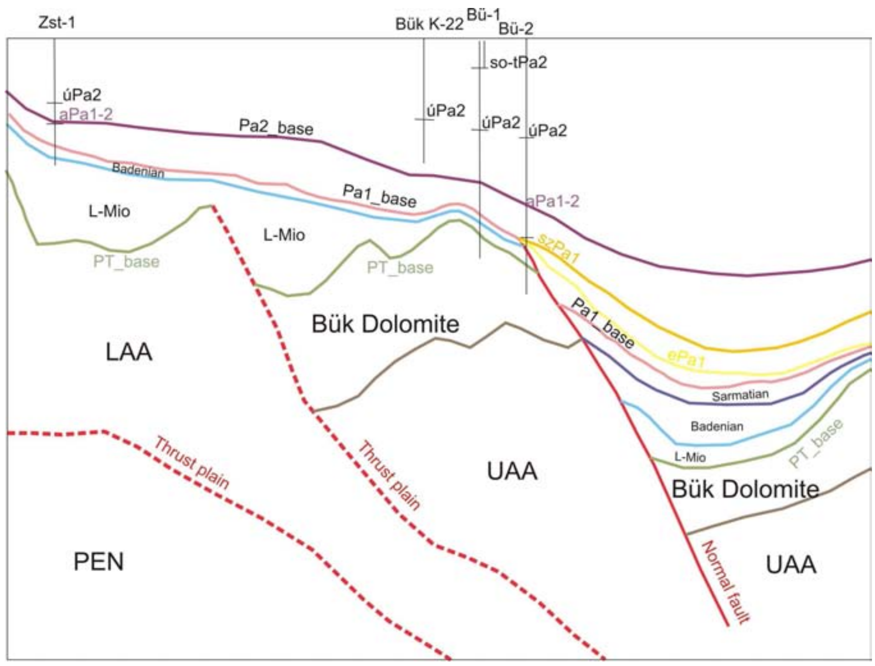

Figure 3. Main structural elements in the seismic section at the eastern part of the Zsira- Lutzmannsburg pilot area (Hungary).

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

3.4 Hydrogeological settings

3.4.1 Hydrostratigraphical units

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

- Crystalline Basement Formations
- Devon Dolomite 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.

The Devonian Dolomite Formation is a special type of basement reservoirs. It can 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 represents 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.

3.4.2 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 and assigned as recharge zones in the model (Figure 4).

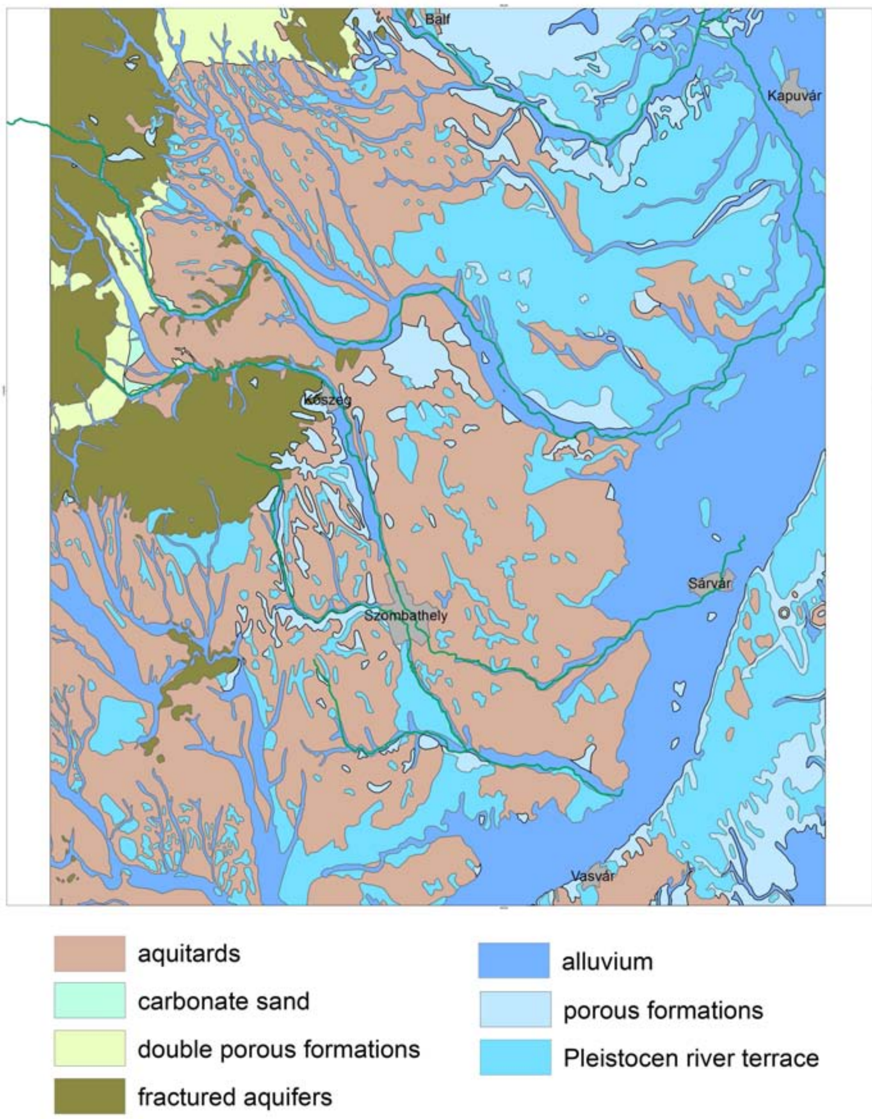

Figure 4. Recharge categories in the modell area

3.4.3 Natural discharge

Natural discharge of groundwater can occur at springs, direct leakage into 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 discharge 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 artificial drainage channel network receives considerable groundwater discharge.

3.4.4 Hydraulic conditions

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 identified.

According to the existing information, the direction of groundwater flow in the Pannonian sediments is W to E in the elevated western regions, then groundwater partly flows towards the Marcal river or turns to N-NE towards the direction of the Hanság region. The NE flow direction is significant in the deepest layers.

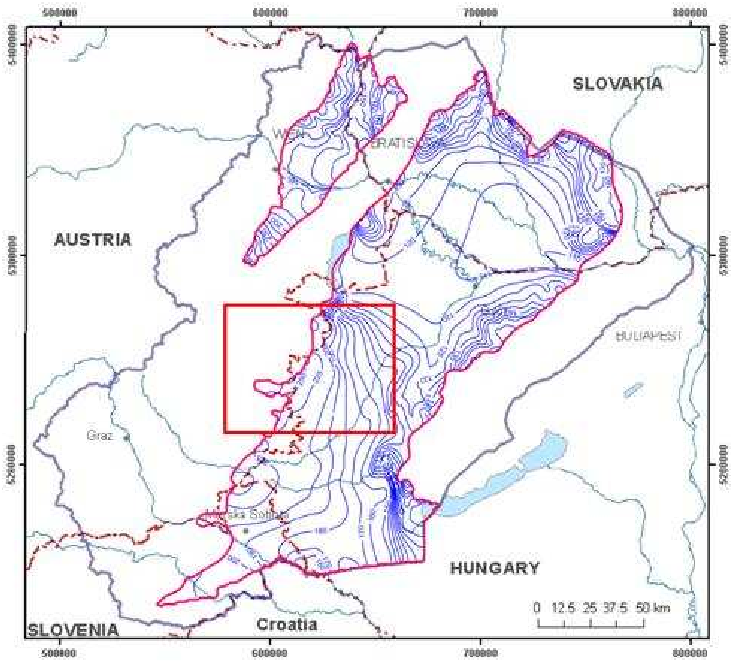

Figure 5. Calculated hydraulic potentials in the Upper Pannonian aquifer of the Supra-Regional model

Several monitoring wells register the hydraulic potential changes in the Pannonian aquifers (Ólmod K-2, Bük K-15, Csepreg K-13). These wells indicate a drawdown of 1-2 m over the past decades. However, in general a regional drawdown of 0-30 m can be observed based on interpolated water table calculations. Significant groundwater depressurisation exist in the Miocene layers due to groundwater extractions (Figure 6). The head drop exceeds 14 m during the 20 years monitoring period.

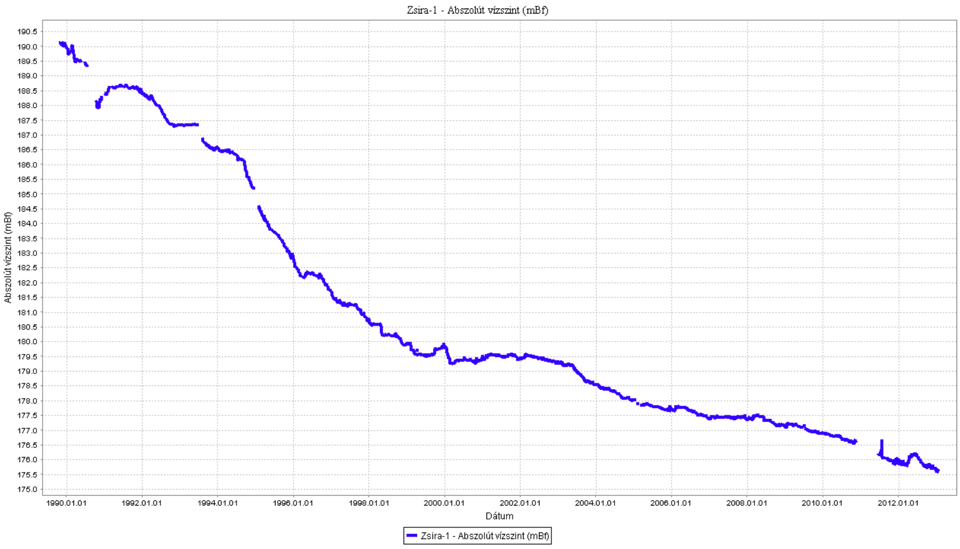

Figure 6. Changes in groundwater hydraulic potential in Zsira monitoring well

3.5 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.

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 Mountains. 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 reached112°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.

Temperature profiles in the area indicate a continuous temperature gradient throughout most of the bore profiles indicating little influence of convective mixing of groundwater. A detailed description of temperature profiles is provided in Kovács and Rotár-Szalkai (2013). Drops or reversals of the temperature gradient can be seen on several profiles within the Devonian reservoir, and within some short sections of the lower and upper Pannonian sequence indicating local convective systems.

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 large-scale 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.

3.6 Groundwater extractions

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 7). The 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 7.

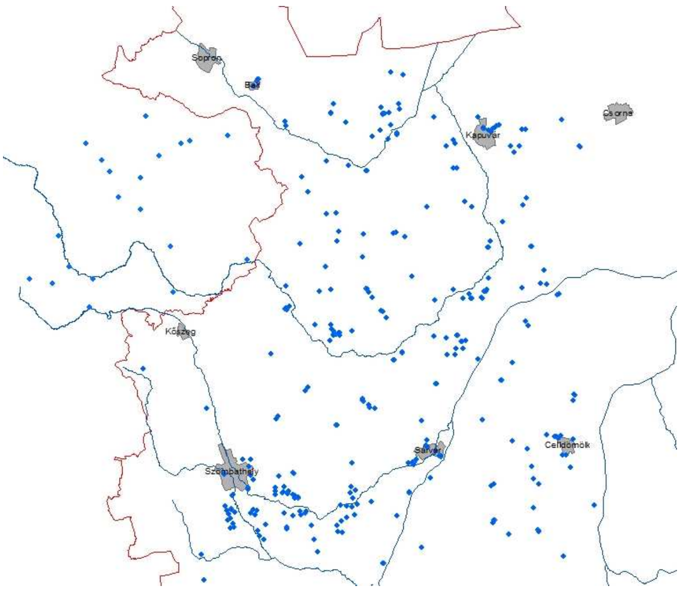

Figure 7. Location of groundwater extraction wells

4 NUMERICAL MODEL

4.1 Modelling methodology

In order to investigate the groundwater flow field and the geothermal conditions in the study area, a three-dimensional finite element model was constructed. The aim of the natural-state numerical modelling was to investigate the natural flow field and temperature distribution in the study area both horizontally and vertically. A previous report (Kovács and Rotár-Szalkai, 2013) described the results of the natural state modelling, the present report describes the simulation of current production conditions and of predictive scenarios.

The simulation of current conditions and predictive scenarios was based on the calibrated natural state model. The calibration of model parameters was refined based on extraction data and groundwater monitoring data. In the production model, known groundwater extractions were assigned to the relevant model layers as well boundary conditions. A steady sate assumption was applied in all model scenarios except for the bore doublet scenario simulated as part of the scenario modelling.

Scenario modelling included the following hypothetical model scenarios:

- No groundwater extractions at Bük;
- No groundwater extractions at Lutzmannsburg;
- No groundwater extractions at Bük or Lutzmannsburg;
- No groundwater extractions in the upper-Pannonian aquifer;
- No groundwater extractions in the Hungarian part of the pilot area;
- No groundwater extractions in the Austrian part of the study area;
- All Groundwater extractions doubled compared to existing discharge rates;
- A geothermal bore doublet installed within the eastern Devonian dolomite block.

4.2 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.

4.3 Hydraulic model

4.3.1 Model geometry

4.3.1.1 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	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 8.

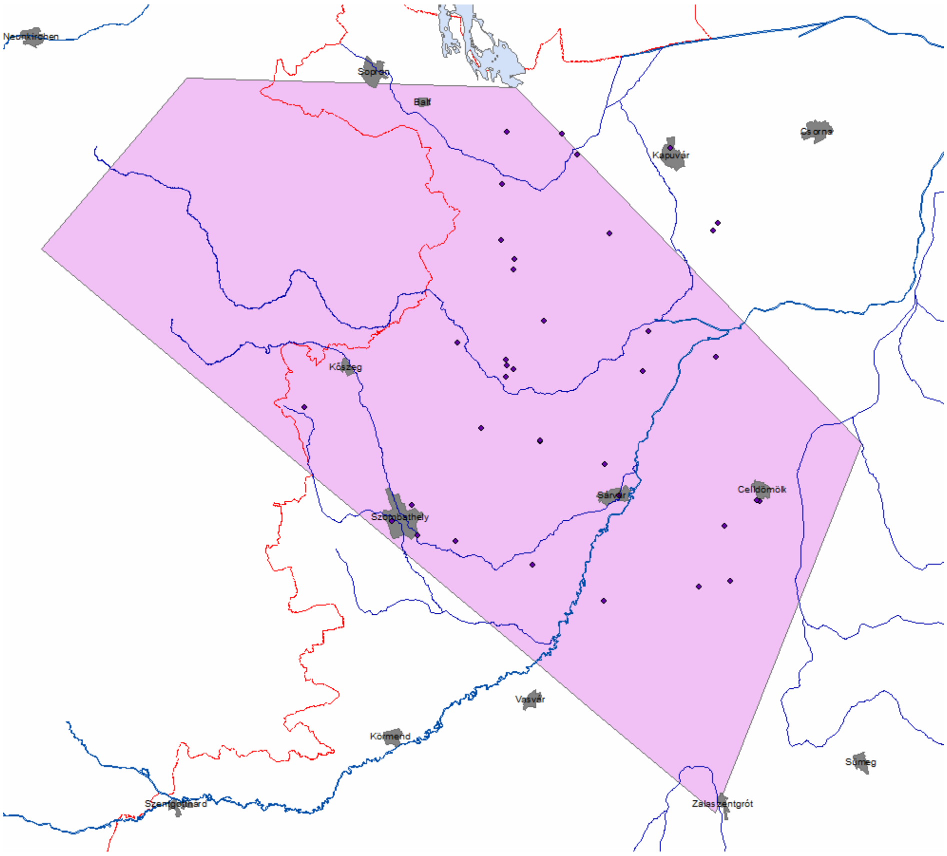

Figure 8. Model domain. Blue dots indicate extraction wells, red line indicates national borders, blue lines indicate surface streams.

4.3.1.2 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 9.

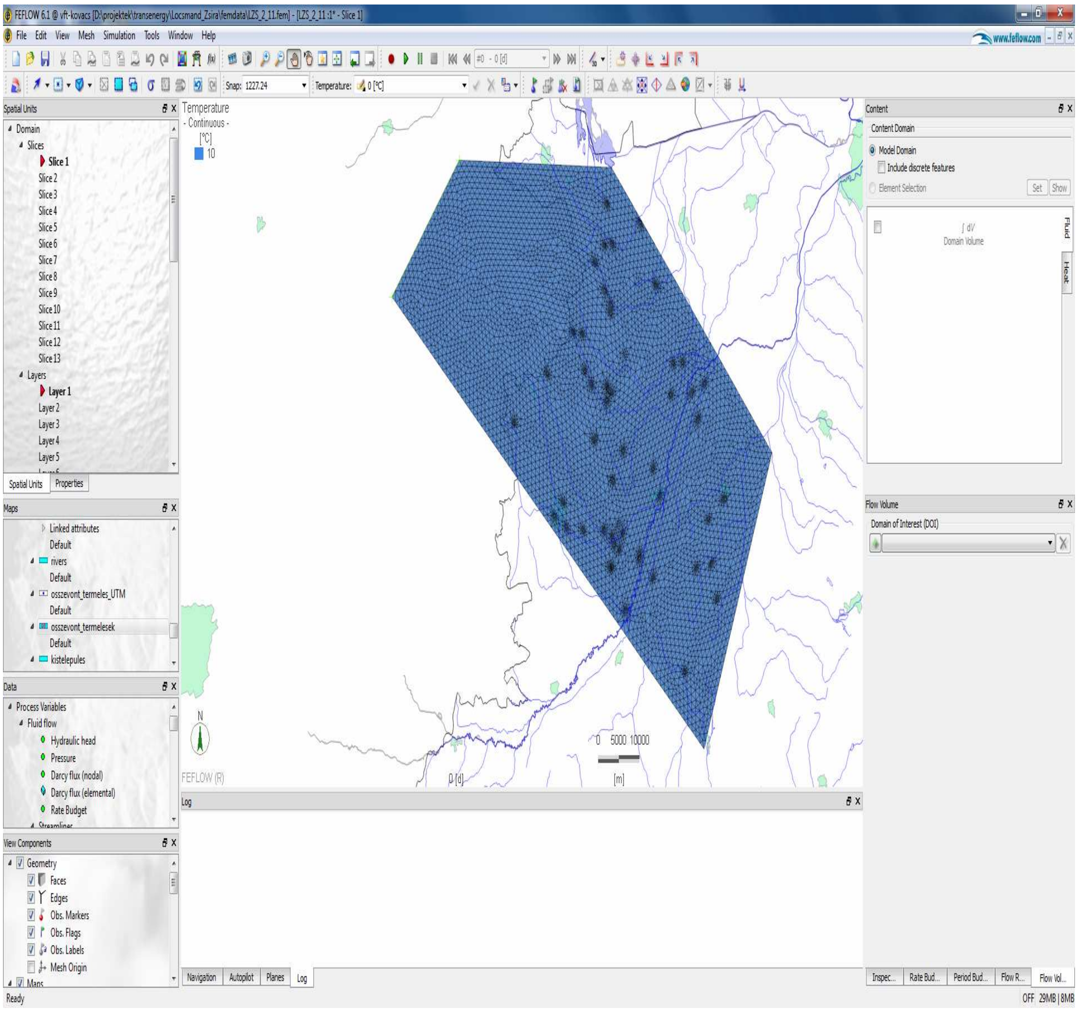

Figure 9. Finite element mesh.

4.3.1.3 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 applied model layering is described in Table 2.

Table 2. Applied model layering.

Unit	Geological code	Lithology	Hydro-stratigraphy	Model layers
Quaternary	Q	sand, silt, clay, gravel	AF1	1
Late Pannonian	Md	clay-marl, silt, sand	AF2	2-4
Early Pannonian	Mplf, Mptb, Mpcm	clay, silt, marl	AC1	5
Sarmatian	Msmf	clay, marls, sand, sandstone	AC2	6
Badenian	Mbls	limestone, conglomerate	AC3	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 10.

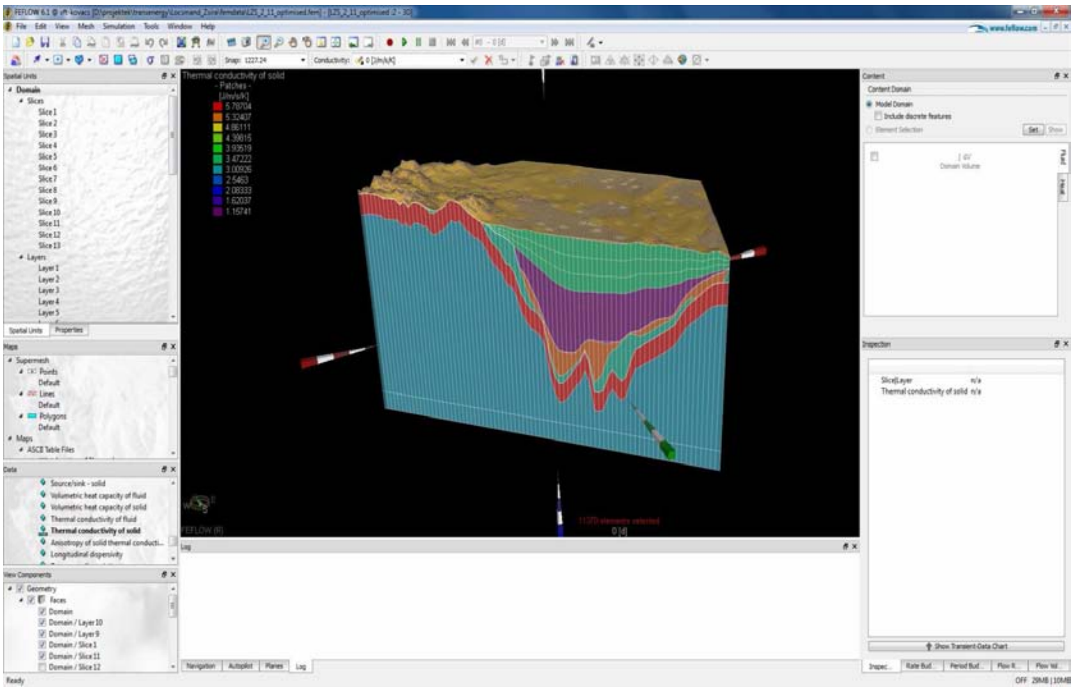

Figure 10. Model layering.

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.

4.3.2 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 11 and Figure 12):

- 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 $q \leq 0$ 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.

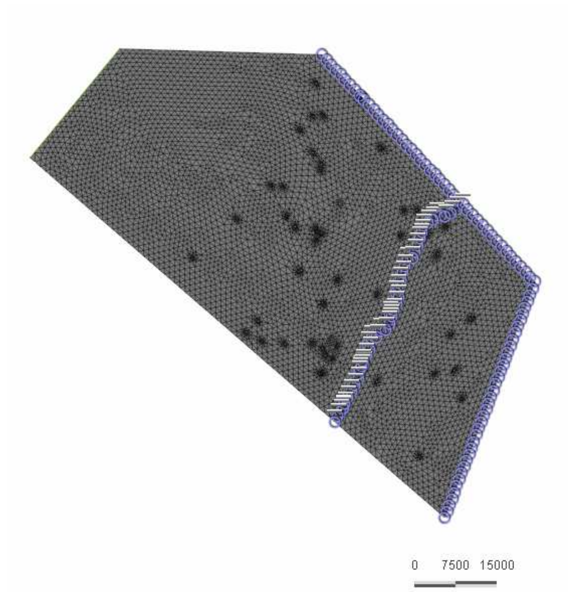

Figure 11. Boundary conditions, slice 1.

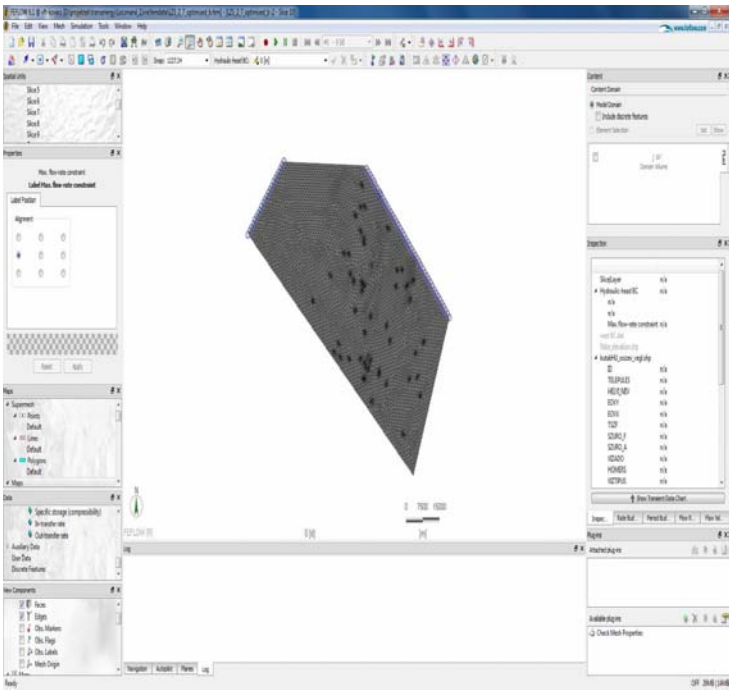

Figure 12. Boundary conditions, slice 10.

4.3.3 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.

Unit	Kxy(m/s)	Kz(m/s)
Quaternary	1.1e-3	1.1e-8
Late Pannonian	1.5e-6	1.1e-8
Early Pannonian	1.1e-8	1.1e-9
Sarmatian	5.0e-8	1.0e-9
Badenian	1.0e-8	1.0e-9
Miocene	8.0e-7	1.0e-7
Devonian	8.0e-7	1.0e-7
Basement upper	1.7e-8	1.6e-9
Basement lower	4.7e-10	8.8e-10

4.3.4 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. PEST (WNC, 2004) is a nonlinear parameter estimation code. Calibration of the natural state model is described in Kovács and Rotár-Szalkai (2013). The observed vs. simulated hydraulic heads (scatter plot) at observation points is indicated in Figure 13. The scatter plot indicates a reasonably good calibration. The difference between the calibration of the natural state and the production models is the consequence of the uncertainty of production data and the temporal variability of observation data used in the calibration of the production state model.

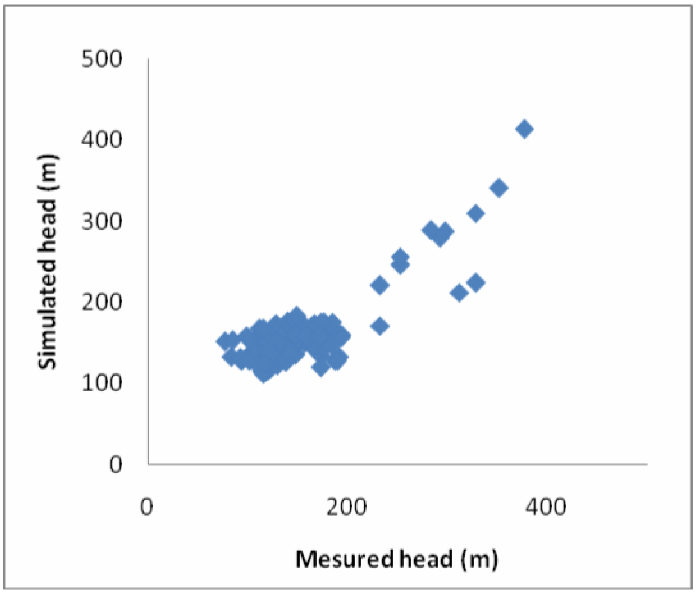

Figure 13. Scatter plot, hydraulic heads, production state model.

4.4 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.

4.4.1 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.

4.4.2 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 4.

Table 4. Thermal properties.

Unit	Model layers	Porosity	Thermal conductivity (W/mK)	Longitudinal dispersivity (m)	Transverse dispersivity (m)
Quaternary	1	0.3	2	5	0.5
Late Pannonian	2-4	0.2	2	5	0.5
Early Pannonian	5	0.2	3	5	0.5
Sarmatian	6	0.2	3	5	0.5
Badenian	7	0.1	3	5	0.5
Miocene	8	0.1	3	5	0.5
Devonian	9	0.1	3	5	0.5
Basement upper	10	0.05	3	5	0.5
Basement lower	11-12	0.05	3	5	0.5

4.4.3 *Model calibration*

Calibration of the geothermal model was achieved by means of the gradual modification of key model parameters (manual calibration). The observed vs. simulated temperatures (scatter plot) at selected observation points is indicated in Figure 14.

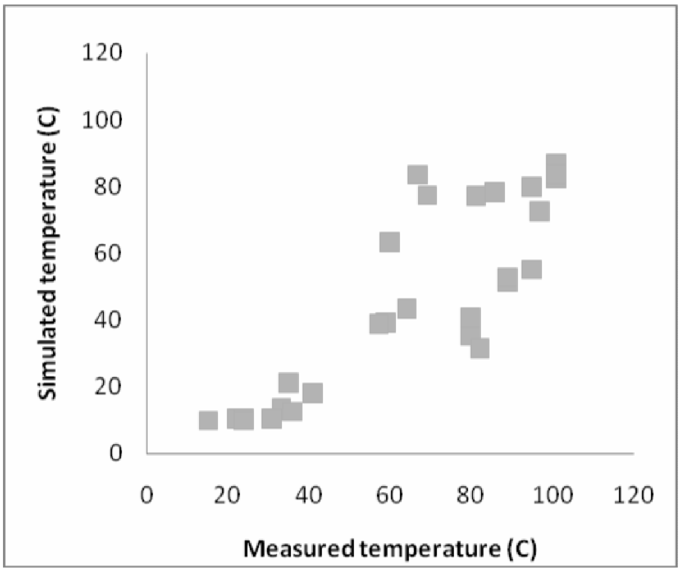

Figure 14. Scatter plot, simulated temperatures, production state model.

5 SIMULATION OF CURRENT PRODUCTION

To simulate the influence of existing groundwater extractions of the regional flow field and to investigate the local-scale groundwater flow conditions in the Zsira-Lutzmannsburg area, extraction bores were added to the model using well boundary conditions.

The vertical position of boundary nodes was defined based on the screen depth of individual wells, and BC’s were assigned to the relevant model slice. The number of extraction bores assigned to the hydrostratigraphical units are listed in Table 5.

Table 5. Extraction bores applied in production model

Formation	Number of bores
Quaternary	38
Upper Pannonian	227
Lower Pannonian	2
Sarmathian	10
Devonian	2

Where temporally varying extraction rates exist, the latest extraction rate was applied as steady state boundary condition, assuming an immediate effect of reservoir depressuristaion.

Special attention was payed to the Zsira and Lutzmannsburg thermal bores, as this system represented the focus of out investigation.

6 MODEL SCENARIOS

Scenario modelling comprised the simulation of hypothetic extraction rates at varios locations to simulate future groundwater and geothermal conditions. The aim of scenario modelling was:

- To separate the influence of different existing groundwater extractions;
- To provide prediction of possible groundwater drawdown rates.

The steady state model calibrated against existing extraction rates represent the long-term equilibrium between groundwater recharge and groundwater extractions, and can be considered as the prediction of future conditions assuming that no additional extraction bores will be installed, and extraction rates remain constant.

To investigate the influence of different extraction groups on regional drawdown, extraction bores in different reservoirs and different geographic locations were “switched off” (***Scenarios 1-6)***.

To investigate the possible effects of increasing groundwater utilisation, a twofold increase of extraction rates at each extraction bore was assigned to the model (***Scenario 7)***.

Simulation of a bore doublet was included in scenario modelling to investigate the applicability of extraction-reinjection systems in the study area (***Scenario 8)***

The scenario modelling involved the following model scenarios:

- No groundwater extractions at Bük (***Scenario 1***);
- No groundwater extractions at Lutzmannsburg (***Scenario 2***);
- No groundwater extractions at Bük or Lutzmannsburg (***Scenario 3***);
- No groundwater extractions in the upper-Pannonian aquifer (***Scenario 4***);
- No groundwater extractions in the Hungarian part of the pilot area (***Scenario 5***);
- No groundwater extractions in the Austrian part of the study area (***Scenario 6***);
- All Groundwater extractions doubled compared to existing discharge rates (***Scenario 7)***;
- Bore doublet (***Scenario 8***).

The results of the above model scenarios are discussed in the following chapter.

7 RESULTS

7.1 Natural state

Results of the natural state modelling are described in the pilot area report (Kovacs et al 2013). A short summary is provided below.

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 15 to 19.

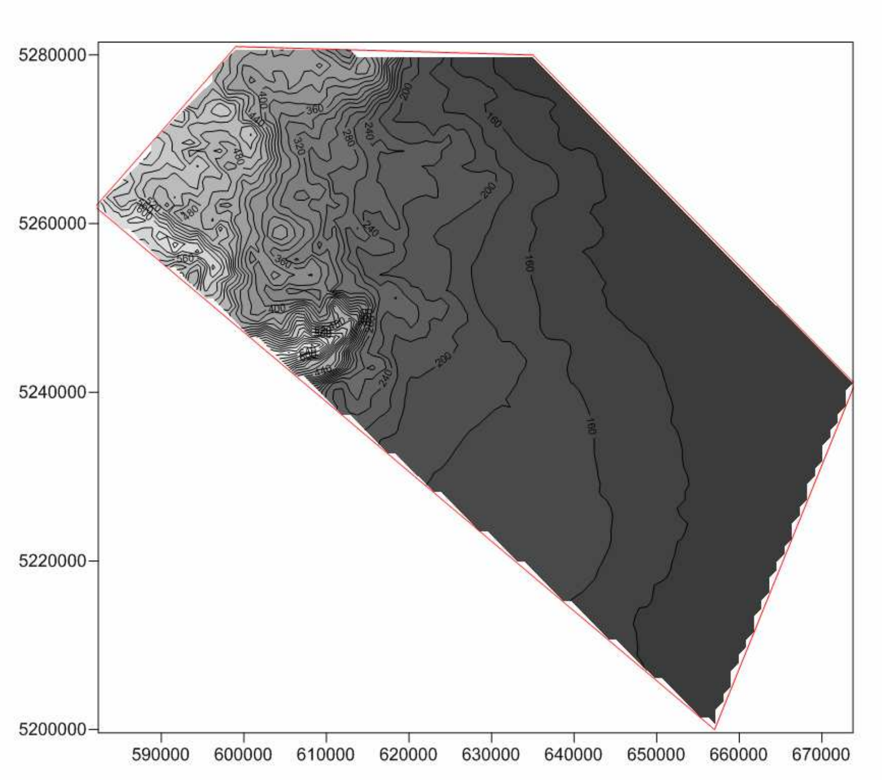

Figure 15. Simulated water table elevation.

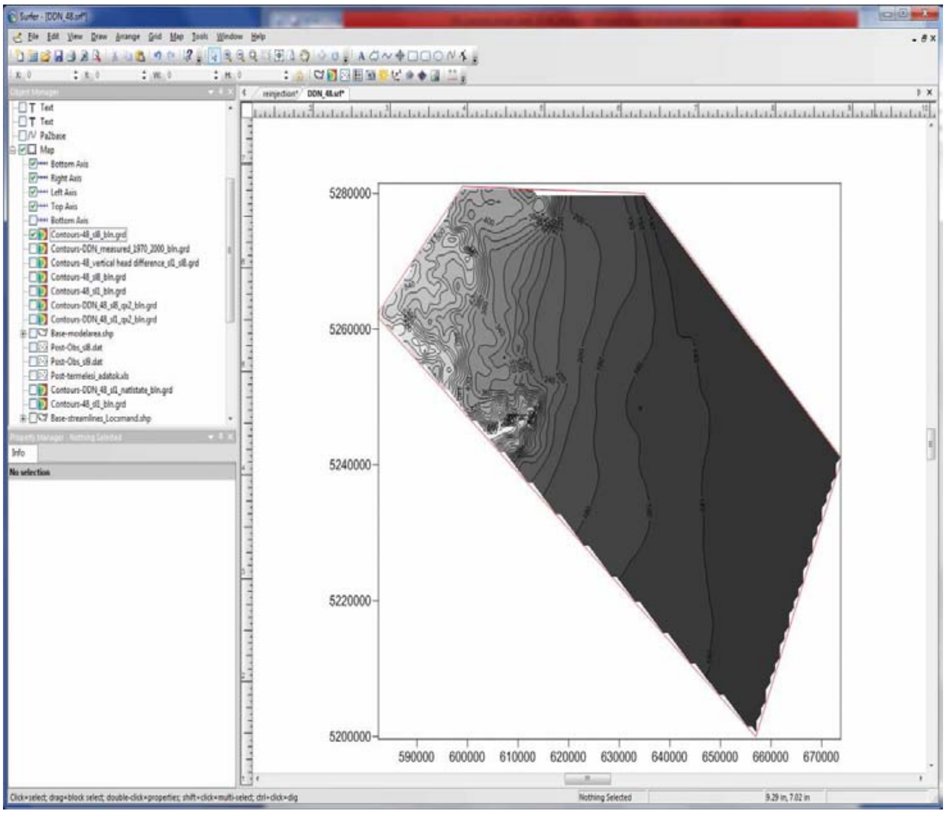

Figure 16. Simulated hydraulic head distribution in the Sarmathian layers (slice 8).

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 97% of groundwater recharge, while the rest arrives as groundwater inflow from the west. The water budget of the area is indicated in Table 6.

Table 6. Simulated water budget.

Boundary	In (m3/d)	Out (m3/d)
Prescribed head	4,180	181,055
Infiltration	176,875	N/A

The simulated temperature distribution at different depths is shown in Figure 17 and Figure 18. A vertical NW-SE profile of simulated temperatures is shown in Figure 19.

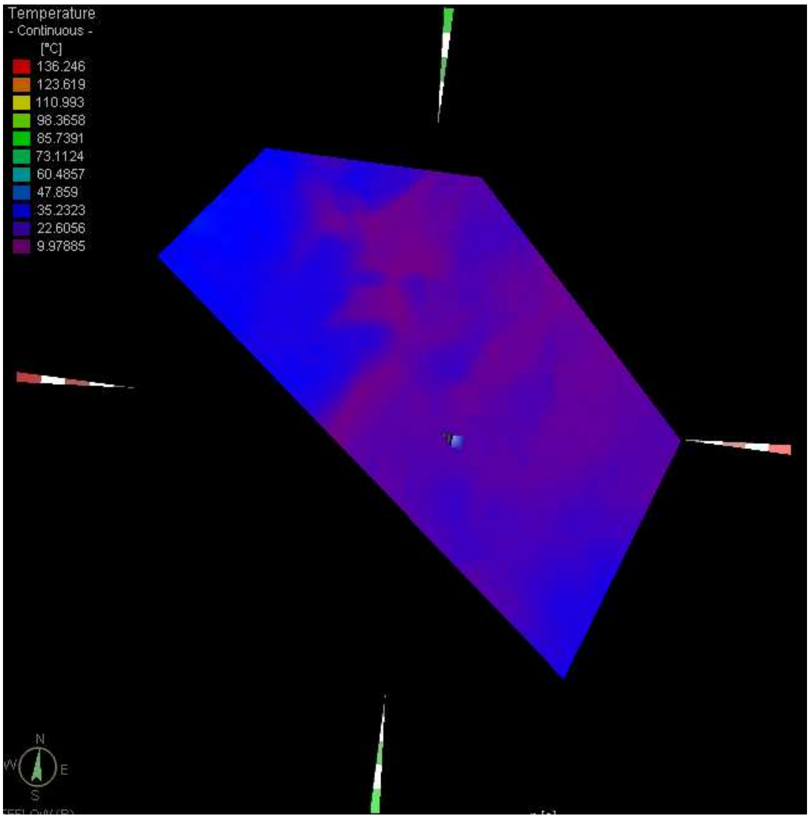

Figure 17. Simulated temperature distribution at -1000 mASL.

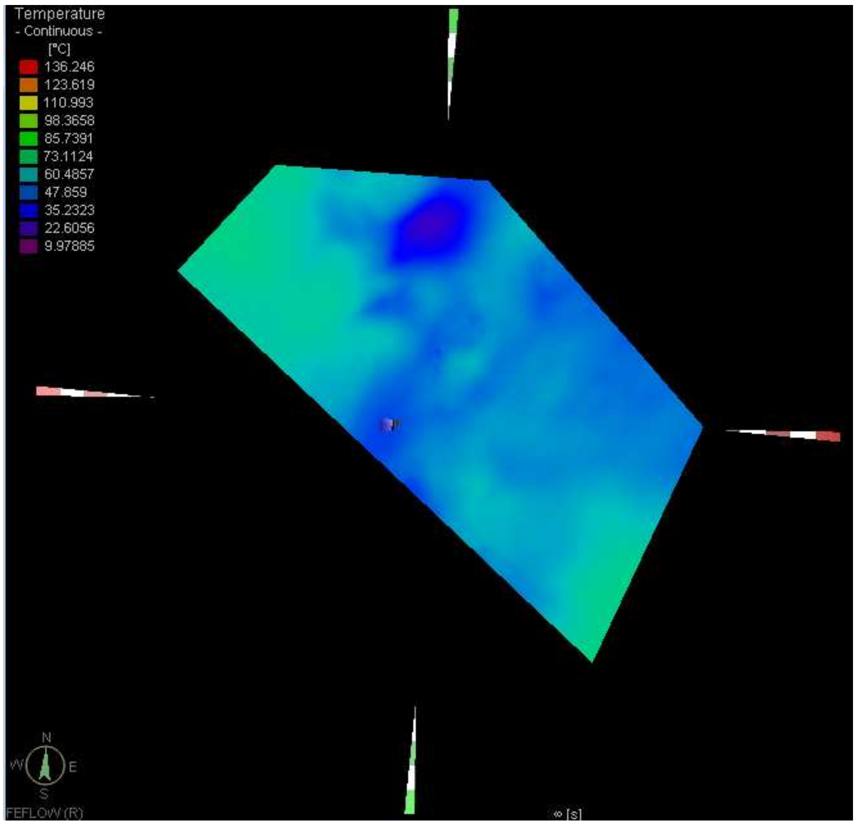

Figure 18. Simulated temperature distribution at -2500 mASL.

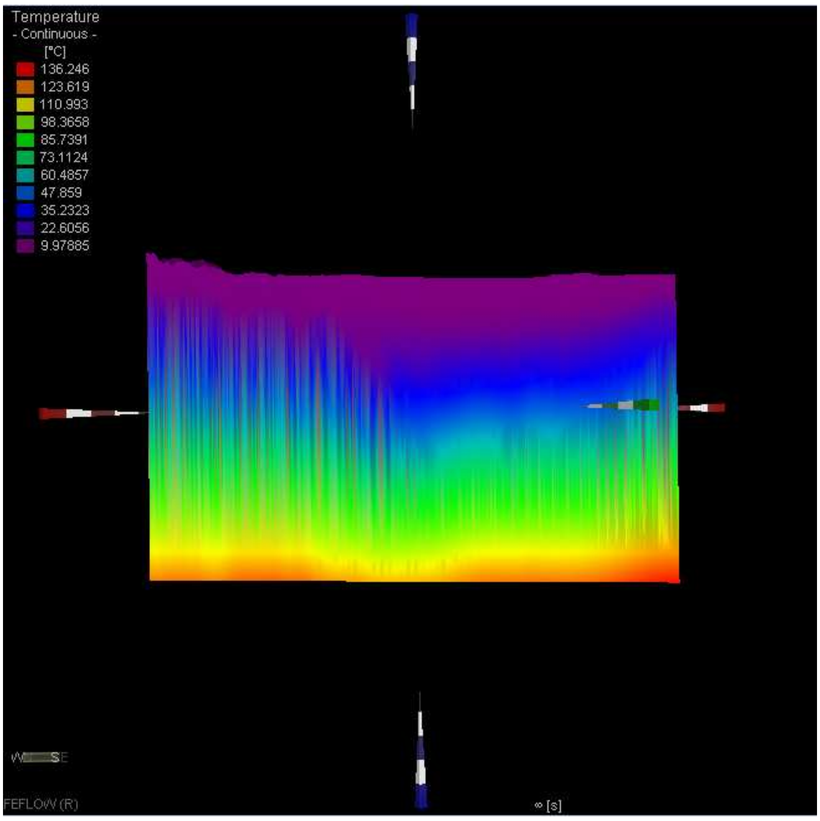

Figure 19. Simulated NW-SE temperature profile.

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.

7.2 Current production

The simulation of the production scenario included all known groundwater extractions within the model area. The majority (53%) of groundwater extractions takes place within the upper-pannonian aquifer. 9% of total extractions occur from the Quaternay aquifer, while 3.5% is extracted from the Sarmathian reservoir. Devonian bores extract 1.5% of the total rates.

For visualisation purposes, the water table and the potentiometric surface within the Sarmathian reservoir were plotted. While the water table is representative of the head distribution in the upper part of the system, head distribution within the Sarmathian approximates the hydraulic conditions within the lower-Miocene - Devonian reservoir system. The simulated production scenario water table is indicated in Figure 20. Simulatede potentiometric surface within the Sarmathian reservoir is indicated in Figure 21.

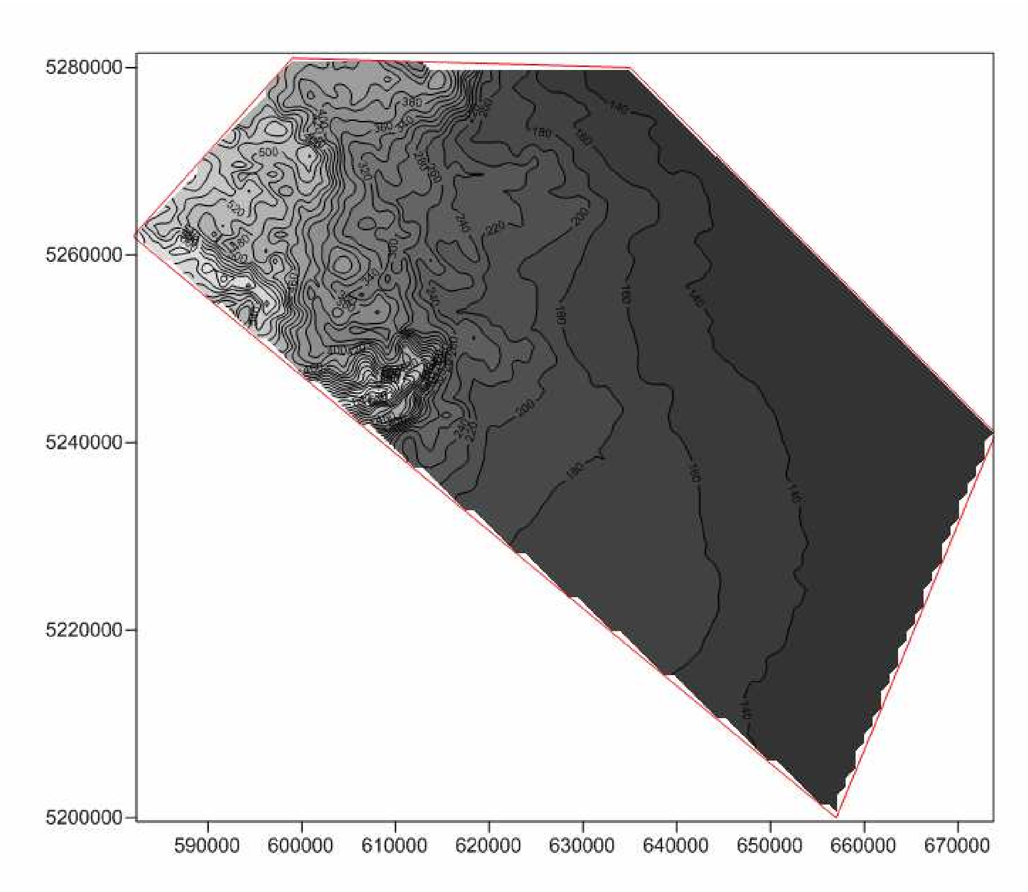

Figure 20. Simulated water table - Production state.

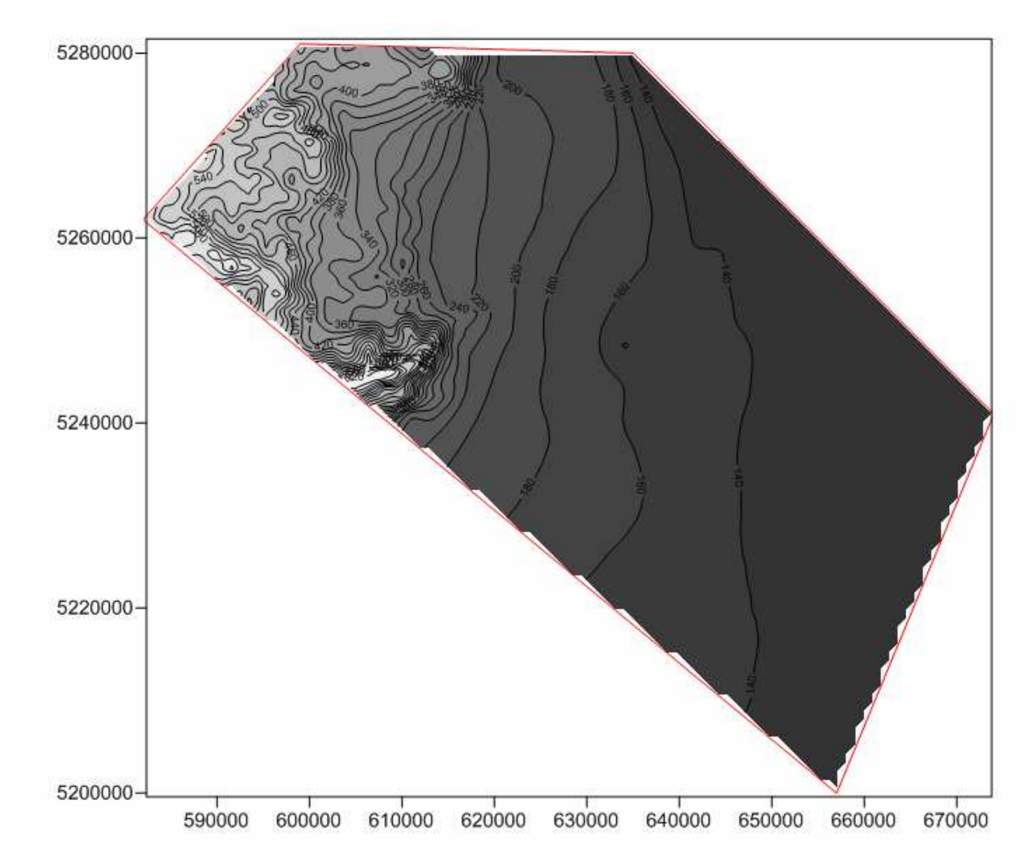

Figure 21. Simulated head distribution in the Sarmathian reservoir - Production state.

The difference between water table elevation and hydraulic head distributions at depth indicates the dominant flow regime obtained from model simulations. Figure 22 indicates the zones of dominantly downward flow areas (recharge zones) and dominantly upward flow areas (discharge areas). As expected, topographic highs represent the main recharge zones within the study area, while lowlands function as discharge areas including the Marcal and Répce valleys.

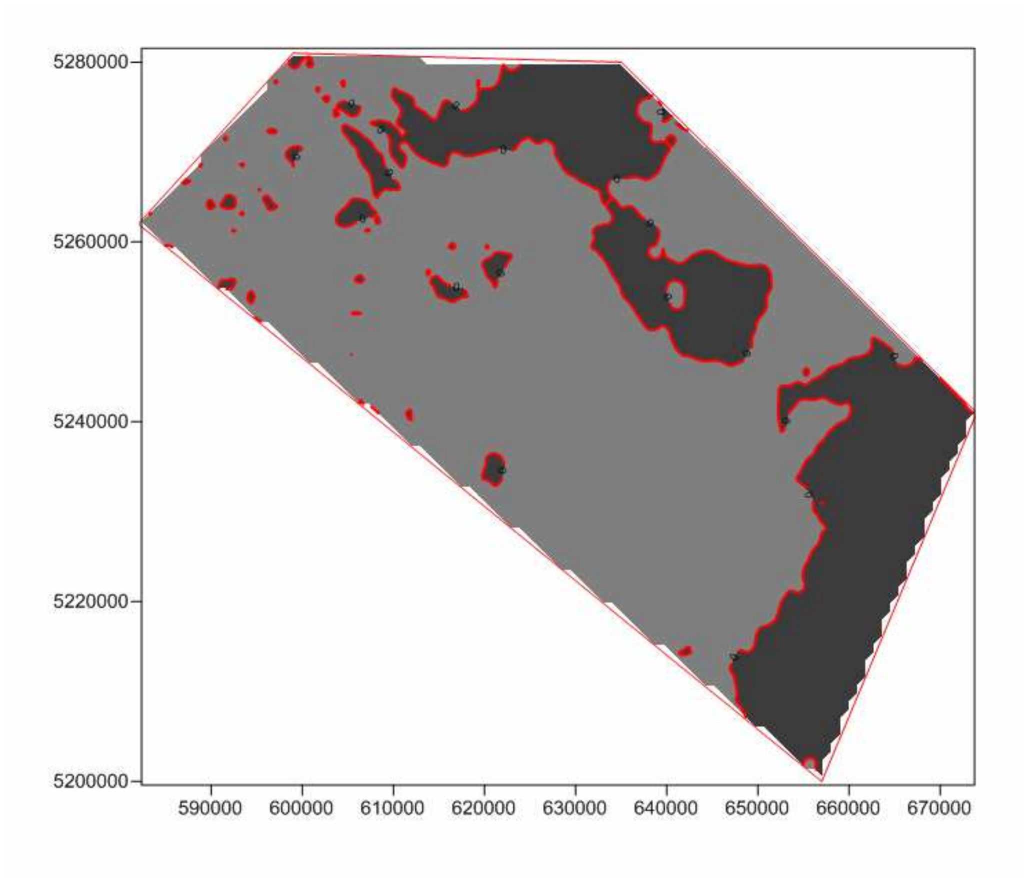

Figure 22. Simulated flow regimes. Gray areas indicate downward flow (recharge areas), while black areas represent upward flow (discharge areas).

Drawdown distributions compared to natural state conditions were also plotted for the above hydrostratigraphic units. The simulated drawdown distributions are provided in Figures 23-24.

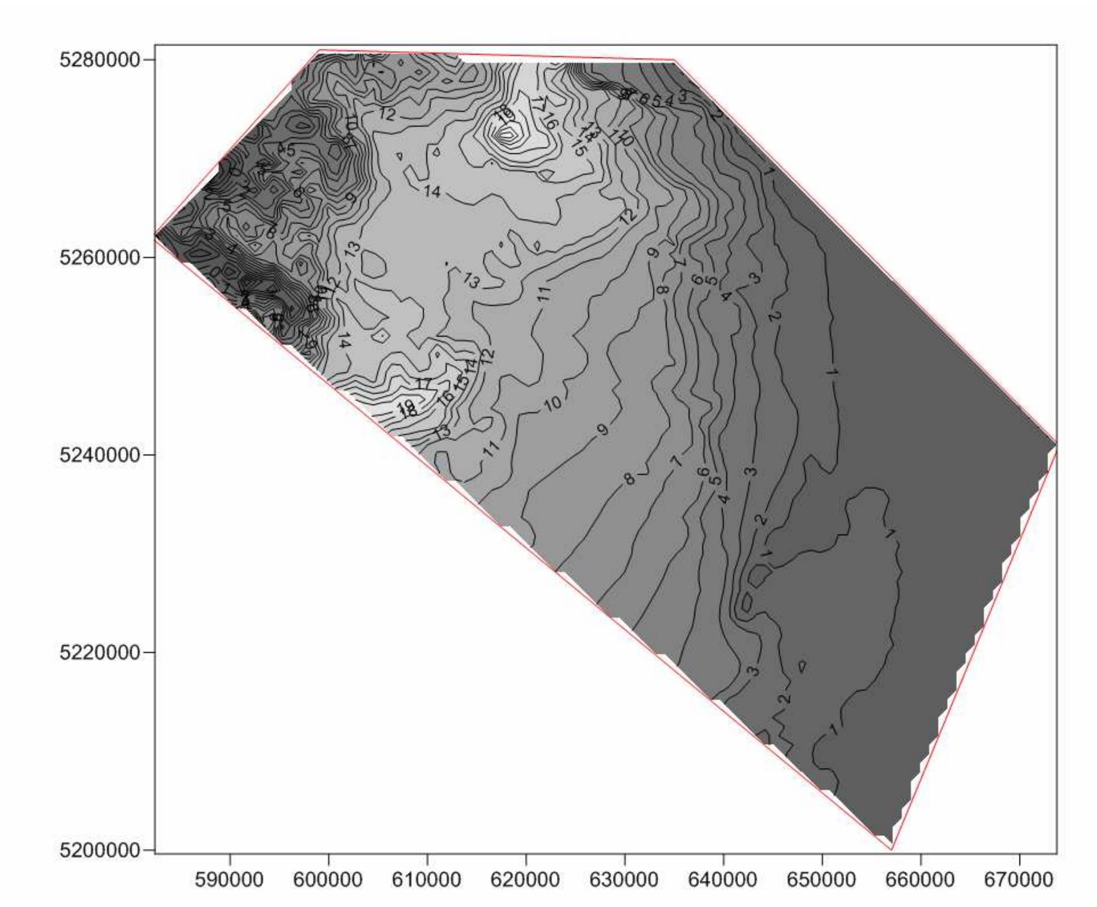

Figure 23. Simulated drawdown, water table aquifer.

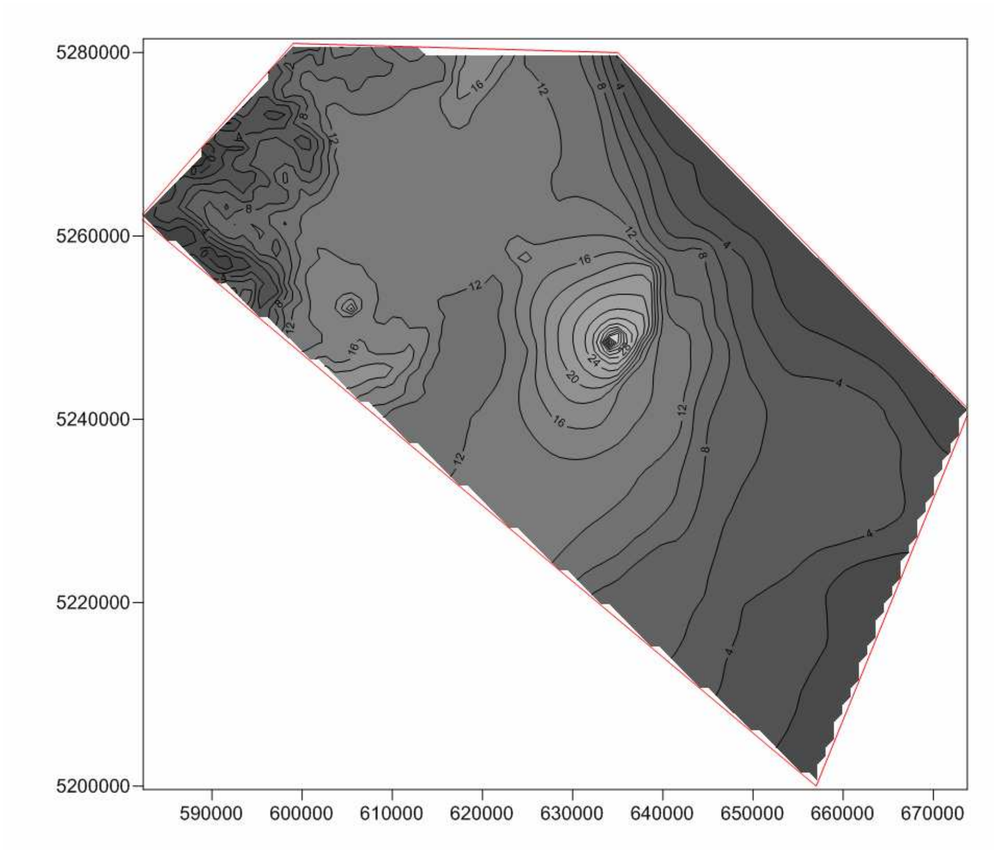

Figure 24. Simulated drawdown, Sarmathian reservoir.

Model simulations indicate that regional groundwater table drawdown varys between 1-15 metres in response to groundwater extraction. The largest drawdowns exists in the western side of the model domain resulting from the depression of resource bores located in Austria.

The depressurisation of pre-neogene aquifers generally varies between 2-12 metres. The largest pressure drop is simulated to exist around the Bük extraction bores. A significant depressurisation is observed around the Lockenaus extraction bore.

The simulated production state water budget is indicated in Table 7.

Table 7. Simulated water budget.

Boundary	In (m3/d)	Out (m3/d)
Prescribed head	4,725	140,805
Infiltration	176,875	N/A
Extraction bores	N/A	40,795

7.2.1 *The Zsira-Lutzmannsburg system (Scenarios 1-6)*

The Zsira-Lutzmannsburg system comprises the following components:

- Two extraction bores at Bük: Bük K-4 and Bük K-10 extract groundwater from the Devonian Bük dolomite at a total rate of 1500 m^3/day. Extraction of thermal groundwater started in 1962 at a rate of 200 m^3/day and was gradually increased over the following years to the current extraction rate. The temperature of the outflowing water is 58 C.
- Two extraction bores at Lutzmannsburg: Thermal- 1 and Thermal -2 started operation in 1994 at an extraction rate of 430 m^3/day. These bores are screened within the Karpatian sediments, and are operated alternately.
- An observation bore at Zsira: Zst-1 is screened within the Karpatian sediments, and is located in between the Zsira and the Lutzmannsburg extraction bores, thus providing information ion the combined effects of these extractions.

The stratigraphic setup of he local system is shown in a cross section in Figure 25. The figure indicates, that the Devonian dolomite block is partially overlain by Karpatian sediments in the west, and Badenian sediments in the East. This is the consequence of the pinching out of Karpatian sediments in the central area of the Dolomite body.

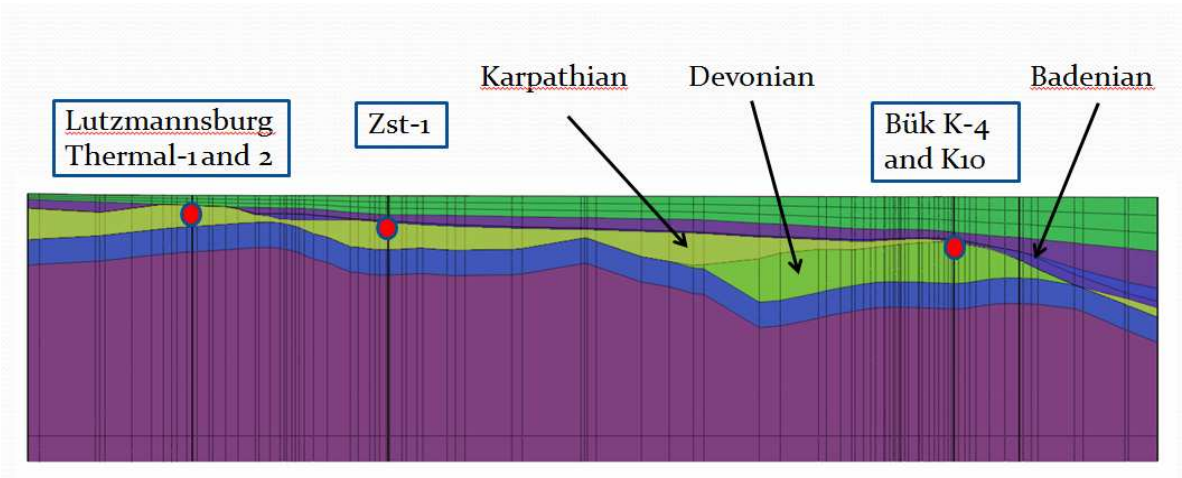

Figure 25. Local hydrostratigraphy of the Zsira-Lutzmannsburg system (NW-SE cross section).

Since the beginning of groundwater extraction at the above locations, the following changes in groundwater conditions were observed:

- A gradual increase in the concentration of main water components including Na, K, HCO_3, Cl and SO_4 was observed in Bük K-4 and K-10;
- A gradual pressure drop up to 15 metres was observed in Zsira Zst-1.

It was suspected, that the pressure drop observed in Zst-1 was caused by the depressurisation of the Bük thermal bores. It was also assumed, that increasing salinity was the result of saline water leakage from underlying or overlying reservoirs. The exact source of saline groundwater has not been identified. The goal of the modelling study with respect to the Zsira-Lutzmannsburg system was to answer the following questions:

- What is the source of saline groundwater observed in the Bük observation bores?
- Which extractions cause the depressurisation observed in the Zsira Zst-1 monitoring bore?

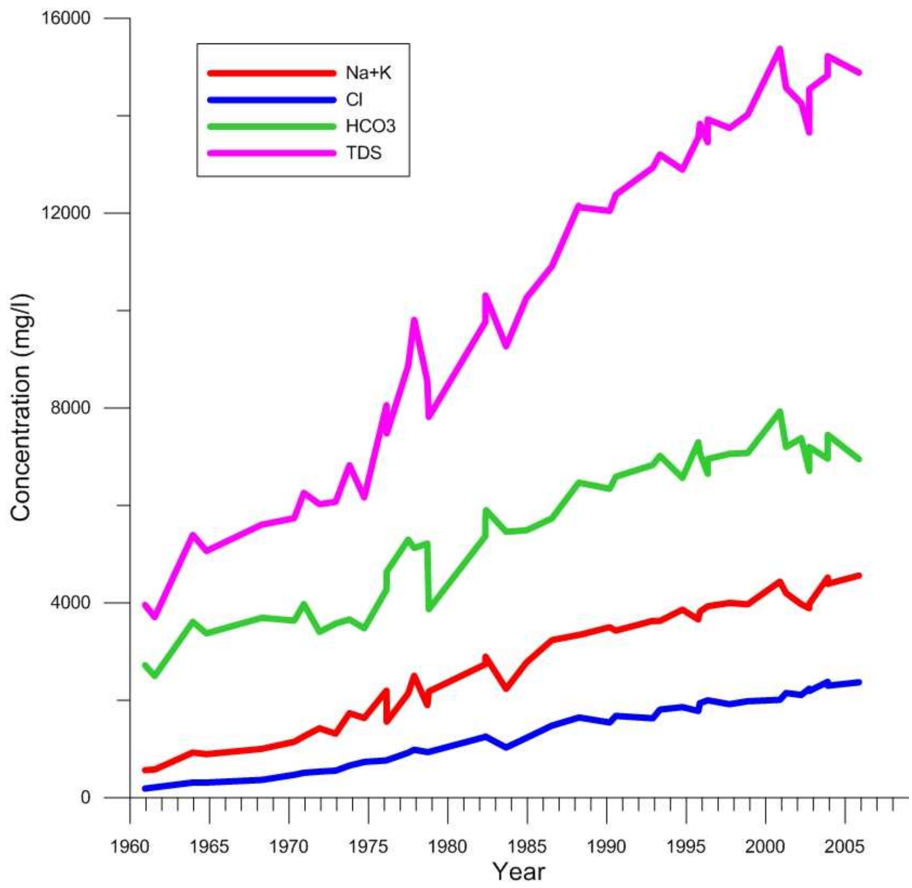

Figure 26. Concentration of main components in the Zsira extraction bores.

To answer the main questions concerning the Zsira-Lutzmannsburg local system, the production state model was utilised. In order to investigate the source of saline water, flow directions were analysed in the vicinity of the Bük extraction bores. Piezometric plots along a cross section including the Lutzmannsburg, Zsira and Bük bores are provided in Figure 27. The flow vectors in natural state and under current production conditions are indicated in Figure 28.

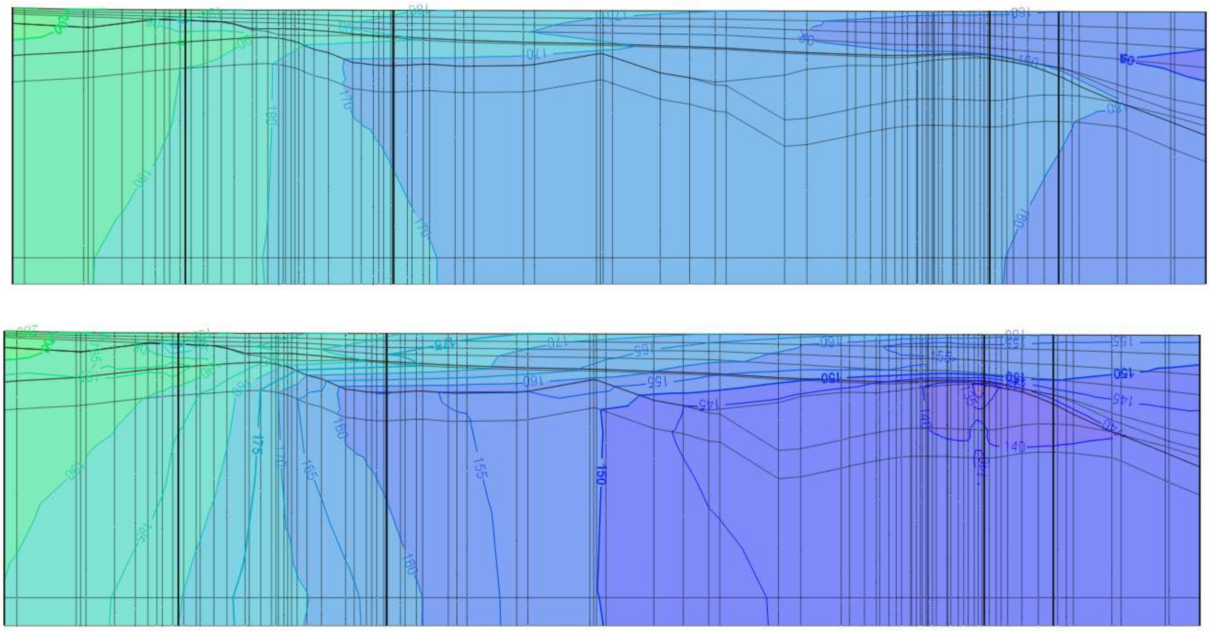

Figure 27. Piezometric cross-sections (NW-SE) across the Lutzmannsburg, Zsira and Bük bores (a. natural state, b. production state).

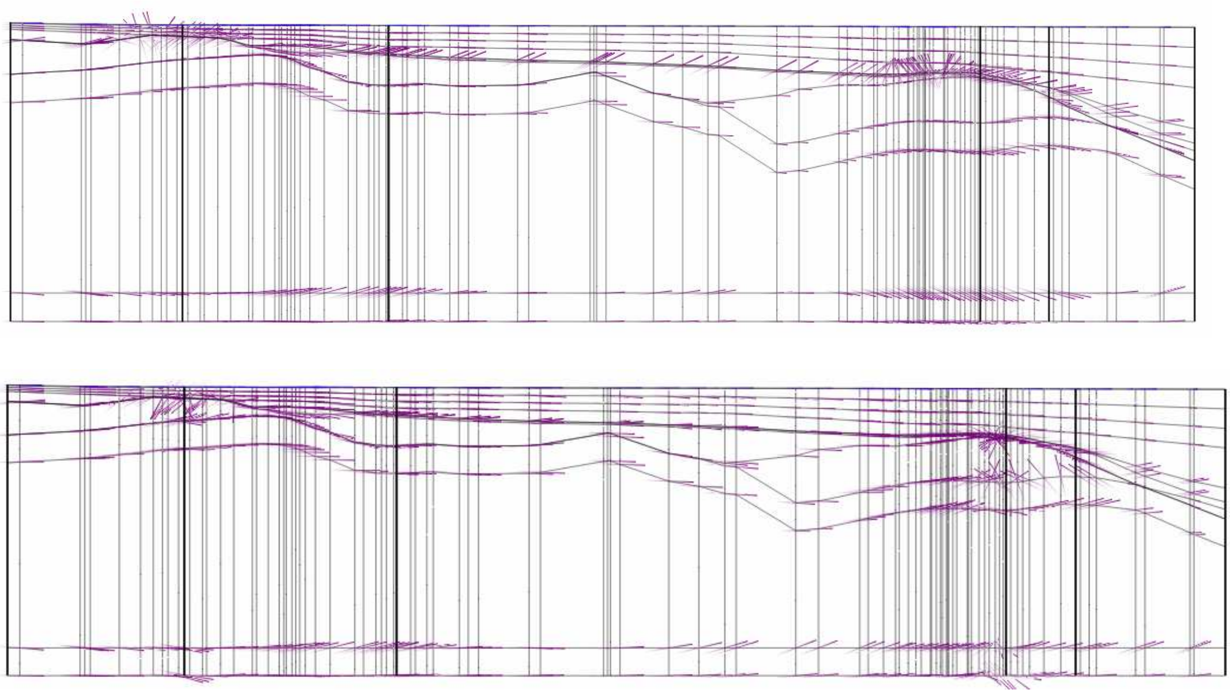

Figure 28. Flow vectors along NW-SE cross-sections across the Lutzmannsburg, Zsira and Bük bores (a. natural state, b. production state).

The piezometric plots indicate significant depressurisation both at the location of the Bük and the Lutzmannsburg bores. The flow vectors indicate the reversal of natural flow directions at these locations. While the natural recharge of the Bük dolomite is through overlying Karpatian sediments from the west, the depressurisation casuses the reversal of natural flow. As a consequence, groundwater leaks into the devonian reservoir from the overlying Badenian sediment located in the west and from the low-permeability basement rocks underlying the Bük dolomite. The production-induced leakage directions are indicated in Figure 29. below.

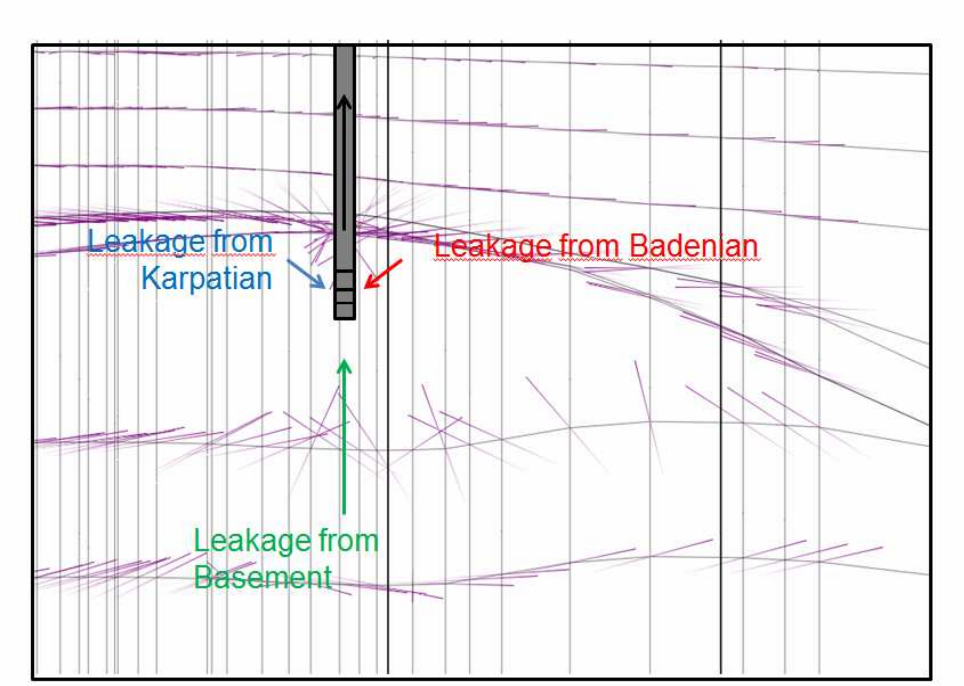

Figure 29. Groundwater leakage in response to production from the Bük dolomite block.

The analysis of water chemistry of the main reservoirs around the Bük dolomite block indicates that Badenian reservoirs contain high-salinity waters which might alter groundwater composition of the Bük dolomite through mixing processes.

The piper plot of main reservoir water types indicate the gradual change in water chemistry of the Bük dolomite between 1960 and 2005 (Figure 30). The plot clearly shows that the increasing salinity originates from mixing with Badenian reservoir waters.

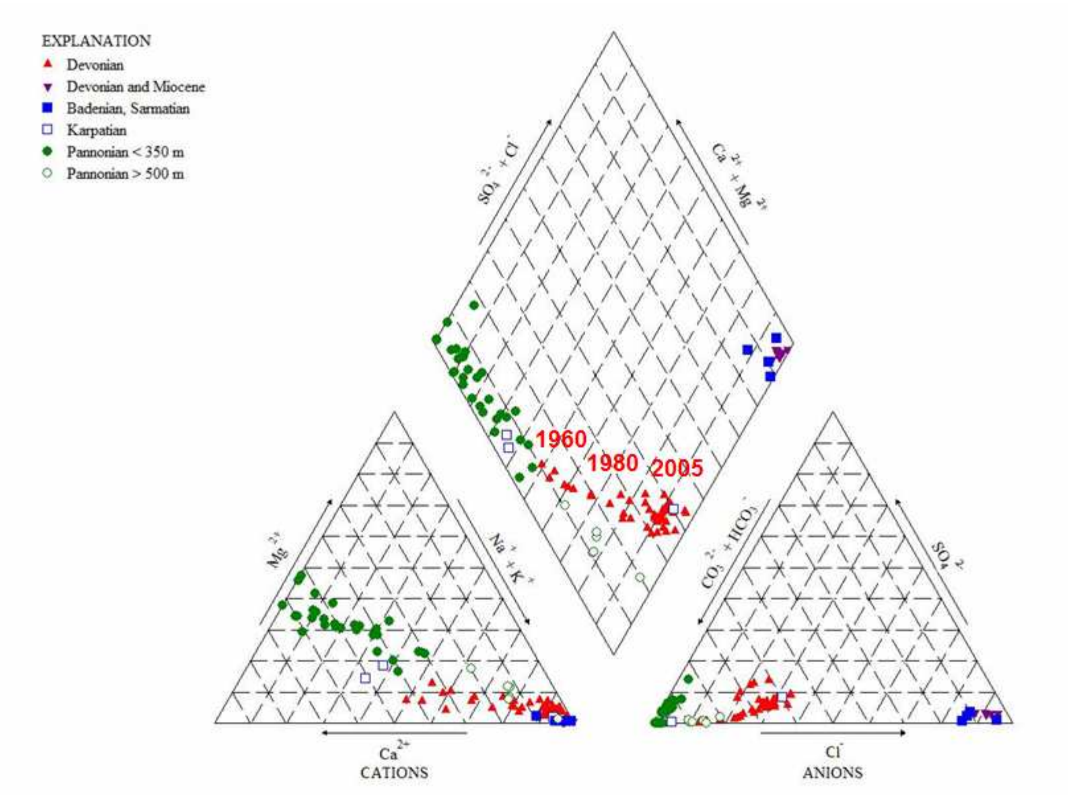

Figure 30. Piper plot of main reservoir waters in the pilot area.

In order to separate the hydraulic influence of different water extractions and to determine the sources of depressurisation observed in the Zsira Zst-1 bore, the production state model was applied. By »switching off« user groups, different scenarios could be investigated and the hydraulic impact of extraction bores could be evaluated. The simulated scenarios included the following:

1. No groundwater extractions at Bük;
2. No groundwater extractions at Lutzmannsburg;
3. No groundwater extractions at Bük or Lutzmannsburg;
4. No groundwater extractions in the upper-Pannonian aquifer;
5. No groundwater extractions in the Hungarian part of the pilot area;
6. No groundwater extractions in the Austrian part of the study area;

The simulated drawdown rates are indicated in Table 8 below.

The calculated steady state drawdown contours are indicated in Figures 31-36. These figures indicate the active extraction bores corresponding to each reservoir type. It was assumed, that the lower Pannonian aquitard behaves as a hydraulic barrier (The model results disprove this assumption). For this reason, the outcrop line of the lower Pannonian strata is also indicated in the drawdown plots.

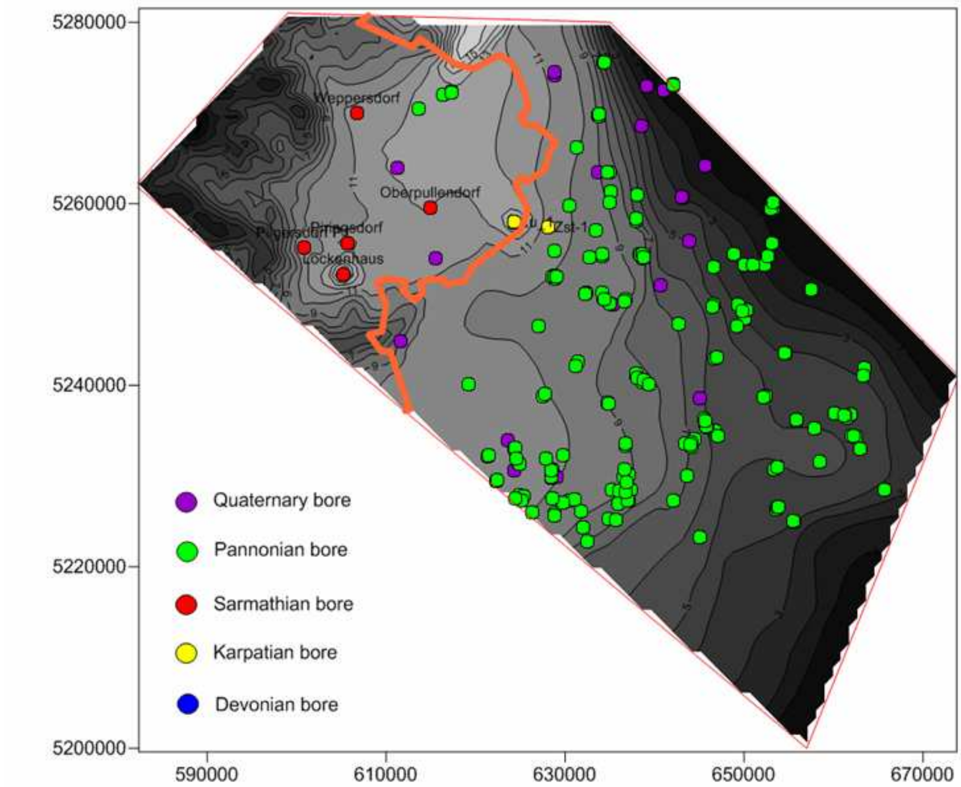

Figure 31. Simulated drawdown in the Sarmathian reservoir - Scenario 1.

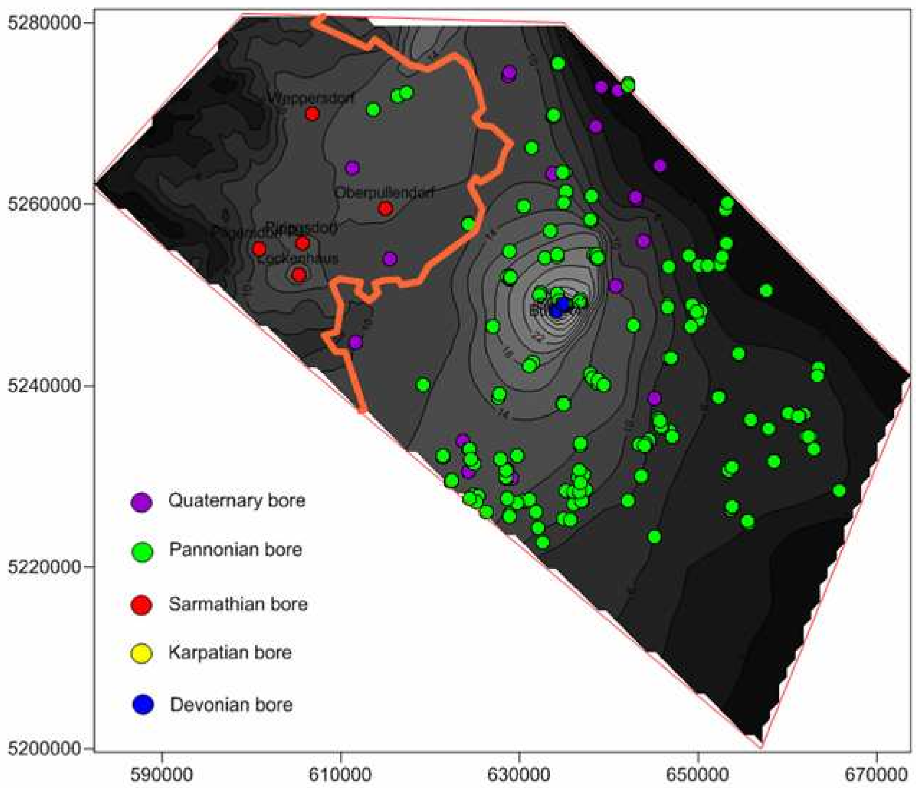

Figure 32. Simulated drawdown in the Sarmathian reservoir - Scenario 2.

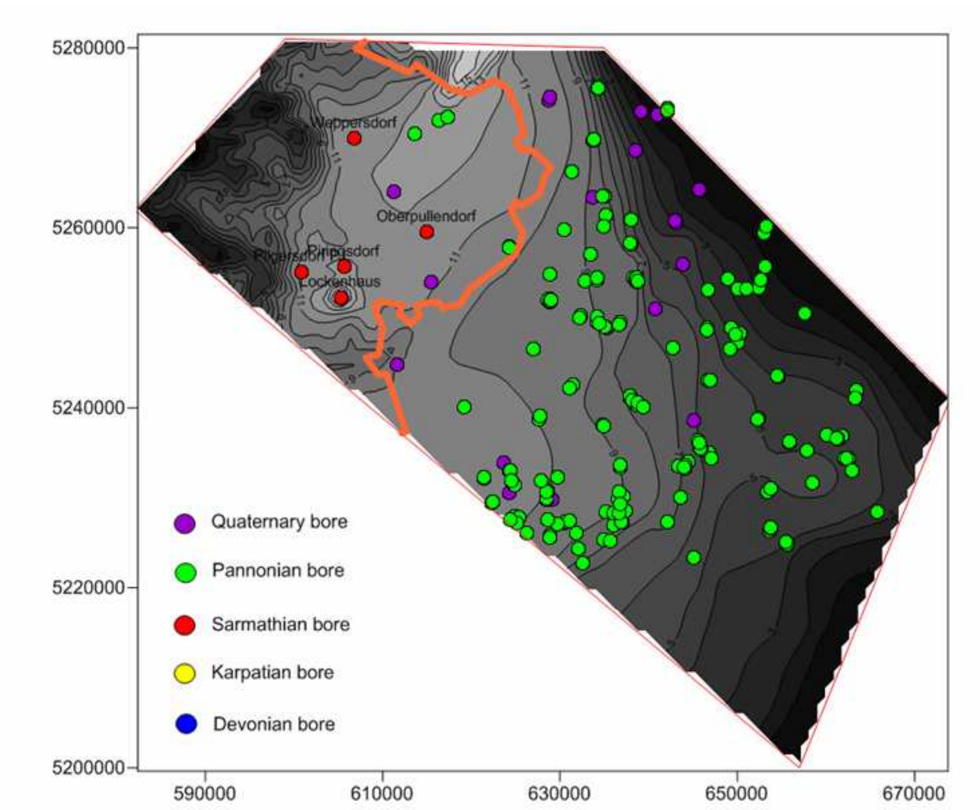

Figure 33. Simulated drawdown in the Sarmathian reservoir - Scenario 3.

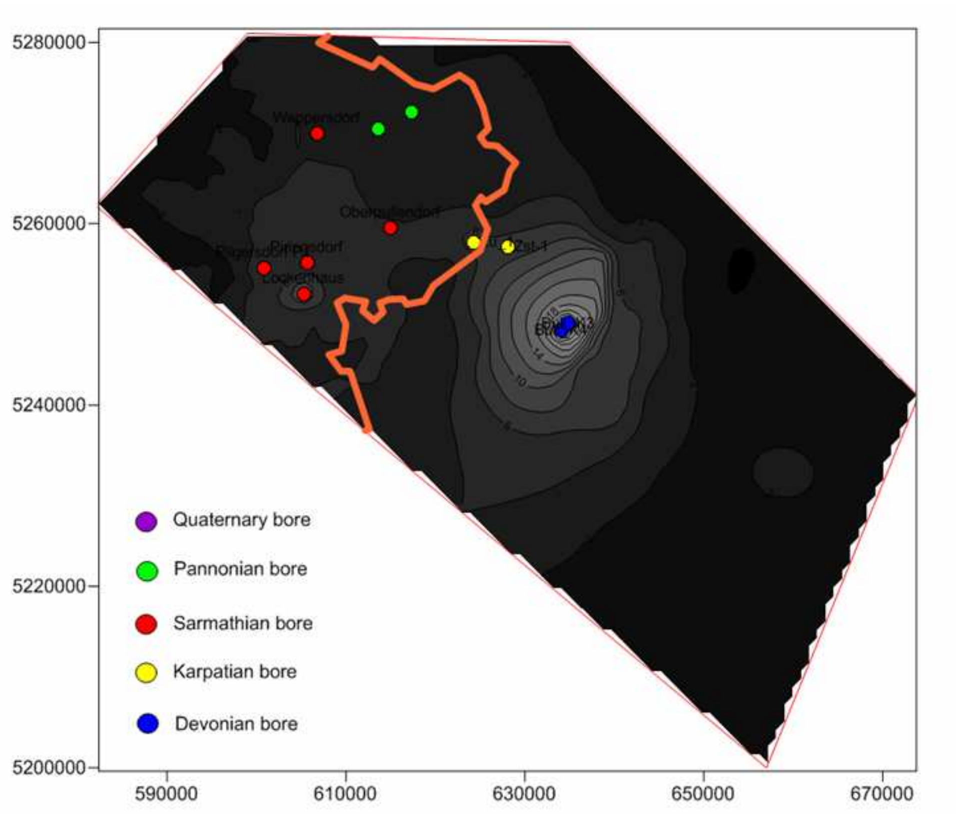

Figure 34. Simulated drawdown in the Sarmathian reservoir - Scenario 4.

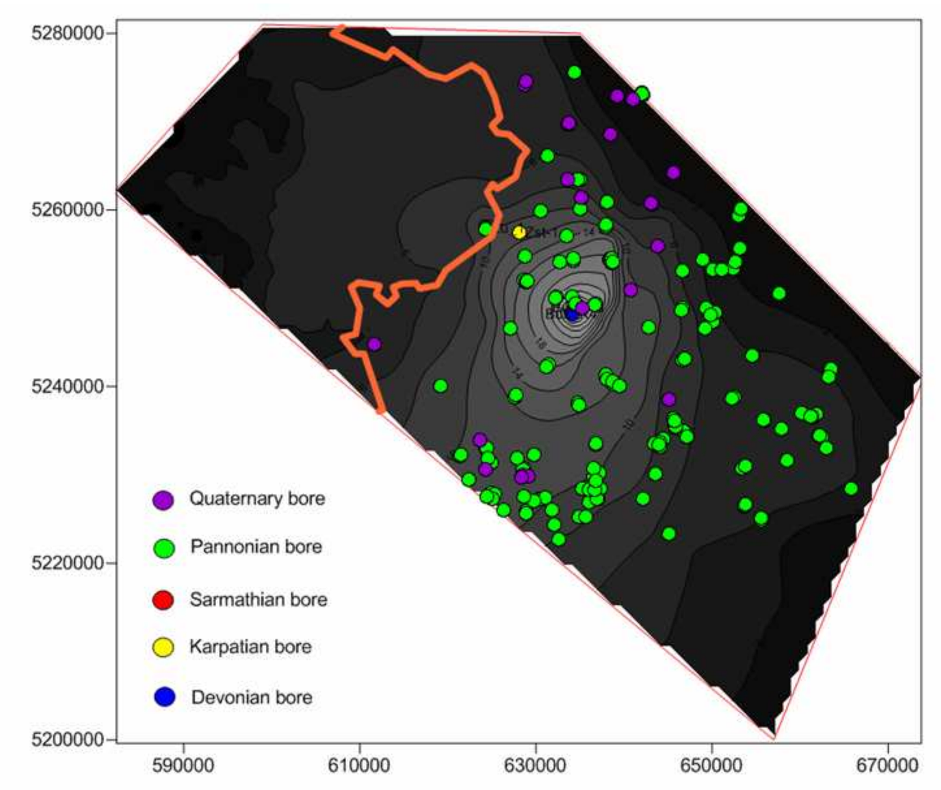

Figure 35. Simulated drawdown in the Sarmathian reservoir - Scenario 5.

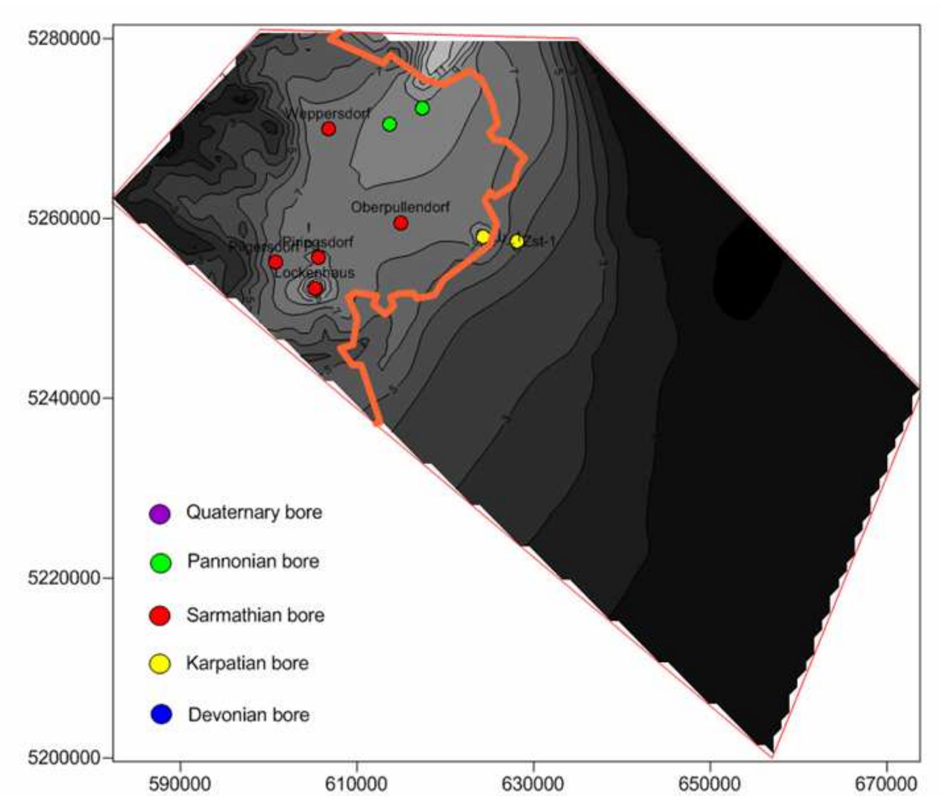

Figure 36. Simulated drawdown in the Sarmathian reservoir - Scenario 6.

The drawdown scenarios indicate the following:

- Both the Bük and Lutzmannsburg extractions contribute to the drawdown observed in Zst-1;
- The upper Pannonian extractions also contribute to the depressurisation observed in Zst-1. When the Bük and Lutzmannsburg bores are switched off, an approximate 10 m depressurisation remains in the borderzone area. This suggests, that the lower Pannonian aquitard is not an effective hydraulic barrier in the long term;
- The contribution of the Upper Pannonian and Quaternary extractions located in Hungary is comparable to that of the Bük and Lutzmannsburg extractions. Both extraction groups contribute to the depressurisation along the borderzone equally;
- The Sarmathian extraction bores located in Austria contribute to the depressurisation in the border zone (especially the groundwater extractions at Lockenhaus);
- Both Austrian and Hungarian extractions contribute to the depressurisation in Zst-1; the contribution of the Hungarian bores is slightly larger.

Table 8. Simulated depressurisations.

Bore	Simulated depressurisation (m)						
	current production	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Zsira-1	15,3	10,6	14,1	9,6	9,7	5,1	11,2
Lutzmsb Th-1	32,3	30,7	11,4	10,1	21,5	25,7	27,3
Bük K-4	59,9	9,4	59,0	9,1	51,5	3,1	56,8
Bük K-10	49,8	9,3	49,3	8,9	41,8	3,0	47,1

The above observations indicate that a harmonised cross-boundary groundwater management is essential for the successful optimisation of groundwater and thermal water utilisation.

7.3 Predictive scenarios

7.3.1 Increased production (Scenario 7)

In order to investigate the potential consequences of the future stress on the geothermal and groundwater systems of the pilot area, a twofold increase in production rates has been simulated. This included the increase of existing productions (no additional production bores were introduced) and the simulation of equilibrium potentials. The simulated groundwater table drawdown contours (compared to natural state) are indicated in Figure 37. The depressurisation of the Sarmathian reservoir (compared to natural state) is indicated in Figure 38.

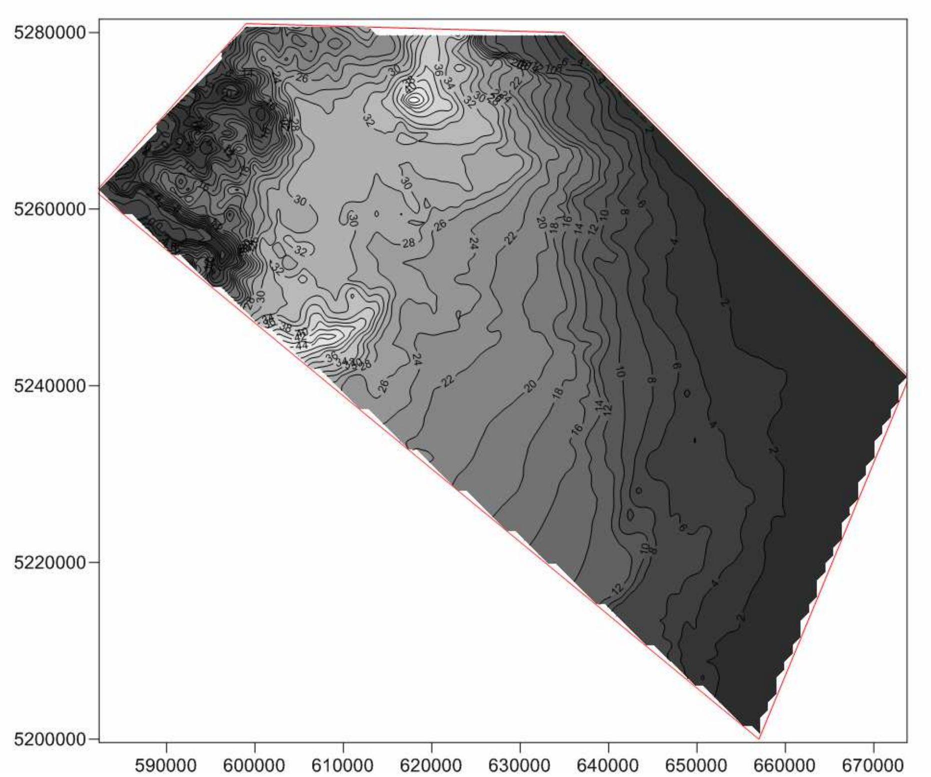

Figure 37. Simulated water table drawdown. Scenario 7 – increased extraction rates .

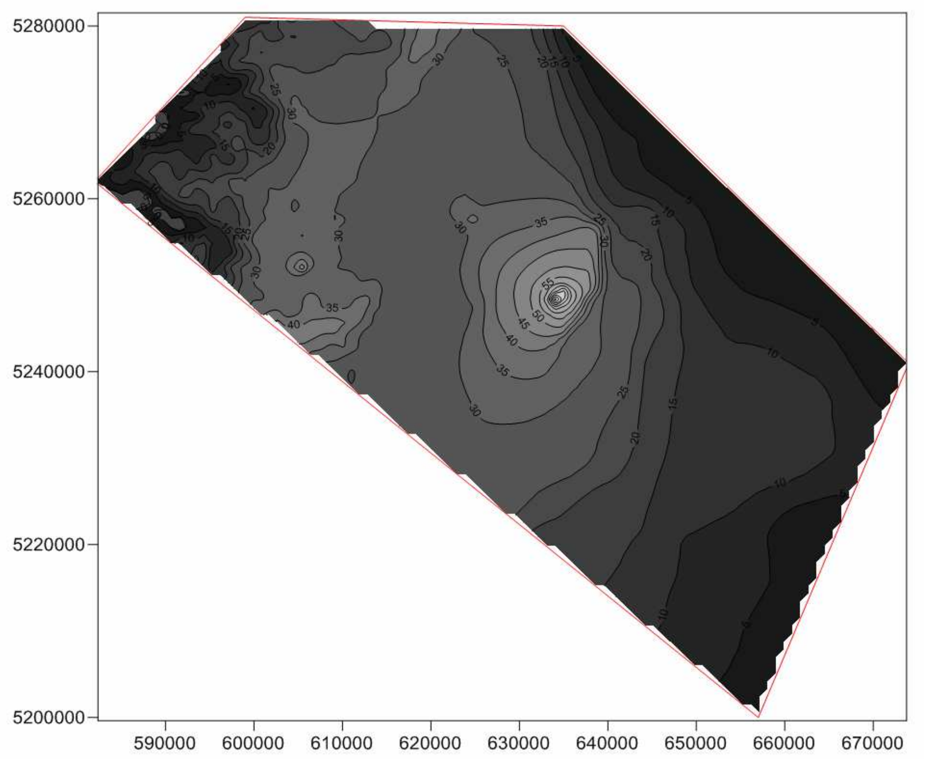

Figure 38. Simulated depressurisation in the Sarmathian reservoir. Scenario 7 – increased extraction rates.

Simulation results predict a significant increase in water table drawdown of up to 16 metres in the border zone of the pilot area. While current simulated drawdown was around 10-12 metres, the predicted drawdown in this area is around 26-28 metres.

Similarly, the current depressurisation of the Sarmathian reservoir of 12 metres simulated in the border zone is predicted to increase to 30 metres in response of a twofold increase in production rates.

Predictive model results suggest that the increase of extraction rates would put a significant stress on the groundwater system.

7.3.2 Bore doublet (Scenario 8)

In order to investigate the thermal effects of reinjection of geothermal heating water, a geothermal bore doublet has been simulated. Scenario 8 included the simulation of an extraction and a reinjection bore in the Eastern Devonian dolomite block. This reservoir is similar to the dolomite reservoir exploited by the Bük extraction bores, but is hydraulically independent and thus not affected by artificial activities. Similarly to the Bük extraction bores, 1500 m3/day extraction rate has been applied. The same amount is reinjected in a bore located approximately 500 metres apart . Using a conservative approach, the temperature drop is plotted in Figure 39, assuming infinite operation time.

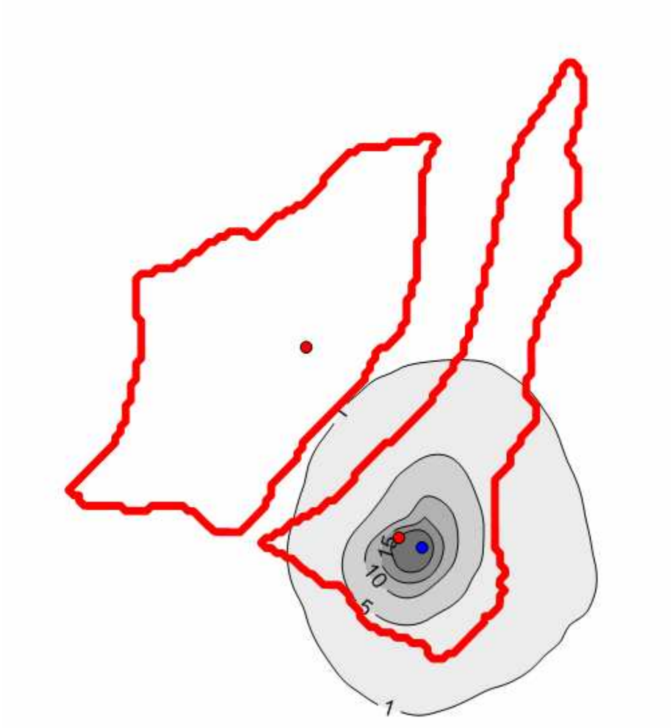

Figure 39. Steady-state temperature drop around the reinjection bore of a virtual bore doublet installed in the Eastern Bük dolomite block. Simulated extraction rate is 1500 m3/day, reinjection temperature is 20 C.

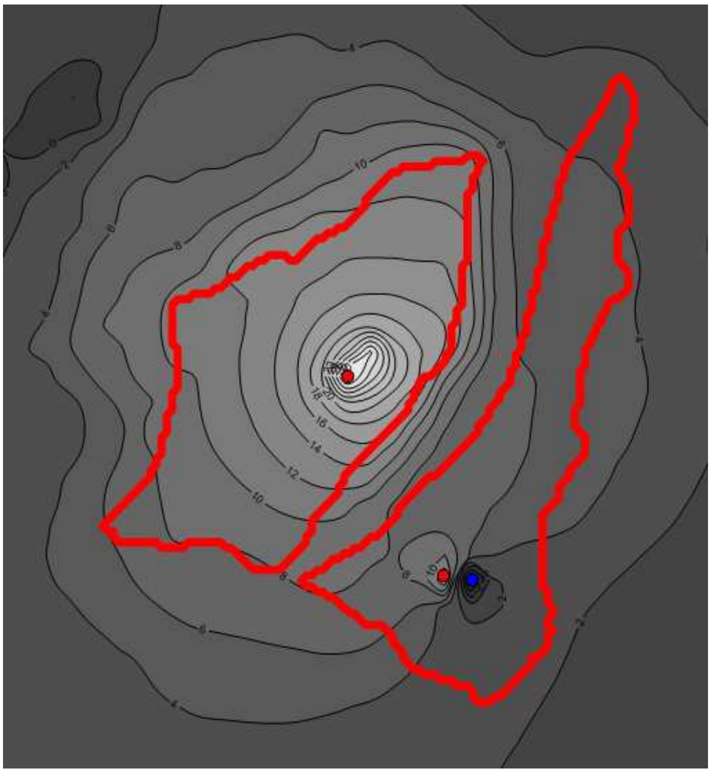

Figure 40. Steady-state drawdown rates around a a virtual bore doublet installed in the Eastern Bük dolomite block. Simulated extraction rate is 1500 m3/day, reinjection temperature is 20 C.

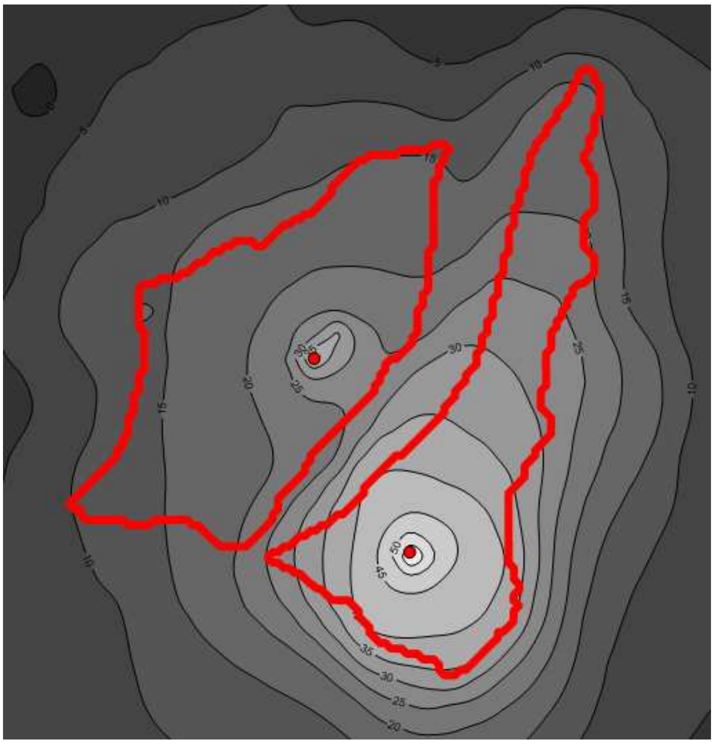

Figure 41. Steady-state drawdown rates around a virtual extraction bore installed in the Eastern Bük dolomite block. No reinjection assumed. Simulated extraction rate is 1500 m3/day.

According to the simulation results, the reinjection bore had a thermal influence in a circle of 4 km radius around the bore. The cooling effect did not extend far beyond the boundaries of the dolomite block. Using a transient simulation, the thermal influence did not extend more than 500 metres around the reinjection bore within 20 years of simulation time.

The simulated drawdown plots indicate, that the extraction bore had a steady state depressurisation of up to 60 metres without reinjection. If reinjection is applied, the maximum depressurisation rate around the extraction bore dropped to 13 metres. At the same time, a pressure increase of 7 m developed around the reinjection bore.

Based on the Scenario 8 simulation, it can be stated that reinjection of the extracted fluids significantly decreases the hydraulic impacts of groundwater extraction. The cooling effect of cold water reinjection had little influence of the temperature distribution within 20 years of simulation time, and has only a local impact on reservoir temperatures in the case of long-term utilisation.

8 RESOURCE ESTIMATION

Estimation of geothermal resources in the model area was undertaken to identify potential geothermal resources. The resource estimation included the calculation of the following:

- Heat In Place (HIP): The heat in Place represents the theoretically available heat content by cooling down the entire rock volume of a reservoir to a defined reference temperature. In reality it is not technically feasible to extract the entire HIP from a rock volume.
- Inferred Geothermal Resource (IR): An Inferred Geothermal Resource is the theoretical extractable amount of heat assuming a multiple well scheme. It is that part of a Geothermal Resource for which recoverable thermal energy can be estimated only with a low level of confidence.
- Measured Geothermal Resource (MR): A Measured Geothermal Resource is the part of a geothermal resource, which has been demonstrated to exist through direct measurements that indicate at least the reservoir temperature, reservoir volume and well deliverability, so that the recoverable thermal energy can be estimated with a high level of confidence.

The above resource parameters were obtained through a grid-based calculation to characterise the spatial variability of geothermal potential. A 1000x1000 m grid was applied. While Heat In Place was calculated for the Devonian, Miocene and upper Pannonian reservoirs, Inferred and Measured resources were only calculated for the Devonain dolomite reservoir as this was the main focus of our investigation.

HIP was calculated for three different utilisation schemes, each characterised by a different reference temperature. These included balneological use (T_{ref} 10 C°), heat supply (T_{ref} 25 C°) and electricity generation (T_{ref} 55 C°). The calculated HIP distributions are shown in Figures 42-44. The IR distributions for the Devonian dolomite reservoir are provided in Figures 45.

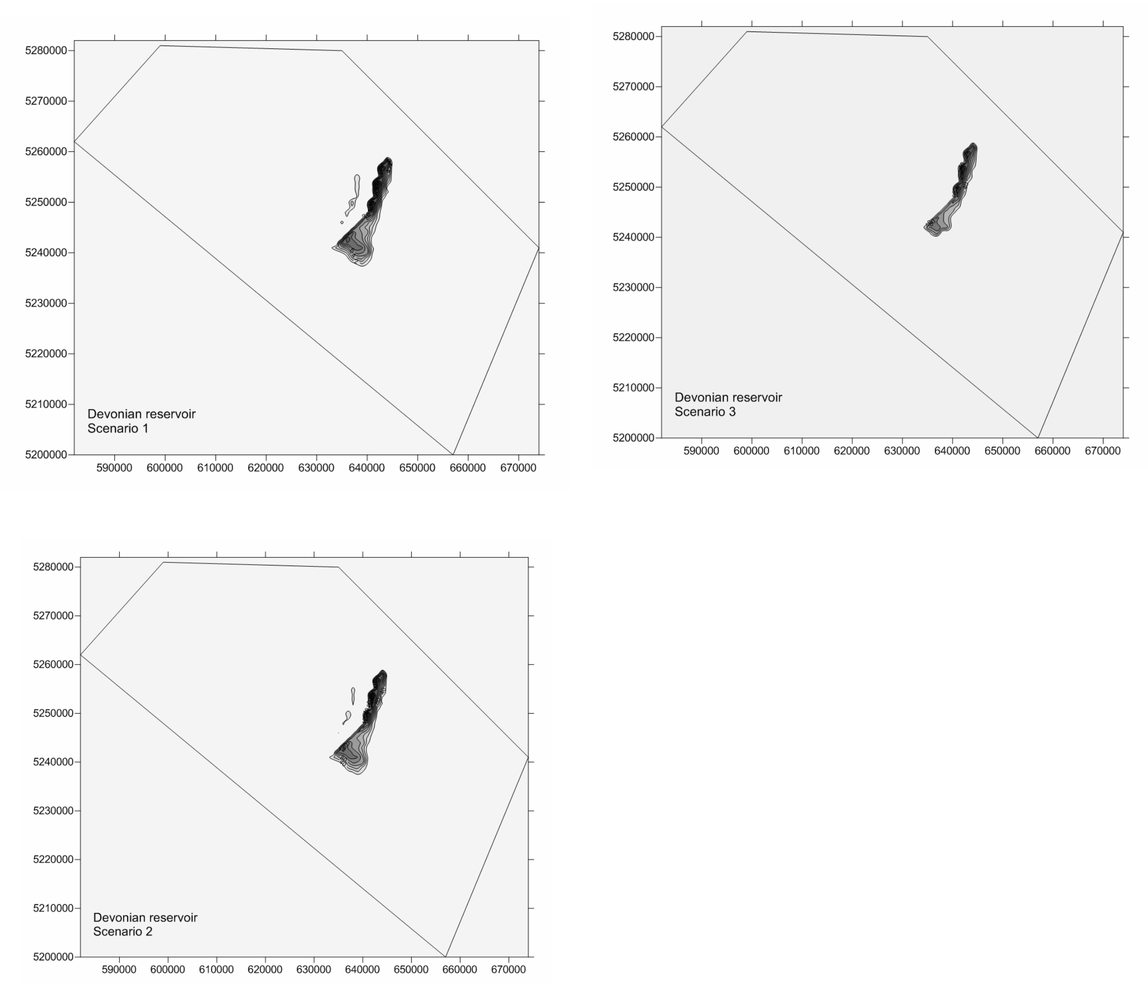

Figure 42. Heat In Place distribution, Devonian reservoir.

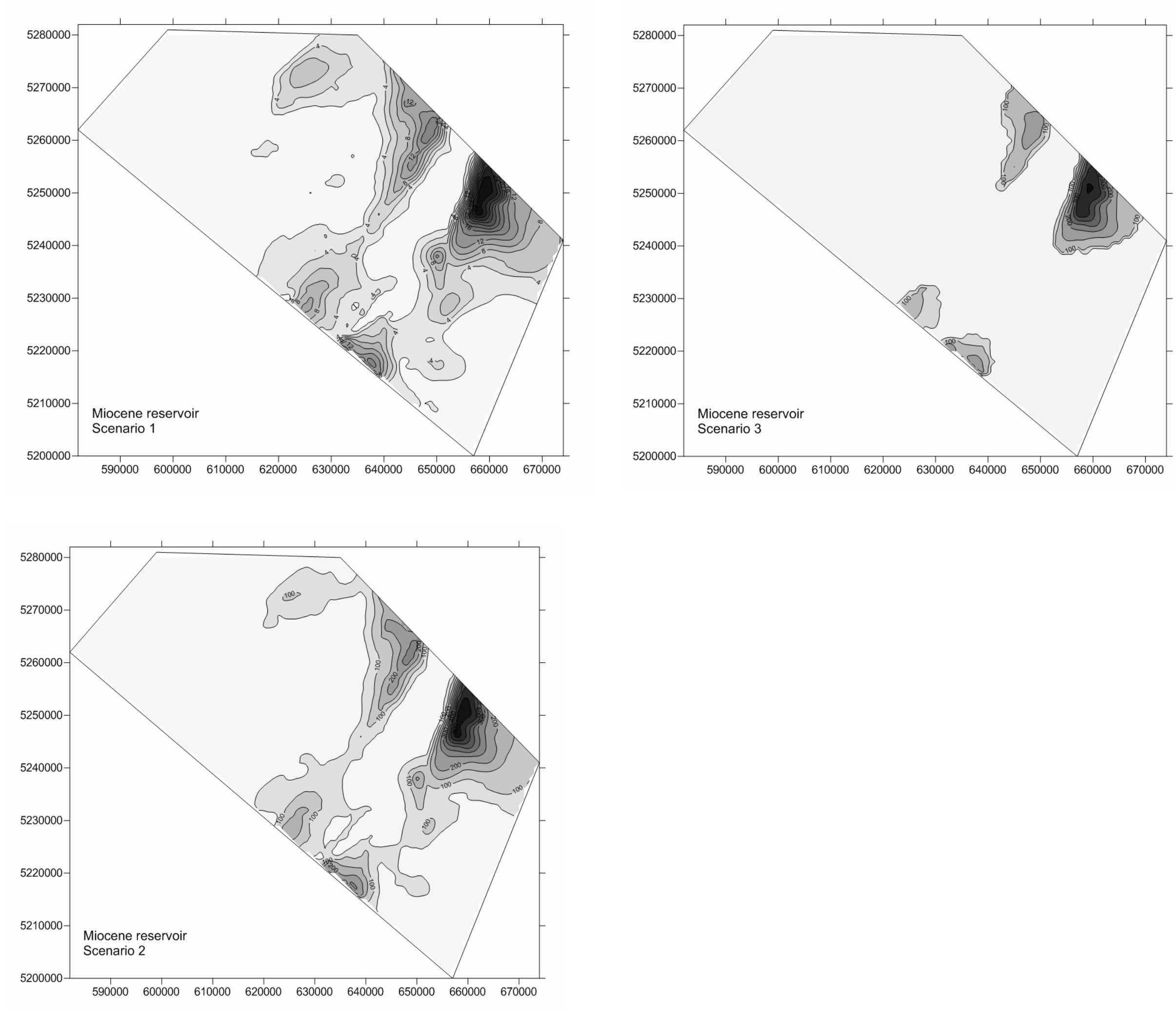

Figure 43. Heat In Place distribution, Miocene reservoir.

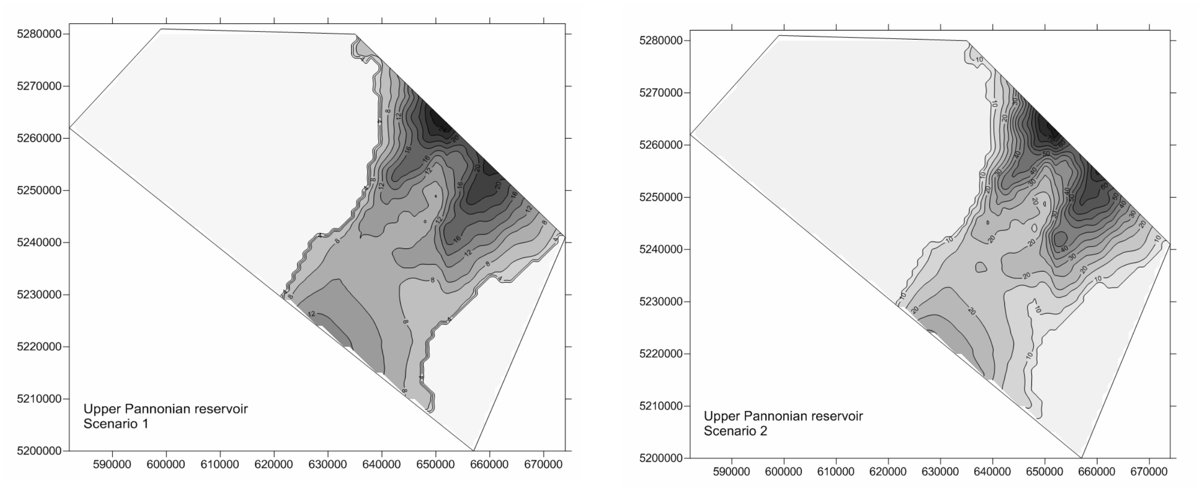

Figure 44. Heat In Place distribution, upper Pannonian reservoir.

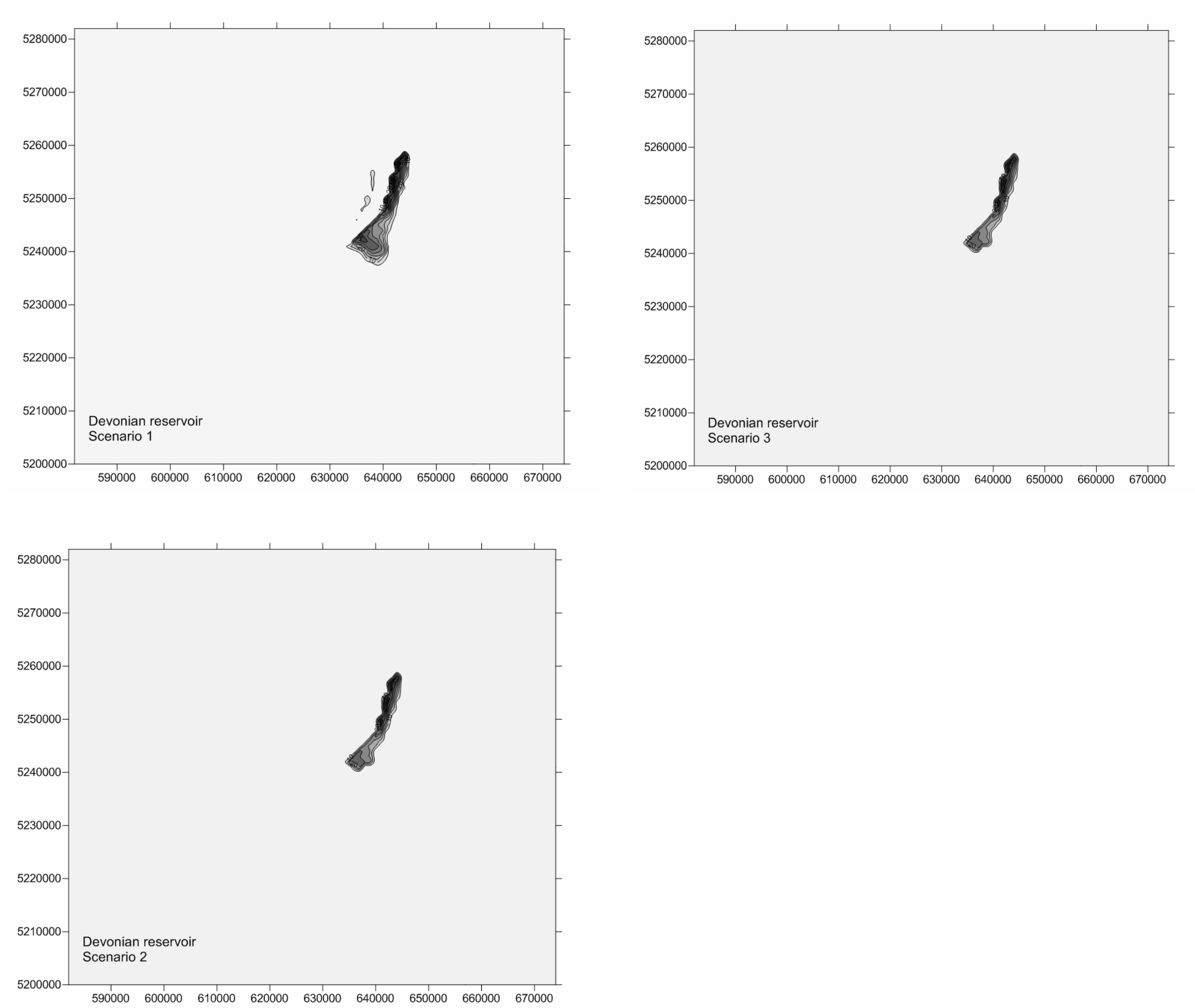

Figure 45. Inferred Resources distribution, Devonian reservoir.

Table 9. Total Heat In Place (MW for 50 years of utilisation).

Reservoir	Scenario	HIP (MW, 50y)
Devonian	scenario1	411,7
	scenario2	7014,1
	scenario3	3602,8
Miocene	scenario1	11471,7
	scenario2	184411,6
	scenario3	64707,8
Pa2	scenario1	16760,2
	scenario2	37198,9
	scenario3	0

Table 10. Total Inferred and Measured Resources (MW for 50 years of utilisation). Devonian dolomite reservoir.

Scenario	IR (MW, 50y)	MR (MW, 50y)
Scenario 1	22,4	22,3
Scenario 2	1809,0	433,8
Scenario 3	919,0	39,4

The Heat in place calculation indicates the following:

- The Devonian reservoir has limited energy resources because of its limited spatial extent. For this reason geothermal development has low potential in the case of this reservoir.
- The most prospective reservoir is the Miocene reservoir, where almost 200 GW energy is stored assuming a heating supply utilisation scheme. An order of magnitude lower energy is estimated for this reservoir assuming balneological or electricity supply utilisation schemes.
- The upper Pannonian reservoir contains 16 GW energy assuming balneological use, and 37 GW energy assuming heating supply utilisation.Temperatures are insufficient for electricity generation in this reservoir.
- The most perspective areas are located along the northeastern model bounday in the areas of Rábakecöl-Pápoc and Himod-Csapod.

9 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 and the production state of the groundwater flow field and geothermal temperature distribution and to investigate future production scenarios, a three-dimensional finite element type coupled groundwater flow and heat transport model was constructed. This report presents the results of scenario modelling in the Zsira-Lutzmannsburgpilot pilot area.

The natural state model provided three-dimensional information on hydraulic head distribution, groundwater fluxes and temperature distribution. The simulated groundwater head distribution and calculated flux distribution indicated that the dominant flow direction is towards the east following a semi-radial pattern. The groundwater is recharged mainly via surface infiltration. The Marcal Valley and the Répce valley represent the regional discharge area, while the north-eastern side of the model is a cross-flow area.

The production state simulation results indicate that regional groundwater table drawdown varys between 1-15 metres in response to groundwater extraction. The largest drawdowns exists in the western side of the model domain resulting from the depression of resource bores located in Austria.

The current depressurisation of pre-neogene aquifers generally varies between 2-12 metres. The largest pressure drop is simulated to exist around the Bük extraction bores. A significant depressurisation is observed around the Lockenaus extraction bore.

With respect to the Zsira-Lutzmannsburg local system, the model scenarios indicate that both the Bük and Lutzmannsburg extractions contribute to the drawdown observed in the Zsira Zst-1 monitoring bore. The upper Pannonian extractions also contribute to the depressurisation observed in Zst-1. The contribution of the Upper Pannonian and Quaternary extractions is comparable to that of the Bük and Lutzmannsburg extractions. Both extraction groups contribute equally to the depressurisation along the borderzone. The Sarmathian extraction bores also contribute to the depressuriastion in the border zone. Both Austrian and Hungarian extractions take part in the depressurisation in Zst-1; the contribution of the Hungarian bores is slightly larger.

Simulation of a twofold increase in existing extraction rates indicates a significant increase in water table drawdown of up to 16 metres in the border zone of the pilot area. Similarly, the current depressurisation of the Sarmathian reservoir was predicted to increase by 18 metres in response to increased production rates. Predictive model results suggest, that the increase of extraction rates would put a significant stress on the groundwater system.

The steady state simulation of a geothermal bore doublet targeting the Devonian dolomite indicated that the reinjection of the extracted fluids would significantly decrease the hydraulic impacts of groundwater extraction. The cooling effect of cold water reinjection had little influence on the temperature distribution within 20 years of simulation time, and has only a local impact on reservoir temperatures in the case of long-term utilisation. Reinjection of the extracted thermal waters is thus the recommended practice for future geothermal developments in this reservoir.

Resource calculations indicate that The Devonian reservoir has limited energy resources because of its limited spatial extent. The most promising reservoir is the Miocene reservoir, where almost 200 GW energy is stored assuming a heating supply utilisation scheme. An order of magnitude lower energy is estimated for this reservoir assuming balneological or electricity supply utilisation schemes. The upper Pannonian reservoir contains 16 GW energy assuming balneological use, and 37 GW energy assuming heating supply utilisation.Temperatures are insufficient for electricity generation in this reservoir. The most promising areas for gethermal utilisation are located along the northeastern model bounday in the areas of Rábakecöl-Pápoc and Himod-Csapod.

10 REFERENCES

Csepregi, A., Gy. Ágotai., Izápy, G. (2006). Wellhead protection zone delineation, Bük thermal spa area. HYDROSYS Ltd.

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

Kovacs, A. & Szalkai-Rotar, A. (2013). Report on the Zsira- Lutzmannsburg pilot area model. Transenergy Project - Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia. Progress report.

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

Maros, G., et al., 2012: Summary report of geological models. Available on 30.1.2013 at: http://transenergy-eu.geologie.ac.at/

Rotar Szalkai Á. (2012): Evaluation of potencial demonstration sites by outlining geothermal reservoirs above 50 °C. http://transenergy-eu.geologie.ac.at/

Tóth, Gy., Rotár-Szalkai, Á., Kerékgyártó, T., Szőcs, T, Gáspár E. (2012): Summary report of the supra-regional hydrogeological model. http://transenergy-eu.geologie.ac.at/

Watermark Numerical Computing (2004): Model-Independent Parameter Estimation. User Manual: 5th Edition.